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The rural vernacular construction of the
Entre-Douro-e-Minho

Carlos Eduardo Santos Barroso

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Universidade do Minho
Escola de Engenharia

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Tese de Doutoramento
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Trabalho efetuado sob a orientação do
Professor Doutor Daniel V. Oliveira
Professor Doutor Luís F. Ramos

janeiro de 2019

STATEMENT OF INTEGRITY

I hereby declare having conducted my thesis with integrity. I confirm that I have not used plagiarism or any form of falsification of results in the process of the thesis elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, [redacted]

Full name: Carlos Eduardo Santos Barroso

Signature:

Aos meus pais, pelo seu amor e apoio incondicional

To my parents, for their love and unconditional support

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ABSTRACT

Vernacular heritage has been recognized by the international community for its high cultural value and economic potential to the development of rural Europe. Although acknowledged as fundamental for collective identity, vernacular heritage is nowadays an endangered heritage. It is threatened by rural exodus and the fading of traditional ways of life, but also by touristic and real estate speculation, and by severe losses of identity caused by lack of knowledge.

This thesis aims to contribute to the discussion around vernacular heritage preservation. This work collects, shares, and contributes with knowledge to the topic, but also puts forward a methodology to support preservation and reuse of vernacular buildings. Focusing in the Entre-Douro-e-Minho region, the first task was to establish suitable methodologic principles for heritage preservation. Based in these and performing exploratory visits, landscape and vernacular architectures were analysed from morphological, typological, constructive, and state of preservation points of view. Results are presented in this thesis as a reference database, useful to set heritage buildings' authenticity and identity criteria.

Severe abandonment and losses of identity on still existing heritage were witnessed in the field. Lack of use and maintenance, poor technical skills and inappropriate human intervention were identified as main causes. Recognizing the scarcity of technical information regarding vernacular constructions, the research focused on contributing with experimental data on rocks used on vernacular buildings. Results of a detailed experimental campaign on granites and schists are presented, making available physical, mechanical and durability characterization data. Results show the influence of rocks' mineral and planar structures on performance and durability.

To demonstrate the potential of the developed methodology, two case studies were analysed. In the first, a scientific-based decision-making process was established and used, and a compromise solution between new and vernacular features was found. The work performed on the second case study proved the potential of multi-skilled teams and of using advanced survey tools to analyse heritage buildings presenting specific features (e.g. complex geometry).

RESUMO

O património vernáculo tem vindo a ser reconhecida pela comunidade internacional pelo seu elevado valor cultural e pelo seu potencial económico para o desenvolvimento da Europa rural. Apesar de reconhecida pelo seu papel fundamental na identidade coletiva, a construção vernácula é atualmente um património em riscos. As ameaçadas resultam do êxodo rural e do desvanecimento dos modos de vida tradicionais, mas também surgem da especulação turístico-imobiliária, e sistemáticas perdas de identidade e autenticidade resultantes da falta de conhecimento.

Nesta tese pretende-se contribuir para a discussão em torno da preservação do património vernáculo. Este trabalho recolhe, partilha e contribui com conhecimento para o tema, mas também apresenta uma metodologia de apoio à preservação e reutilização de edifícios vernáculos. O estudo foca-se na região do Entre-Douro-e-Minho, e tem como primeira tarefa estabelecer os princípios adequados à preservação do património. Baseado nestes e na realização de visitas exploratórias ao território, a paisagem e a seu edifícios arquitetura vernácula foram analisados quer do ponto de vista morfológico e tipológico, mas também construtivo e estado de preservação. Os resultados obtidos apresentados nesta tese, tem como objetivo constituir uma base de dados de referência, utilizável para estabelecer critérios de autenticidade e identidade. No decorrer do trabalho foi possível testemunhar o profundo abandono e as perdas de identidade do património ainda existente. Como principais causas identificou-se a falta de uso e ausência de manutenção, os débeis conhecimentos técnicos e as intervenções inadequadas. Reconhecendo a escassa informação técnica referente à construção vernácula, a pesquisa realizada focou-se no contributo com dados experimentais sobre rochas utilizadas na construção vernácula. São apresentados os resultados da campanha experimental feita em granitos e xistos, disponibilizando-se dados de caracterização física, mecânica e de durabilidade.

Para demonstrar o potencial da metodologia desenvolvida, recorreu-se a dois casos de estudo. No primeiro caso, foi utilizado um processo de decisão de índole científico, obtendo-se uma solução de compromisso entre novo e o vernacular. O trabalho elaborado no segundo caso de estudo provou o potencial das equipas multidisciplinares e da aplicação de ferramentas avançadas de levantamento na análise de construções patrimoniais específicas (ex.: geometria complexa).

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

-	No information available
A	Direction of walls transversal to the door
aa'	internal axis transversal to the door
A_b	Water absorption at atmospheric pressure (%)
A^I	Usable internal area
ANs	Anisotropic scale calculated for schists, based on parameters variations accordantly to orthogonal orientations (N, P1 and P2) (%)
ANs_E	Anisotropic scale calculated for schists elastic behaviour, based on N to P variation (%)
ANs_F	Anisotropic scale calculated for schists flexural behaviour, based on N to P variation (%)
ANs_R	Anisotropic scale calculated for schists strength behaviour, based on N to P variation (%)
ANs_w	Anisotropic scale calculated for schists capillary water absorption behaviour, based on *C* parameter N to P variation (%)
A_P	Gross built area of walls, being PA for direction A and PB for direction B
A_{PA}	Gross built area of walls for direction A
A_{PB}	Gross built area of walls for direction B
A^T	Gross built area
Avg	Average calculated from a range of results
B	Direction of walls parallel to the door
b	Width of specimen (mm)
bb’	Internal axis parallel to the door
C	Boundary between walls and corbelled domes
C	Capillary coefficient (g/m^{2}s^{0,5})
c	Number of testing cycles concluded [see each specific testing for time measure]
coord.	Coordinating entity
CoV	Coefficient of variation
c_{peak}	Crack opening at peak load
d_{peak}	Displacement at peak load
dry	Specimens tested under dry mass conditions
$_{dry}$	Specimens tested under dry mass conditions
E	Static elastic modulus (GPa)
e_1e_1'	Average cross-section width at the top of the wall
e_2e_2'	Average cross-section width at the base of the wall
E_d	Dynamic modulus of elasticity, in this research calculated based on P-waves
ee'	Average cross-section width at the centre of the wall)
F_{cu}	Number of rows of corbelled domes
F_G	Final grade obtained from the average value of added parameters on a decision-making methodology
$_{fin}$	Final result
FR	Freezing cycle
GA	Amarela Granite
G*cycles*	Group of 5 specimens tested for frost resistance, with the number indicating the respective number of freeze-thaw cycles repeated
GE	Edge Granite
H	External average height
h	Average height of walls
h	Thickness of specimen (mm)

H'	External average height
h'	Average height of corbelled domes
i	Span or distance between the axis of the support rollers on beams under flexural testing (mm)
IC	Ice cycle
IM	Immersion cycle
indv.	Individual unit or element
$_{\text{ini}}$	Initial result
int.	Internal dimension or area
L*n*	External axis
l	Internal axis
L	Length of specimen (mm)
LD	Level of damage
MAX; *min.*	Maximum value calculated from a range of results
m_{d}	Dry mass (g/cm^3)
m_{h}	Mass immersed in water (g/cm^3)
m_{i}	Intermediate successive specimens mass weighing (gr)
min	Minutes
MIN; *max.*	Minimum value calculated from a range of results
m_{s}	Water saturated mass (g/cm^3)
N	Specimens tested in a normal direction to foliation
n.a.	Not acquired
P(1 - 5)	Weighted parameters used on a decision-making methodology
P1/P2	Specimens tested in a parallel direction to foliation
P^{e}	External built perimeter
PFo	Preferred orientation scale calculated for granites, based on parameters variations accordantly to orthogonal orientations (N, P1 and P2) (%)
P^{i}	Internal built perimeter
P^{im}	Base plan configuration
R	Strength resistance (MPa)
REF.	Reference values
R_{tc}	Flexural strength under constant moment (MPa)
Ru	Failure by rupture of specimens, due to specimens splitting into independent halves
sat	Specimens tested under dry water saturated conditions
$_{\text{sat}}$	Specimens tested under water saturated conditions
TH	Thawing cycle
un.	Unit (s)
var	Variation between two successive or initial and final values
var.	Variation of a parameter calculated between na initial and a final parameter, or resulting from a time progression (%)
V_{b}	Apparent volume (ml)
V_{o}	Volume of open pores (ml)
vol.	Volume
V_{P}	Estimate volume of walls
XA	Andalizitic Schist
XL	Granetiferous schist (Light Ochre)
XM	Mica schist

XR	Granetiferous schist (Light Red)
ΔM	Mass variation between testing initial and final values (gain or loss) (%)
ρ_b	Apparent density (kg/m^3)
ρ_o	Open porosity (%)

LIST OF ACRONYMS

AG	Applied Geotechnologies Research Group
ASTM	American Society for Testing and Materials
CA	Casa Portuguesa (Portuguese House movement)
DT	Destructive Testing
EN	European Standard
ER	Ethnology Research group
FAUP-CEAU	Faculty of Architecture of University of Porto/Centre for Studies in Architecture and Urbanism
IAGE	International Association for Engineering Geology
IARP	*“Inquérito à Arquitectura Regional em Portugal”* (Survey to the Popular Architecture in Portugal
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOM	International Council of Museums
ICOMOS	International Council on Monuments and Sites
ICOMOS-CIAV	International Committee of Vernacular Architecture
ICOMOS-ISCS	International Scientific Committee for Stone
ICOMOS-ISCARSAH	International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage
IHR	*“Inquértio à Habitação Rural”* (Inquiry to Rural Housing)
ISA	Instituto Superior Agrário (Agrarian Superior Institute)
ISISE	Institute for Sustainability and Innovation in Structural Engineering
ISO	International Organization for Standardization
LEST	Laboratory of Structures, University of Minho
LIDAR	Light Detection and Ranging
ND	Non-Destructive Testing
NP EN	European standard Portuguese version
ONU	United Nations Organization
PDM	*“Plano Directo Municipal”* (Municipal Master Plan)
REGEU	*“Regulamento geral para edificações Urbanas”* (General Regulation for Urban Buildings)
RH	Relative humidity
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPV	Ultrasonic Pulse Velocity

Chapter 1

INTRODUCTION

In the search for a more sustainable future for contemporary society, the preservation and reuse of heritage come as one of its main strengths in what concerns territory management policies and resources management [1]. In this sense, the future of Europe does not only relay on preserving the heritage of its urban territories, but also the heritage existing in its vast extensions of its rural landscape, densely occupied for centuries by all sorts of context adapted communities. . From intense territory occupation, resulted a strongly humanized landscape covered by all types of extraordinarily rich examples of rural architectures [2].

Among such heritage, and adopting ICOMOS [3] definition, vernacular heritage can be described as an intuitive response of human inventiveness to survival needs, using available resources and knowledge perfected by centuries-old building experience to humanize and make the territory productive [2,4]. Following the definitions presented by Gilberto et al. [2], although being a part of a broader group known as traditional architecture, vernacular examples distinguish themselves for being a product of o local knowledge and building solutions, not related to elaborated or monumental models of building. Being either the outcome of self-construction or the product of skilled-labour, vernacular buildings' character is defined by the lack of scholarly influences, or the use of complexed or scientific based building techniques. Although similar in many ways, vernacular architecture dissociates itself from the excessive pragmatism of typical popular architecture, and by absence in its buildings of industrial materials and foreign models an building techniques [2].

Although neglected in the past, vernacular heritage has been recognized in recent decades by the international community for its cultural value (both tangible and intangible), related to its high levels of authenticity and unrepeatability, and for being an inseparable half of the identity of rural communities [3,5–7]. Nowadays, vernacular heritage management is integrated in the EU strategies for rural sustainable development and it is seen as a valuable endogenous economic resource, of high tourist potential, and very appealing to the eco-tourist consumer searching for authentic environments [8,9].

However, vernacular heritage and its centuries-old knowledge is nowadays endangered, with its cultural value and preservation facing several significative challenges.

From a sociologic point of view, vernacular buildings, in particular the vernacular house, are threaten by the negative image resulting from being the tangible symbol of a harsh and difficult past lives, incompatible with contemporary comfort standards and with new ways of life [10–12]. Related to the loss of the traditional ways of life, vernacular heritage decay process was early reported at the Entre-Douro-e-Minho by the end of the 19th century [13]. It became unstoppable from the mid-20th century onwards, caused by new life standards brought by the returning emigrants, that were latter adopted by the general rural population. Therefore, the vernacular house was progressively replaced by new models [12], and its constructive knowledge slowly faded away due to a construction industry that specialized in industrial materials and building techniques [8,14]. During this process, vernacular constructive knowledge was taken for granted, and therefore excluded until recently from the scientific discussion, focused on the study and preservation of monumental and urban centres cultural heritage.

As for the Portuguese rural context, the strong increase of migrations during the mid-20th century onwards, on one hand caused a strong rural exodus phenomena, particularly in its most economically depressed inland territories [11,12,15], leading to the abandonment of vernacular structures and loss of the traditional agro-pastoral production methods [8]. On the other hand, at the coast and near larger urban centres, population grew intensively, leading to uncontrolled growth of urban space into the rural territory [11,12,15]. In this process, with loss of the old ways, the rural territory development from the mid-20th century onward was mostly dictated by real estate, the construction industry and changes to the agrarian production methods, that radically changed the rural settlements and landscape [14,16,17]. However, to the severe loss of authenticity and identity of the rural landscape, other factors can be highlighted. Among others, the insufficient number of technicians and builders able to deal with the demand for improved housing conditions and new buildings, the loss of old masters and break of the constructive knowledge transmission, and the unprepared territory management authorities that followed a legal framework focused on sanitation, urban and new construction, but neglected the specificities of heritage buildings (e.g. REGEU or the Decreto-Lei 73/73 of 28 of February) [12,14,16].

Presently, and particularly in territories of immense unexplored touristic potential such as the Northwest, the focus of present economic activity on rehabilitation and tourism, creates simultaneously an opportunity and a threat to vernacular heritage. On one hand, vernacular heritage and landscape are an opportunity for investment on the extremely eco-appealing, yet economically depressed, rural territories, taking advantage of the growing search of Europeans for eco-friendly products and authentic destinations. On the other, stands for a threat regarding the lack of knowledge of communities for the cultural potential of their heritage, exposing vernacular heritage to losses of authenticity and identity. In this context, the fragile and already endangered vernacular heritage is facing a difficult balance between its potential as an economic asset and loss and destruction hazards that come with such status [18]. Alternative strategies that pass by the musealization of high value vernacular heritage examples have shown not be a feasible solution, seeming the restitution of vernacular heritage to the use of the community a more sustainable and possibly successful long-term strategy [19]. These strategies, recognized as a fundamental step to revive the rural world, require a careful adaptation and retrofitting of existing vernacular structures [7].

Therefore, it is part of the educational, social, and economic role of the academia to produce accurate and reliable scientific data regarding such topic, usable at a multidisciplinary level by all involved in the preservation and reuse of vernacular heritage (e.g. technicians, authorities, promoters, and communities). By doing so, an especially important first step is taken towards vernacular heritage successful preservation, and for its sustainable future.

1.1 Motivations

The need for studies such as the one presented in the following chapters, comes from the recognition of scarce and poor access to knowledge regarding vernacular heritage preservation possibilities in the Portuguese context. It was also recognized that, although in recent years, the scientific community became aware of such need and data has been produced, it is focused on specific topics, being global and multidisciplinary perspectives on the topic still very residual.

Regarding the existing scientific literature on the topic from other fields of expertise (e.g. architecture, anthropology or ethnography) [20], although offering detailed morphological and typological information about examples of vernacular buildings observed until the mid-20th century, their contribution with constructive data is residual. Understanding such limitation, particularly the scarce scientific information regarding the characterization of vernacular materials such as stone, the need of adding a technical perspective to the topic of vernacular heritage preservation became a main motivation for the current research. For its very high level of cultural diversity, the Portuguese Northwest rural landscape, previously known as Entre-Douro-e-Minho [16], is a territory recognized by its common and unique cultural identity, but also by very specific and authentic local cultural expressions. With scarce and disarticulated information regarding the regional vernacular heritage, and the need to provide tools to assist in its protection, made Entre-Douro-e-Minho the perfect case study area for the intended research. Taking into consideration that most of the above-mentioned detailed surveys on the rural world is from mid-20th century, and few updates were performed during the following decades, it was an extra motivational factor to contribute to the researchers enlighten regarding the current vernacular heritage’s state of preservation.

1.2 Objectives and methodologies

The research presented in the following chapters was planned and executed based on four objectives. As for the first, the research aims to contribute to the protection of vernacular knowledge by promoting is safeguarding and sharing. To do so, it was set as goal to collect and critically analyse the dispersed data on the topic, creating a data base of multidisciplinary knowledge, accessible to all actors involved in vernacular heritage preservation and management. With it, this research aims to assist on authenticity and identity features identification on vernacular buildings, and therefore, to contribute to the safeguarding of their cultural value.

As for the second, it was a central objective of the research to contribute to the knowledge field’s enlargement, by adding a technical perspective to the discussion. Therefore, and taking into consideration the scares scientific literature on the topic, the research focus on providing technical and scientific data regarding vernacular stones, in this particular case of schists and granites. Special attention was given to the experimental characterization of schists.

As for the third objective, within the time frame and scope of the research, it focuses on providing an overview regarding the vernacular building tradition, and for being an inseparable dimension of construction, of vernacular buildings state of preservation.

As a final and fourth objective, this document was planned to set a methodological example for addressing the topic of vernacular heritage preservation and rehabilitation. Therefore, examples of specific preservation methodologies were design using case studies of real challenges faced by rural landscape and vernacular heritage preservation. These methodologies were based in the international best practices and principles, supported by the knowledge of the data bases created in this research.

Regarding the methodology prepared to achieve the above-presented objectives, taking into consideration the complexity of the research topic under analysis, it was planned to reach different scales of analysis and levels of information. Therefore, the analysis was divided into a qualitative macro (territory), medium (settlements) and micro scale (buildings and building elements) analysis, followed by a qualitative and quantitative detailed scale analysis of vernacular stones. This system based in several different scales of analysis was a compromise solution between the research objectives and the overwhelmingly large territory and the diversity involving vernacular architecture phenomena under analysis. Therefore, the multi-scale analysis can provide an overview of all different topics under analysis, with suitable scientific accuracy needed for each, and to create conditions to support future and more detailed research.

As for the experimental campaign, it was designed taking into consideration rocks' experimental characterization from engineering and construction points of view. It is noteworthy that the exhaustive characterization and explanation of the mineralogic, physical, mechanical and durability phenomena under analysis overshoots the scope of this present work. Despite not directly related to vernacular heritage preservation, such topics are exhaustively documented in scientific literature of different fields of expertise.

As for the data collection during this research, it was based on: *i)* strong scientific literature support; *ii)* fieldwork exploratory visits; *iii)* detailed case study analysis; and *iv)* experimental analysis. The literature review, besides supporting the analysis of the different tasks, allowed directing exploratory visits to specific targets that required a more detailed analysis, either for being mentioned or for being absent in literature. The exploratory visits were a fundamental tool used for assessing in the field all information collected by reference studies on the rural world, but also to collected missing information regarding the architectural and constructive characterization of buildings, and to perform the state of preservation surveys. The choice of the case studies, and the identification of the tested vernacular stones were also based on data collected during exploratory visits. In these visits, information was mainly collected by observation and visual inspections (qualitative assessments), only using geometric and statistical survey methods (quantitative assessments) for very specific cases.

Therefore, the photographic surveys and the images presented is this document are fundamental as testimony of the conditions found on the field. On each image, location of the shown examples is presented inside rounded brackets by parish location or site, followed by municipality. It is noteworthy the difficulties faced on accessing the interior of buildings, thus the reason of the very few shown examples.

To be noticed that all figures, tables, and charts that do not mention another authorship, were produced and are outputs of this research, meaning they are property of the author of this document.

As for the experimental campaign, schists and granites were collected from the cases study addressed in this work and tested according to international standards. However, soil mortars and schists masonry wallets were, and still are, under analysis. By overshooting the time frame of this current work, results from these analyses will be presented in future publications on this topic.

1.3 Outline of the thesis

As for the thesis' outline, as previously mentioned, it was planned to demonstrate a suitable methodologic approach to address the topic of vernacular heritage preservation. Therefore, from Chapter 2 to Chapter 8, the constructed database is presented and provide all necessary support information regarding the case study analysis and intervention methodologies presented on Chapter 9. The chapters are as follows:

- Chapter 1 – Introduction: this chapter presents an introduction to the research topic, followed by main motivations, objectives, methodologies, and outline of the thesis;
- Chapter 2 - Overview Regarding Preservation and Rehabilitation Principles: this chapter presents an overview on best international practices on the heritage preservation's topic, with a special attention payed to vernacular heritage preservation guidelines and reference methodologies;
- Chapter 3 – Review of Studies on the Portuguese Rural World: this chapter presents a review of multidisciplinary scientific literature on the Portuguese rural world, produced over the 20th century.

The analysed studies shaped for decades the discussions on the Portuguese rural realities. Their information was used in this research for providing a first-hand testimony of lost rural contexts and buildings. Therefore, these studies supported the characterization of Entre-Douro-e-Minho vernacular heritage presented in the following chapters;

- Chapter 4 – Characterization of the Survey Area: this chapter presents an overview regarding the characterization of Entre-Douro-e-Minho study area. Multidisciplinary information is present regarding the territory geographic, human occupation strategies, and traditional social organization’s characterization. The information in this chapter helps to understand the context and purpose of regional vernacular heritage, a fundamental criterion to understand and identify heritage authenticity and identity principles. It results from an exhaustive literature review on the topic, with support from data collected during the exploratory visits;
- Chapter 5 – Morphologies and Typologies of Vernacular Heritage: this chapter presents a global overview on Entre-Douro-e-Minho vernacular architecture main morphological and topological features. As expected, this chapter represents a glimpse of the wide diversity observed during the exploratory visits. However, it shows the most representative types of buildings observed. As for the information presented, it is mainly from a qualitative origin, although with very specific quantitative assessments. The starting point of this task was the information collected from the literature review, exhaustively confirmed during the exploratory visits, as shown by the photographic material presented;
- Chapter 6 - Vernacular Building Techniques and State of Preservation: this chapter complements the characterization’s information of Chapter 5 and follows the same survey and analysis strategies. An overview on Entre-Douro-e-Minho vernacular construction’s tradition and materials is given, simultaneously with the main causes and types of damage observed. As a limitation to consider, ruined or partially demolished buildings were used as case studies. As for the damage assessment’s overview, exploratory visits provided most of the information presented;
- Chapter 7 – Experimental Characterization of Stones from Vernacular Buildings: this chapter presents a detailed experimental physical and mechanical characterization of vernacular schist and granites, collected from the case studies presented on Chapter 9.
- Chapter 8 – Durability Assessment of Stones from Vernacular Buildings: this chapter complements the previous chapter and presents a detailed experimental durability characterization of vernacular schists and granites. Both types of weathering processes selected were based on the most severe type weathering observed during the exploratory visits;
- Chapter 9 – Analysis of Two Case Studies: based on two case studies, this chapter demonstrates the research methodological approach to vernacular heritage preservation. The information in this chapter was collected by using all levels of analysis previously mentioned, and with the data base support presented in the previous chapters.
- Chapter 10 – Conclusions and Future Works: this last chapter presents the main conclusion taken from the research presented on previous chapters, and points topics requiring future research.

Chapter 2

OVERVIEW REGARDING PRESERVATION AND REHABILITATION PRINCIPLES

In present days, the concept of Cultural Heritage is at the head of international and multidisciplinary World Heritage preservation efforts. For the important role played in the definition of populations cultural identity, architectural heritage preservation was recognized by leading international institutions such as UNESCO (1945) [21] or the Council of Europe (1949) [22], as a universal task that requires the full involvement of each state in the safeguarding of their own individual cultural heritage [23]. To be achieved, states can count on the guidance and support given by reference organizations such as the ICOM (1946) and ICCROM (1956), and later the ICOMOS (1964) [24]. According to Jokilehto [23], the concept of cultural heritage developed gradually during the 18th and 19th centuries, became universally accepted regarding high value historic monuments, evolving to represent humankind common cultural background. Later, the concept of cultural heritage evolved with the recognition of cultural value in smaller forms of architecture and minor works. It included broader and complex concepts of tangible and intangible cultural heritage, universally recognized as inseparable halves of communities cultural identity [5,21,25]. From a methodological perspective, the three main approaches to heritage preservation are highlighted by Jokilehto [23]: *i)* through a functional approach in which heritage buildings were maintained as long as they served a purpose, either regarding their use or a memorial function; *ii)* through a stylistic and historical restoration approach, in which heritage buildings were maintained from a nostalgic and romantic perspective, being restored to a state and aesthetic corresponding to its most significant period; *iii)* through an authenticity based approach, in which heritage buildings were maintained by preserving historical stratification and original physical and material features. According to the author, the first approach comes since immemorial times, whereas the second and third can be traced back to the Renaissance period. Although similar in several aspects of their preservation theory, the authenticity based preservation prevailed in the 20th century, becoming the basis for the most significant heritage preservation and protection international standards and methodologies [23].

2.1 Cultural heritage preservation and protection principles

Based on the principles and ethical code of The Venice Charter [26] (1964), heritage value was defined by the principle of cultural significance in a specific context. The authenticity concept, recognized as a fundamental criterion for cultural diversity, was set as the main qualifying factor to establish cultural significance. Therefore, to safeguard authenticity, preservation ethics based on integrity principles and credible and truthful information regarding heritage features, was established [5,26]. Although recognized as a universal concept, as established in The Nara document in Authenticity (1994) [5], authenticity must be understood as an outcome of individual and constantly changing contexts. Thus, when addressing authenticity and its value, a multidisciplinary effort must be put in motion for its correct identification and interpretation, otherwise, as shown in Fig. 2.1, cultural value is at risk [5].

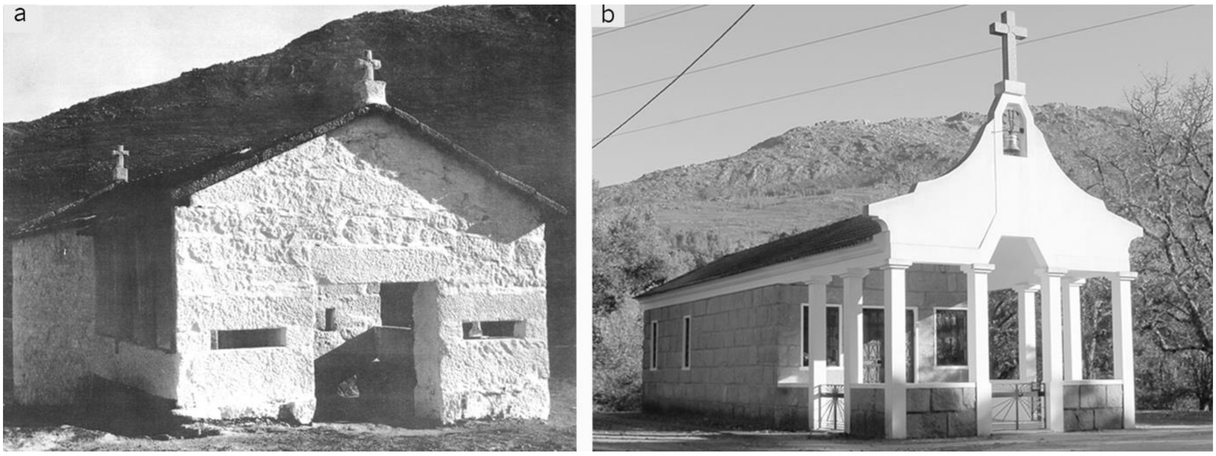


Fig. 2.1 – Chapel of St. Mary Madeleine (Lindoso, Ponte da Barca): a – image collected during the *"Inquérito à Arquitectura Regional em Portugal"* (1950's) [27]; b – image collected in 2017, after a deep rehabilitation intervention.

According to Jokilehto [23], a decisive moment in contemporary heritage preservation and protection was achieved with The Athens Charter (1931) [28]. According to the author, the principles and recommendations introduced by this document replaced previous conservation and restoration theories such as the stylistic or historical restoration theory, see examples in Fig. 2.2. Based on them, a contemporary methodological approach to heritage preservation was set in motion, anchored in principles of historic authenticity, and supported in international guidelines and recommendations. Among others, recommendations in favour of preserving rather than restoring, the principle of coexistence of different historical periods in the same buildings, or concerning keeping heritage buildings in use (if compatible with the heritage's value) were set [28]. Previous practices such as the historical reconstruction of ruins, at the exception of anastylosis or, as shown in Fig. 2.3, the removal of heritage elements such as sculptural elements or works of art, were ruled out, except if no other protection measures were feasible [28]. The accurate study of heritage buildings, heritage maintenance and damage identification were also highlighted for their importance [28]. Special cares regarding authenticity were recommended for highly invasive interventions such as the stabilization of endangered structures, or when using new materials by making them clearly distinguishable. According to Jokilehto [23], although later recognized as a mistake, the lack of scientific knowledge of the time led to the encouragement of the use of contemporary materials and techniques such as concrete, in conservation and restoring interventions.

Fig. 2.2 – Examples of historical reconstruction of ruins: a – historical restauration of the roman temple of Évora (1863); b – full reconstruction of the Campanile di San Marco (1912), after its catastrophic collapse in 1902; c – restauration of the St. Maria da Feira castle (first half of the 20th century).

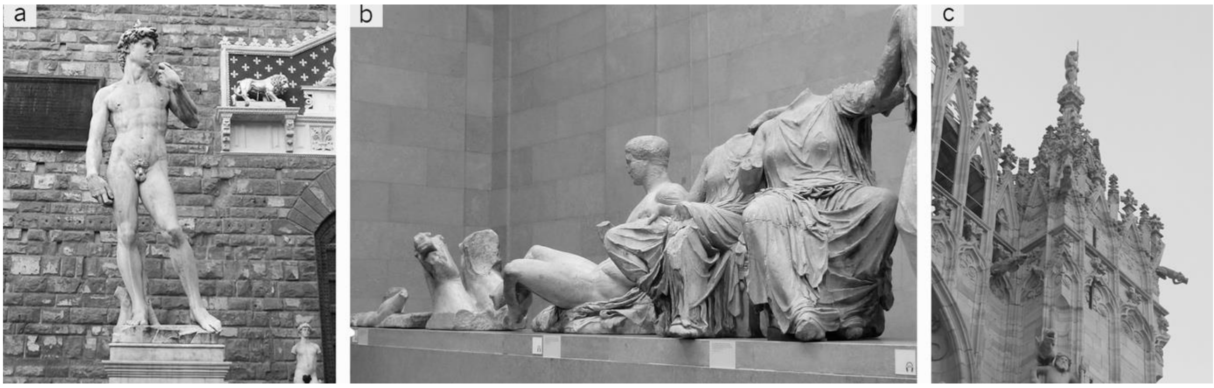


Fig. 2.3 – Examples of heritage removed from its original context: a – replica of the David of Michelangelo, placed in Piazza della Signoria in 1863 (original kept in the Accademia Gallery for safekeeping) (Florence, Italy); b – sculptural elements removed from the Parthenon (Athens, Greece) in display at the British Museum (London, United Kingdom); c – sculptural elements in the Duomo of St. Mary of the Nativity, some removed for safekeeping (Milan, Italy).

The devastating events of the World War II and the post-war context led to the creation of the ONU, and with it, of UNESCO [23], and later to the International Charter for the Conservation and Restoration of Monuments and Sites: The Venice Charter (1964) [26]. Besides the novelty introduced by the previously mentioned concept of cultural significance based in authenticity, this new charter introduced a new methodological perspective regarding the interpretation of historical monuments, now addressed as historical testimonies and not as works of art [26]. Jokilehto [23] refers to The Venice Charter as resulting from a mature consciousness regarding heritage preservation, that followed and clarified most of the concepts of the previous Athens Charter. Examples are the concept of restoration or the definition of cultural heritage, see Fig. 2.4, that in face of the post-war reconstruction context, was enlarged to include urban and rural settings and other smaller works with cultural significance [26].

Fig. 2.4 – Cultural heritage definition: a – historical monuments (Duomo of St. Mary of the Nativity, Milan Italy); b – urban and rural settings (villages in the Quarzazate oasis, Morocco); c – smaller works with cultural significance (tanneries of the Medina of Fez, Morocco).

In the new document, the role of preservation methodologies and production and sharing of knowledge became a priority, gaining a clear multidisciplinary and a decision-process of scientific character. Permanent maintenance and the involvement of the communities also gained a higher importance. Understanding the limitation of the Athens Charter regarding the use of new buildings materials and resulting consequences, led to the principle of protecting and promoting the use of original and traditional materials over the introduction of new ones. The latter were only allowed if no other option was possible, and only if material compatibility was scientifically proven [26].

Being cultural heritage preservation a dynamic process, the principles of The Venice Charter were developed in the following decades with the introduction of new documents. In these, concepts were enlightened and made clearer, such as the concept of *authenticity* [5], whereas others were introduced, such as the concepts of *place* [29] or *“spirit of place”* [30], of *tangible* and *intangible* heritage [25] or concerning the cultural value of small settlements [6]. Taking into consideration over time social and cultural evolutions and context changes, the discussion regarding heritage preservation gained new topics such as heritage and sustainable development [1], heritage as touristic asset [4,31] or concerning changes in the relationship between communities and their cultural heritage [32].

Concerning vernacular architecture, it was initially recognized for its cultural value in The Venice Charter, Article 1, as part of rural settings, [26]. It was later recognized by UNESCO at its 17th session (Convention Concerning the Protection of the World Cultural and Natural Heritage - Paris, 1972 [21]), among groups of buildings and sites of universal and endangered high cultural heritage, that required state involvement in its protection and preservation. Rural heritage was recognized by the Council of Europe (Convention for the Protection of Architectural Heritage in Europe, Granada – 1985) as a priority to EU state members [7,22,33]. Among other specific committees created to address the topic of heritage preservation, by recognizing the need for a specific committee to address the topic of vernacular architecture, the ICOMOS-CIAV International Committee on Vernacular Architecture was founded in 1976 by the Executive Committee of ICOMOS [34]. Recognizing the importance of preserving stone used on heritage buildings, the ICOMOS-ISCS was created in 1967 [35,36].

With the Tlaxcala Declaration on the Revitalization of Small Settlements (1982) [6], small settlements were recognized for their strong and wide cultural significance, based on high authenticity and identity levels resulting from a rich diversity of ways of life. This charter presents a major methodological breakthrough, based on the recognition that simple conservation of vernacular heritage buildings, without the preservation of the communities' ways of life, was ineffective [6]. Therefore, multidisciplinary methodologies were recommended for the protection of such sites.

With the Charter on the built Vernacular Heritage (1999) [3], the topic of vernacular architecture preservation is addressed directly, being vernacular buildings high cultural value recognition strengthen. However, its condition as endangered heritage due to high vulnerability when facing significant lifestyle changes was also stated. Particularly destructive threats were identified resulting from society and culture homogenisation caused by socio-economic globalization pressures [3]. In this charter, vernacular heritage buildings were presented as taking part in the concept of *place* [29]. Therefore, as shown in Fig. 2.5, meaningful preservation and management policies were presented as dependent of extending preservation efforts and investments to the rural setting, the humanized cultural landscape and specific associated tangible and intangible cultural values safeguarding [3,29].

Fig. 2.5 – The cultural heritage of the Schist Villages network (Piodão, Portugal): a – the rural setting (tangible); b – the vernacular architecture and constructive tradition (tangible); c – local traditions (intangible).

From a methodological point of view, effective vernacular heritage protection and knowledge transfer to the enlarged communities, are presented as the basis of the different stages required for heritage preservation and management policy (intervention, maintenance, and results monitoring) [3,29,37]. From a practical and functional points of view, and always in the spirit of The Venice Charter, the charter points out the need of assuring vernacular heritage buildings continuous use. It recognizes the need to adapt heritage buildings and to implement compatible uses, to be able to meet communities' lifestyle expectations, and therefore ensuring buildings continuous maintenance and protection [3,26].

Over the last decade, the topic of vernacular heritage protection and preservation [29] has caught the attention of the academic heritage preservation communities, resulting in the production and sharing of scientific knowledge (e.g. CIAV 2013 [38], VERSUS 2014 [39] or SOStierra 2017 [40]). Research focus on fully understanding vernacular building tradition specificities and on developing proper conservation techniques and good practices guidelines (e.g. Apulia Data Base [41], Coupoles et Habitats Project [42], or SEISMIC V – Local seismic culture in Portugal [43]). Simultaneously, the need to preserve vernacular heritage and the rural landscape high cultural values has led in recent years to growing investment to transfer knowledge and technical skills, either through sharing of good practices manuals [44] or by direct involvement with the communities (e.g. Associazione Internazionale Città della Terra Cruda [45] or the Asociación TERRACHIDIA [46]).

2.2 Rehabilitation methodologies

Based on Petzet et al. [47] description regarding different types of preservation actions, rehabilitation interventions are described as able to reach a compromise between the spirit of The Venice Charter [26], and the typically adaptations and upgrades required to make vernacular heritage buildings able to sustain contemporary life standards. Therefore, such type of interventions can reach high levels of intrusion, due to typical upgrades such as replacing vernacular kitchens and bathrooms (if existent) by contemporary ones, the installation of infrastructures (e.g. electricity, water, or gas supply) or the improvement of buildings internal environmental conditions (e.g. adding heating systems, changing frames, or adding thermic insolation). In this sense, risks, and the need for suitable methodologies to implement such deep changes, without compromising cultural value and authenticity are high. Examples of several types of rehabilitation interventions are shown in Fig. 2.6.

Fig. 2.6 – Examples of different rehabilitation operations: a – adaptation and upgrade of an heritage building (Guimarães, Portugal); b – introduction of a new use and new elements into a ruin area of the Tibães Monastery (Braga, Portugal); c – rehabilitation and reconstruction of the St. Domingos church, keeping the memory of the fire that ruined it (Lisbon, Portugal).

Following The Krakow Charter: Principles for Conservation and Restoration of Built Heritage (2000), a proper design for rehabilitation methodology should led to decisions, selections, and responsibilities by ensuring: *i)* the utmost respect by heritage authenticity, integrity and identity preservation; *ii)* a flexible and dynamic decision-making process, able to reach adequate compromises between needs and cultural significance, and to establish a communication platform to ensure the participation of all; and *iii)* the transfer of knowledge to users, thus assuring the sustainability and resilience of the intervention results [48].

Following the international best preservation good practices, to suitable rehabilitation methodologies is required scientific accuracy and multidisciplinarity, and a flexible and adaptive multi-step methodological design, able to adapt to changes in circumstances and to introduce improvements [48]. Regarding its steps, and following the schematic example presented in The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance (1979) [29], see Fig. 2.7, a rehabilitation methodology design should be organized as follows [29,48,49]:

1. Cultural significance identification, by characterizing authenticity and identity features (tangible and intangible) and establishing criteria for their preservation. The collected knowledge works as a scientific and multidisciplinary data base to support the decision-making process, but also to allow vernacular knowledge transfer safeguarding;
2. Decision-making process, starting from the analysis and diagnosis of the problems (needs, opportunities, and constricts identification), able to reach conclusions and to design a vernacular heritage management policy (e.g. compatible uses, community involvement strategy or rules creation) and plan (intervention design, maintenance, and monitoring plan);
3. Implementation of the plan (rehabilitation actions and maintenance plan) and of over time monitoring and assessment of the intervention results to ensure its effectiveness. Analysing the results, improvements should be added to the management plan, if needed.

Taking into consideration the example given by The Burra Charter [29], and for its vital role, the opportunity of contributing to the rehabilitation process should be ensured to all participants throughout all its stages, in a dynamic and transversal way.

Fig. 2.7 – Schematic of a reference multi-step preservation methodology presented in The Burra Charter [29].

Addressing the specific topic of structural preservation and rehabilitation, the ICOMOS-ISCARSAH Committee Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (2003) [49], places safety and the preservation of human life above all other types of priorities. Taking into consideration existent risk, safety issues are presented always as the highest level of priority and must be solved before all others. Regarding safety evaluation, it must be based on damage assessment. Implemented stabilization measures must be focused on treating the causes and not the symptoms of damage [49]. According to these principles, intervention should achieve proportionality between measures and safety risk, to ensure the most effective and sustainable solutions to the problem at hand, through a balanced cost/benefit intervention [49]. As a main recommendation, preventive maintenance is presented as the most effective therapy for heritage preservation.

Therefore, interventions over vernacular structures should be designed to sequentially: *i)* ensure structural safety; *ii)* damage treatment; and *iii)* ensure durability and resilience through preventive maintenance plans. To achieve such goals, a four consecutive and interactive steps methodology, similar to the ones used in medicine, is given as example of good practices [47]:

1. Anamnesis, corresponding to the gathering of significant and accurate data concerning vernacular heritage context;
2. Diagnosis focused on damage identification through historic (relevant damage causing events), qualitative (observation and damage identification) and quantitative (experimental, monitoring, and mathematic simulation, see Fig. 2.8) data collection and analysis;
3. Therapy, corresponding to the selection of remedial measures and solutions;
4. Control, over the efficiency of the results.

Fig. 2.8 – Examples of different on-site structures analysis techniques, applied to heritage buildings (Almeida city wall, Portugal): a – visual inspection of damage; b and c – dynamic identification through sonic testing; d – inspection by geo-radar [50].

Based on international good practices regarding interventions in heritage buildings, rehabilitation operations should also comply with the following recommendations:

i) The principle of respect for heritage integrity, meaning that all vernacular buildings external and internal elements, including internal layouts, original materials, building techniques, decoration and artistic elements require the same level of protection and preservation commitment. Intervention design based just in appearance criterions, such as the conservation of facades and destruction of the remaining elements are not acceptable as heritage preservation practice;

ii) The principle of preserving over time changes in vernacular heritage, therefore, enforcing heritage truthfulness, even if meaning to preserve conflicting periods of time, see Fig. 2.9a. The same principle is applied to the preservation of historic non-threatening damage considerate part of vernacular heritage identity;

iii) The implementation of new uses must be compatible with heritage cultural significance, and must ensure buildings continuous use without jeopardizing its value, see Fig. 2.10;

iv) The principle of heritage truthfulness by clearly distinguishing new from original, although not compromising heritage cultural values, see Fig. 2.9b;

v) The principle of minimal and indispensable intervention, at an appropriate and sustainable cost/benefit compromise;

vi) Preventive and continuous maintenance and monitoring are mandatory for lasting and efficient rehabilitation interventions;

vii) Risk identification and its management plans should be part of the intervention design, meaning also that prevention and emergency plans should be prepared.

Fig. 2.9 – Monumental heritage preservation examples: a – preservation of the historical damage in the Pantheon (Rome, Italy); b – stabilization and reconstruction intervention using new but clearly distinguishable materials in the Colosseum (Rome, Italy).

Fig. 2.10 – Transformation of the St. Mary of Bouro monastery into an hotel, by rehabilitating and modernizing specific areas of the building, and keeping others as stabilized ruins not to alter the present aesthetics (Terras de Bouro, Portugal).

Addressing the use of building materials and techniques, international good practices also recommend:

- *i)* Priority in using or reusing traditional and original materials, being the use of new materials and techniques restricted to situations when another option is not feasible;
- *ii)* To assure scientifically proven compatibility between added new materials and building techniques, with original and vernacular materials;
- *iii)* The principle of reversibility must be implemented, either in the use of new building materials and techniques, but also concerning layout changes;
- *iv)* Resilience and durability of intervention techniques and materials must be assured and scientifically proven, to reduce damage hazards caused by unpredicted early decay;

Addressing vernacular heritage preservation at the territory macro scale, as mentioned previously, existent vernacular architecture presents very distinct levels of cultural value, resulting from a wide variety of different circumstances, but also from the representativeness of models and solutions throughout the territory. In most cases, the rural landscape is occupied by a very high amount of buildings covering large extensions of territory and showing very different states of durability and authenticity [5,29,51]. Therefore, rehabilitation methodologies deal with very different levels of investment and legal frameworks, resulting in different types of preservation actions, and requiring tools to direct investments and efforts to the most effective culture value protection interventions [29,47]. Research in this topic has been developed in recent years [52–54]. An example is given by Fuentes [51], see Fig. 2.11, using as study case a vast rural territory in the centre of Spain. The author established a multi-step assessment methodology, aimed at distinguishing vernacular buildings with higher cultural value and stronger reuse potential from redundant ones, resorting to a pre-established checklist.

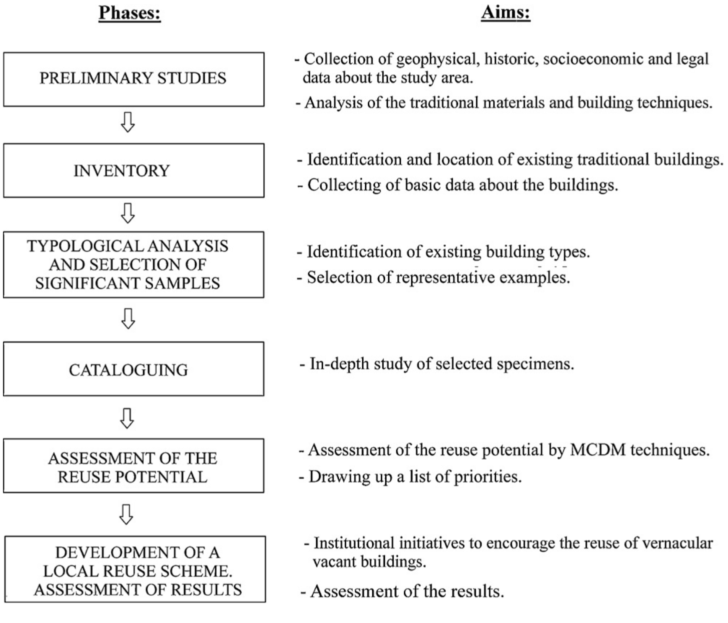


Fig. 2.11 – Methodological basis for documenting and reusing vernacular farm architecture by Fuentes [51].

The outcome was the creation of a scientifically accurate inventory, assessed by a weighted parameter decision‑making process, in which parameters are based in pre-established intervention requirements. The result is a more effective cost/benefit compromise between intervention features and buildings rehabilitation potential.

2.3 Final Remarks

Contemporary heritage preservation is based on scientific methodologies, established through universally recognized standards, produced by reference international institutions (UNESCO, Council of Europe, ICOMOS, etc.). In the past century, the concept of heritage preservation evolved from conservation and restoration of historical monuments, to the preservation of a wider range of architectural works, places, and multiple forms of tangible and intangible cultural heritage. Cultural value was set as the basis of the above-mentioned effort, being established though a process of authenticity based cultural significance. The recognition of the high cultural value of vernacular architecture and small settlements came later, acknowledged for their strong authenticity and identity levels, but also due to their condition of highly endangered heritage.

Preservation guidelines and recommendations were adopted and adapted to vernacular heritage specific features, taking into consideration the acknowledgement that the communities’ cultural identity is a wider concept that involves a large and inseparable diversity of tangible and intangible forms of culture. Recommended methodological approaches establish as priorities, not only the careful preservation of heritage buildings, but also of their setting and specific contexts. Simultaneously, continuous use and preventive maintenance are considered the most effective form of preserving vernacular heritage cultural value. Although the latent risk associated to potential authenticity and identity losses resulting from adapting vernacular heritage buildings to meet with contemporary life standards, the rehabilitation of such types of architectures comes as the most sustainable path for their sustainable preservation. International good practices recommend the development of scientifically organized step-based rehabilitation methodologies, supported by accurate information concerning authenticity features identification, and dynamic and flexible decision-making process, able to establish a communication platform among those involve in the rehabilitation process. Efficient methodologies should also be able to evolve and adapt to context changes and to introduce improvements along the way. Full and global preservation effort is requited, from an intervention design based in a macro scale management policy and intervention plan, to assuring the durability of the implemented solutions through active maintenance planning monitoring. The role of knowledge production and transfer among all participants in heritage preservation and rehabilitation comes as an internationally recognized priority. Therefore, enlightening communities regarding their heritage high cultural value is seen as fundamental to ensure their involvement in the active preservation and protection of their own vernacular heritage, and the assure the access of future generations to small communities everyday fading identity.

Chapter 3

REVIEW OF STUDIES ON THE PORTUGUESE RURAL WORLD

The study of vernacular heritage in Portugal, dates back to the mid-19th century as a fundamental element of the study of different aspects the rural world, resulting in several pioneer studies [13]. Until mid-20th century, the study of the rural realities can be described as balancing between a mean to support the nationalistic ideologies of the time and approaches to scientific methodologies. Although based on a romantic image of the rural world, vernacular architecture was used to shape the concept of a national traditional architectural style. According to Leal [13], and for its importance, the strongest output from this period was the architectural movement known as the *"Casa Portuguesa"*, later used by the fascist agenda of the Estado Novo regime (New State regime, 1933-1974) [20,55], that for half a century shaped the discussion around vernacular architecture. As a mid-20th century ideological counter-reaction to it, modernist Portuguese architects through authors such as Távora [45], pointed out to the misleading use of vernacular heritage principles to fabricate a false view of the rural world [13,56]. A first a nationwide and state funded vernacular architecture survey, the *"Inquérito à Arquitectura Regional em Portugal"* (Survey to the Vernacular Architecture in Portugal) [27] was performed during the 50’s. Along with the data collected, a more rationalist and functionalist view of rural buildings and landscapes emerged and shaped architects an researchers perspectives on the topic in the following decades [20]. According to Leal [13], and parallelly with the discussion on the field of expertise of architecture, the first accurate and systematic scientific survey on the rural world, named *“Inquérito à Habitação Rural”* (Inquiry to Rural Housing) [57], was performed in the 30’s. For its conclusions, was later suspended and censored by the Estado Novo. Solid scientific methodologies and criterions would come later in the mid-20th century, with the ethnological research undertaken by Jorge Dias (coord.) and his research group [58–60]. These studies, implemented until the 70’s, constitute a valuable testimony of an already very decaying rural reality, almost inexistent today [13]. According to researchers such as Ribeiro [61], Villanova et al. [12] or Saraiva [11], from the 60’s onwards, deep changes to rural society and economy set in motion a revolution that would radically change the traditional way of life. Authors point out to migrations as the main cause of profound changes in the rural landscape, reaching from its social to its economic fabric. In this uneven process, in more isolated areas, vernacular heritage was faced with abandonment and ruin [12,62]. More attractive areas faced overpopulation and uncontrolled urban growth and construction, that put under pressure small settlements, as shown in Fig. 3.1., causing permanent authenticity and identity losses [12,63].

Fig. 3.1 - Examples of uncontrolled growth: a – poorly planned transformation of low density rural occupation into high density urban occupation (Apúlia, Esposende); b – occupation of valleys with non-agrarian uses (Vila Nova de Muía, Ponte da Barca).

3.1 Initial studies

According to Leal [13], starting in Portugal from 1840 onwards, the effort of the emerging scientific fields of anthropology and ethnology was focused on the study of Portuguese rural roots. Involved in a larger European nationalistic movement, according to the author, the study of the rural world, of its buildings and the peasant way of life, was seen at the time as a way to strengthen national identity. This effort, although sometimes made from an idealized and even romantic conception of the rural realities [13], was undertaken by pioneer researchers, with very different scientific and professional backgrounds such as Henrique das Neves (1841-1905, military), Martins Sarmento (1833-1899, archaeologist and writer) [64], Alberto Sampaio (1841-1908, historian) [65,66], Rocha Peixoto (1866-1909, archaeologist and ethnologist) [67–69], or José Leite de Vasconcelos (1858-1941, archaeologist and ethnologist) [70,71], Tude de Sousa (1874-1951, agronomist and ethnologist) [72] or Teófilo Braga (1843-1924, writer and politician). The performed surveys and the information collected, see Fig. 3.2, although some showing low scientific accuracy, are a first-hand testimony of the initial symptoms of decay of the old rural world and of the traditional way of life. As described by these authors, such context was clearly visible by the very strong emigration wave to Brazil [12,73,74]. From these studies, most of descriptive character [75,76], a global and transversal overview regarding Portuguese rural society from the late 19th century and beginning of the 20th century is given. As shown in Fig. 3.3 and Fig. 3.4, collected information covered from traditions and religious beliefs, to social structures, work and economic revenues [66,69,71,77].

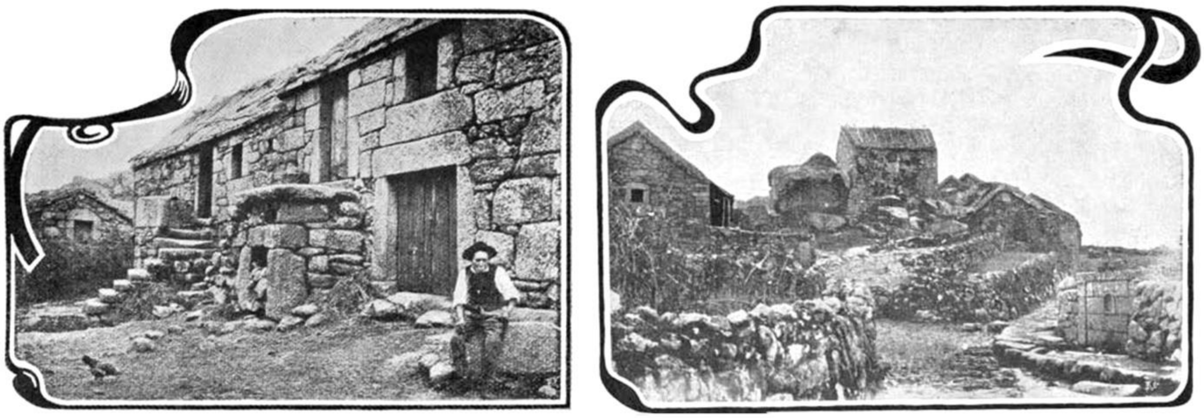


Fig. 3.2 - Images from Castro Laboreiro collected by Rocha Peixoto (1904) [73].

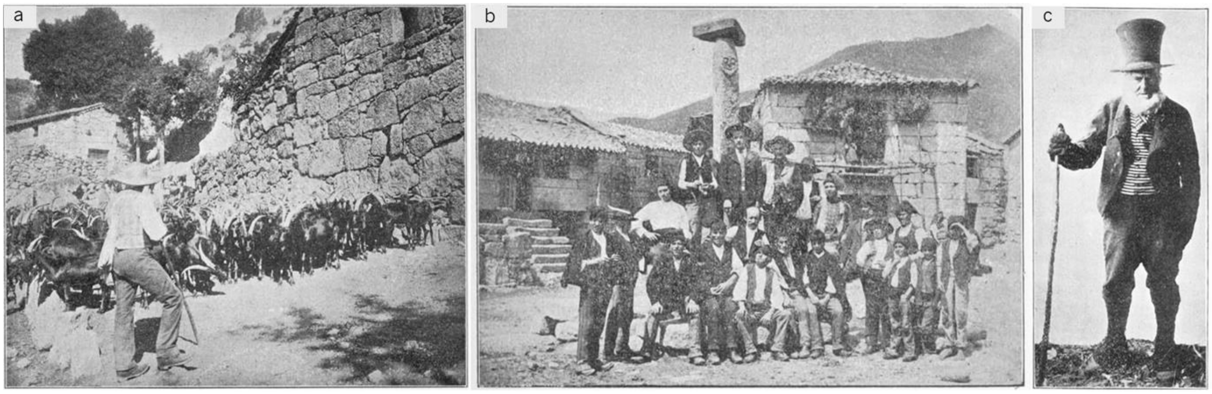


Fig. 3.3 – Images from Rocha Peixoto studies (1907): a – image of a *"vezeira"* (St. João of Campo of Gerês); b – men posing for an image at the village centre, near the *"pelourinho"* (Soajo, Arcos de Valdevez); c – image of a men (Lindoso, Ponte da Barca) [69].

Fig. 3.4 - Exterior and interior views of a simple *"palhaça"* (with straw roofing) *"Minhota"* house (location unkn.) [78].

Among the collected information, are the first records related to rural housing, to its living and comfort conditions. However, rural architecture was addressed as essential elements of the rural landscape, although not exhaustively analysed. According to the work of researchers such as Rocha Peixoto [73] or José Leite de Vasconcelos [79] regarding the rural house, besides seen as shelter for peasants and their families, it was also understood as the main support for their agrarian ways of life. Therefore, the rural dwelling was interpreted as vital to agrarian economics and populations survival [74,78].

3.2 The *“Casa Portuguesa”* movement (Portuguese house movement - CA)

The *“Casa Portuguesa”* movement (CA) came as an initial reaction against the penetration of architectural foreign models, such as the *“chalet”* or the *“cottage”*, and to the growing influence of neo-gothic and *“neo-manuelino”* architecture styles of the time [56,80]. The movement lost influence with the arrival of Art Deco and the Modern Movement (from the 20’s to the 40’s). With the Estado Novo, the CA was used as support for the regime ideological program, manly as an anti-modernism barrier [13]. During the 50’s, facing the growing influence of the principles and ideas of the Modern Movement, that publicly renounced to the regime’s imposed architecture guidelines at the 1st National Congress of Architects (1948) [20,81], the CA underwent an unstoppable loss of influence and disappeared during the 60’s [13].

According to Leal [20], the CA movement was based in the interpretation of vernacular heritage accordingly to a stylistic theory that ignored nationwide diversity. Based in this principle, a theory that pointed to the existence of a Portuguese common type of vernacular house, sharing the same characteristic elements, took shape [13,56]. From this theoretical support, initially pointed out by Henrique das Neves in 1893, the CA movement promoted a national architectural style of modern buildings, inspired in vernacular architectural features and elements [13]. Both where summarized in the writings (the stylistic guidelines) and architectural works (examples of the implementation of the CA aesthetic lexicon) of Raúl Lino (1879-1974, architect), recognized as the leading figure of the movement [13,80,82], see Fig. 3.5.

Influenced by Ruskin and Morris and the Arts and Crafts movement, but also by the vernacular architecture of the South of Portugal and Morocco [80], Raúl Lino’s buildings were hybrids. As shown in Fig. 3.6, his buildings resulted from combining: *i)* modern principles (e.g. internal organization and constructive models); *ii)* vernacular buildings design features of southern influence (e.g. predominance of volumes of horizontal proportion or the attention paid to their integration in the natural landscape); *iii)* combined with vernacular elements used in a scenographic and not in a functional way (e.g. porches, roof eaves, or large chimneys), and *iv)* the use of traditional materials (e.g. handcraft roof tiles, decorative tiles or traditional lime painting in different colours) [20,80,82]. According to Leal [20], the CA movement theoretical approach showed debilities regarding the interpretation of vernacular heritage and its context, resulting from the idealized conception of the rural world and the created misleading pastoralist image of rural reality [20,56]. This perspective, initially questioned by the conclusions of the above-mentioned initial studies, was completely deconstructed by the results of the surveys conducted in the 30’s [57], that undeniably showed a very different and harsher rural reality.

Fig. 3.5 – House of the *“cipreste”* (1914). Raúl Lino, architect (Sintra) [83].

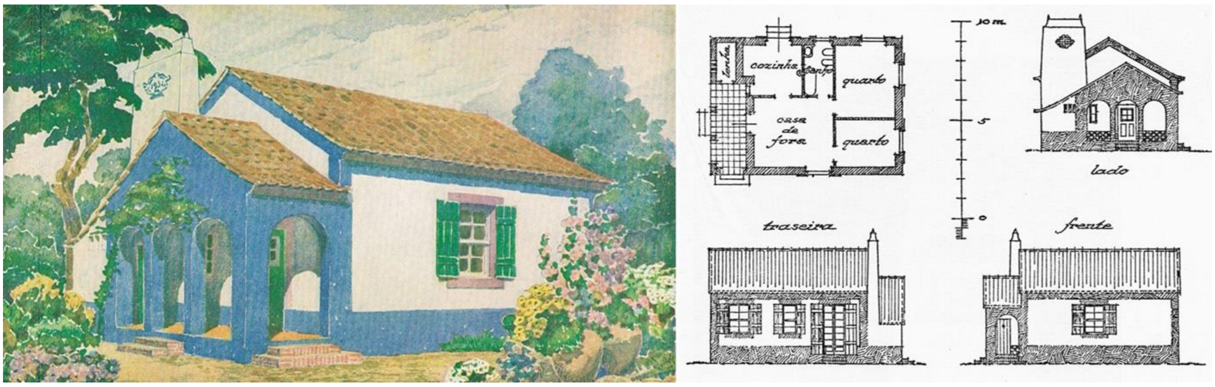
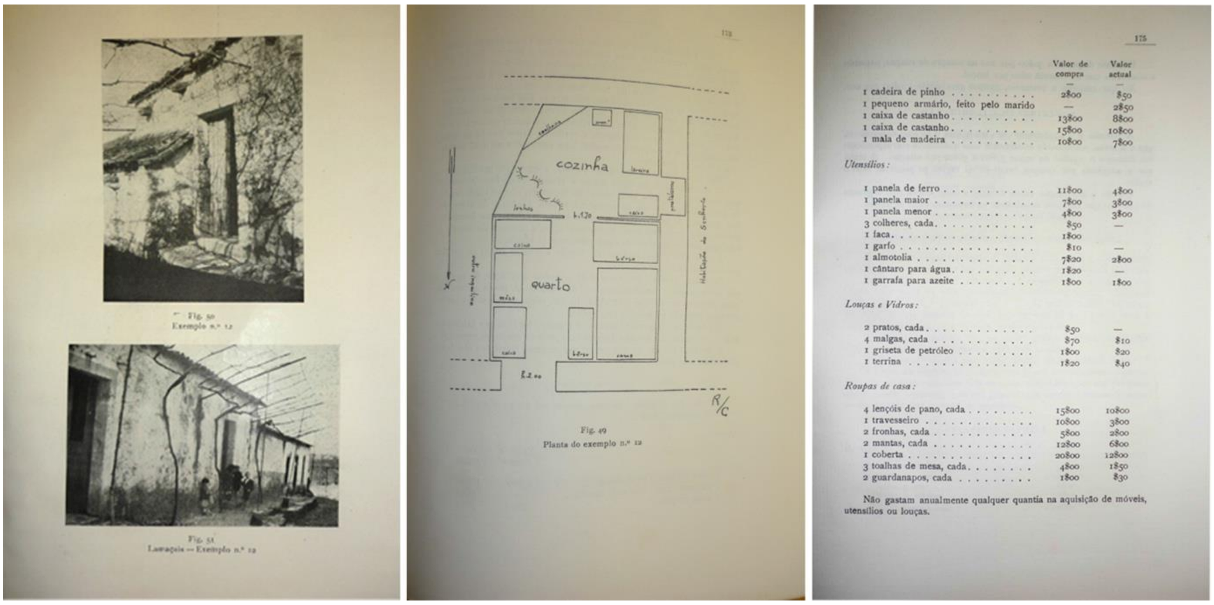


Fig. 3.6 – Example of a Raúl Lino model for one-storey Ribatejo house [84].

Leal [20] also points out as major flaw to the CA, its theoretical concept of homogenous and stylistic interpretation regarding vernacular heritage diversity. Some of the CA most important supporters such as Rocha Peixoto (1904) [73] or Leite de Vasconcelos (1909) [70], initially questioned these positions. Their deconstruction came in later in the mid-20th century, with extensive survey-based studies, that undeniably confirmed vernacular architecture overwhelming nationwide morphologic, typological, and constructive diversity, caused by different contexts and ways of life.

3.3 *“Inquérito à Habitação Rural”* (Inquiry to Rural Housing - IHR)

According to Leal [13], the *“Inquérito à Habitação Rural”* (IHR) [57] was the first extensive survey performed to gather scientific data on the Portuguese rural populations. Following similar initiatives performed in other European countries, in this particular case of Mussolini’s Italy, the IHR was part of a larger project that aimed at the preparation of a new agrarian policy for Portugal [13,57]. Among other basic concepts, the IHR interpreted the rural house from a functional perspective as an essential agrarian tool and the peasants living conditions, in particularly in the agrarian context of the North of Portugal [61], as directly related to the success of farming enterprises [57]. Therefore, improving housing conditions was seen as fundamental to promote any type of agrarian development [20]. The IHR researchers ideological and methodological approach to the rural house was based on its analysis from inside out, and focused in features with a direct impact in family life and farming productivity [13]. The survey was underlined and implemented by the Agrarian Engineers of the Instituto Superior Agrário (ISA), initially under the coordination of Lima Bastos (1875-1942), later of Henrique de Barros (1904-2000) and Castro Caldas (1914-1999). It was implemented during the mid-30's [13]. The fieldwork survey followed a very exhaustive checklist that collected statistic, geometric and photographic data from 80 different case studies [57]. The research addressed the basis of the rural social pyramid, formed at the time by small landowners and rural workers, gathering information on family size, income, property, and farming capability. From the dwelling, internal living conditions, building's conservation, hygiene conditions, and comfort standards were analysed. The existence and proper dimensioning of common and individual spaces was also one of the main surveyed topics. The results were published in three volumes, being the Entre-Douro-e-Minho region included in the first volume dedicated to the North region (1943), see Fig. 3.7.



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	Valor de compra	Valor actual
1 cadeira de pinho	2$00	$50
1 pequeno armário, feito pelo marido	—	2$50
1 caixa de castanho	13$00	8$00
1 caixa de castanho	15$00	10$00
1 mala de madeira	10$00	7$00
Utensílios:		
1 panela de ferro	11$00	4$00
1 panela maior	7$00	3$00
1 panela menor	4$00	3$00
3 colheres, cada	$50	—
1 faca	1$00	
1 garfo	$10	—
1 almotolia	7$20	2$00
1 cântaro para água	1$20	—
1 garrafa para azeite	1$00	1$00
Louças e Vidros:		
2 pratos, cada	$50	—
4 malgas, cada	$70	$10
1 griseta de petróleo	1$00	$20
1 terrina	1$20	$40
Roupas de casa:		
4 lençóis de pano, cada	15$00	10$00
1 travesseiro	10$00	3$00
2 fronhas, cada	5$00	2$00
2 mantas, cada	12$00	6$00
1 coberta	20$00	12$00
3 toalhas de mesa, cada	4$00	1$50
2 guardanapos, cada	1$00	$30

Não gastam anualmente qualquer quantia na aquisição de móveis, utensílios ou louças.

Fig. 3.7 – Example of the survey methodology of the *"Inquérito à Habitação Rural"* (Lamaçais, Braga) [57].

A major result, the IHR unveiled the poor living conditions of rural population's lower ranks. It was also clear the severe shortage of housing in rural Portugal, caused by the economic crises that followed World War I, and the lack of economic capability of the humble Portuguese farmer [57]. Regarding the common peasant housing conditions, they showed an overall state of severe conservation problems caused by lack of maintenance, poor construction quality, deficient internal ventilation, and lighting, with almost no internal comfort. Thermic comfort or protection against humidity was almost non-existent. A considerable number of case studies of dwellings reduced to simple sheltering functions was reported. The absence of individual spaces, and its influence in family life, was mentioned in this study and pointed out as one of the main problems. Hygiene issues such as inexistence of basic infrastructures, toilets, and bathrooms, and the proximity to livestock placed under or inside the dwelling, particularly in the northern houses, was pointed as severe public health problem.

Leal [20], highlights some limitations regarding the conclusions of the IHR. Due to the researchers' background and context, the rural housing topic was interpreted under the filter of the European agrarian renovation ideals of their time, and by the 19th century hygienist theories. According to the author [20], context specificities of the peasant traditional way of life were underestimated and frequently taken for lack of conditions and poverty, not always being the case (e.g. rational use of resources or the strong sense of protection over the cattle by placing it under or inside the house, etc.). The absence of other higher rural social groups in the study, that Leal identifies as the majority of the rural population [13], contributed for the exacerbation of the global state of misery in the rural world.

3.4 *"Inquérito à Arquitectura Regional em Portugal"* (Survey to the Popular Architecture in Portugal - IARP)

As mentioned previously, the *"Inquérito à Arquitectura Regional em Portugal"* (IARP) came as a reaction against a specific way of addressing architecture in Portugal [13]. Among others, Fernando Távora (1923-2005, architect) in 1945 [55], based his opposition to the CA principles on one hand in the lack of coherence of its hybrid buildings, on the other in the misleading use of vernacular building traditions and its transformation it mere decoration without any kind of authenticity. The same author and, later in 1947, Francisco Keil do Amaral (1910-1975, architect), proposed a full survey and study of vernacular buildings to preserve and learn with their knowledge. The IARP came to life in 1955, organized by the Sindicato Nacional de Arquitectos (National Architects Syndicate) and State sponsorship, under the coordination of Francisco Keil do Amaral [20]. Its results were published in 1961 in the book *"Arquitectura Popular em Portugal"* [27]. From a methodological point of view, the territory was divided in six different areas, being each analysed by a team lead by a senior architect and two junior architects. According to Amaral et al. [27], researchers followed a pre-established fieldwork methodology, designed to allow a considerable degree of flexibility to deal with unforeseen circumstances.

Geometric and photographic information were some of the data gathered. According to Leal [13], close contact with other fields of scientific expertise and researchers such as Jorge Dias (1907-1973, anthropologist), or Orlando Ribeiro (1911-1997, geographer), and the close contact with populations were key elements of the survey methodology, by allowing a privileged level of access to information. The Entre-Douro-e-Minho was part of Zone 1, and had as senior researcher Fernando Távora, and as junior researchers António Menéres (1930, architect) and Rui Pimentel (1924-2005, architect).

As shown in Fig. 3.8, the IARP survey built up a very extensive data base of different types of vernacular architectures, from very modest to very elaborated buildings, including farmhouses, agrarian production buildings (e.g. granaries, stables or sheds), churches, *"solares"* (nobility houses) and some examples of urban buildings [27,85]. The analysis was extended to settlements and landscape [27,85]. According to Leal [86], in comparison with the IHR, the IARP included examples from all representative rural social classes, giving a less impacting image of rural poverty. Nevertheless, results confirmed the lack of living conditions and overall poor conservation state of the more humble buildings [27,85].

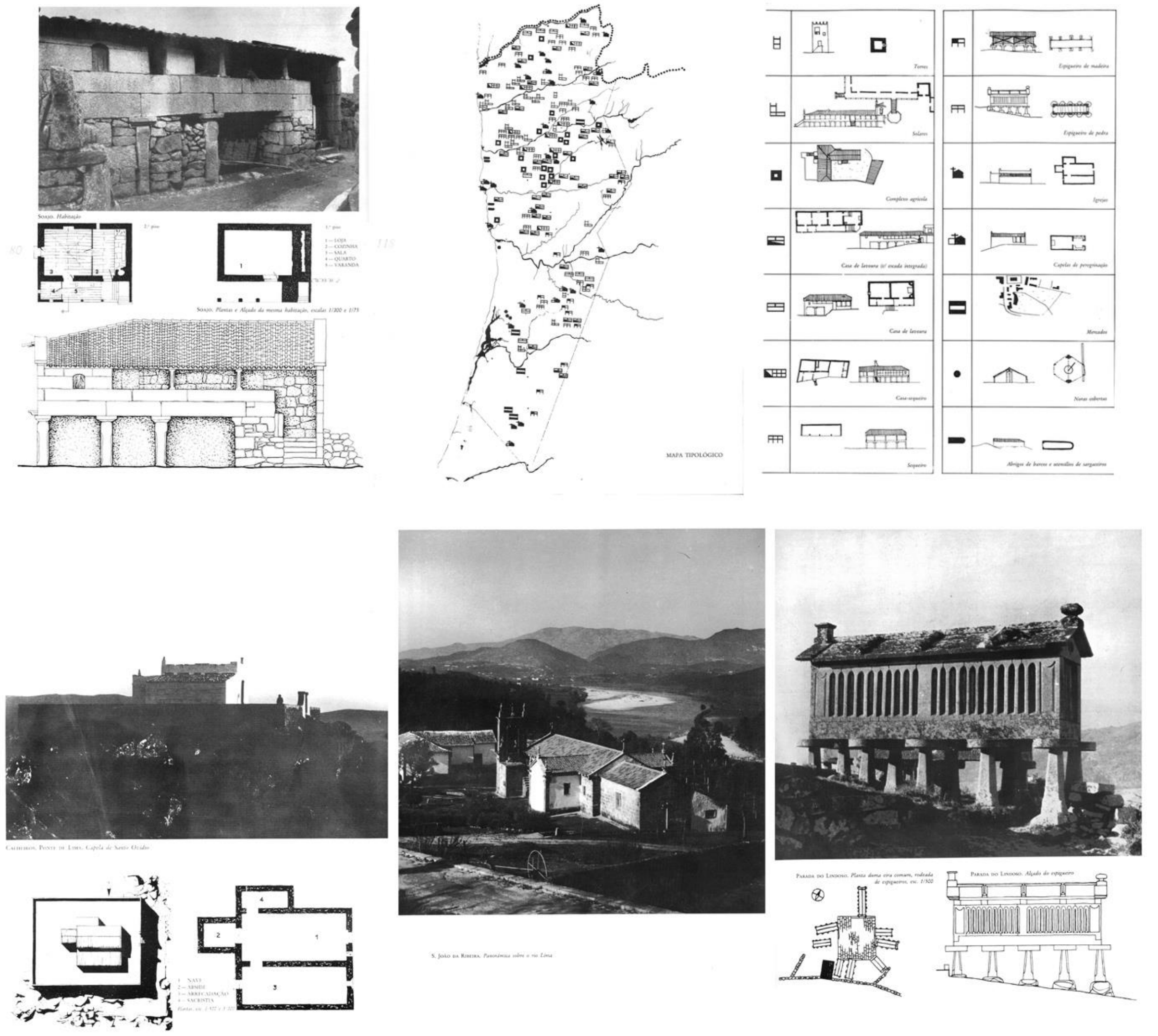


Fig. 3.8 – Examples of the IARP published results, showing the diversity of study cases and information levels [27].

Although the IARP, in comparison to the CA, reported rural buildings high morphological, typological and constructive diversity and inventiveness [13,27], the IARP identified some common basic principles. The rationality of building's design and in the use of materials, the functionality of solutions or the overall simplicity and linearity of building's aesthetics, were some of the common principles identified [13,27]. Although representing a major breakthrough in the study of Portuguese vernacular heritage, according to Leal [20], the IARP survey and its results were ideological influenced by the modernist ideological alignment of its researchers, that to a certain extent, affected the selection of the case studies selected.

Other limitations concern the exclusion or less importance given to examples of rural buildings with a stronger urban influence (e.g. non-traditional aesthetics or built in industrial materials), of imported models such as the *"brazilian house"*, and of very specific and less significant constructions (e.g. shelters, specific fishing or riverside communities' buildings, water infrastructures or farm walls). As for its outputs, the IARP promoted the rediscover of values and knowledge of the vernacular building traditions. It also had a profound impact over the new generations of architectures of the mid-20th century, particularly from the *"Oporto School"* [20], either during their academic preparation or in their initial works. According to Frampton [87], the architecture produced under such influence, named by the author as *"critical regionalism"*, see Fig. 3.9, emerged all over Europe in the mid-20th century, and it self was a reaction against the impersonal and rootless "*International Style"*.

Fig. 3.9 – House Dr. Ribeiro da Silva, known as the *"casa de Ofir"* (1950), architect Fernando Távora (Fão, Esposende).

3.5 Ethnology research of the mid-20th century (ER)

According to Leal [13], for the study of the Portuguese rural world, is fundamental the research of Jorge Dias [59,88] and the data collected by his research group. Under is coordination, were researchers such as Ernesto Veiga de Oliveira (1910-1990, ethnologist), later coordinator of the Museu Nacional de Etnologia (National Ethnology Museum) and of the institution research program, Fernando Galhano (1904-1995, ethnologist) and Benjamim Pereira (1928, anthropologist), in close cooperation with the geographic research of Orlando Ribeiro [13].

In these studies, the rural world is seen globally and not partially, for its culture and social landscape, in need of understanding and already threaten by profound lifestyle changes. According to Oliveira et al. [14], the rural house was integrated in these studies as another agrarian technology, being only conceivable for the support it would give farmers in their efforts to sustain their families. In comparison with the IARP, the range and multidisciplinarity of the information collected by the ER, goes a step forward based on each researcher specific research interests, allowing to embrace a wider rural reality. Concerning buildings, the diversity and level of authenticity of the recorded examples is higher than in all previous studies, being analysed for their morphological and typological diversity, and some for their specific construction technics, design, and functionality principles.

The several performed surveys originated an extensive publications list, starting from the 60's onward, see Fig. 3.10. Among them one can found detailed studies dedicated to different types of vernacular houses [14], agrarian production methods and farming tools [89–91], but also to complex production structures such as water mechanisms [92], granaries [93], mills [94]. Simple structures such as mountain range shelters, stables, stilt fishing structures or temporary structures such as huts were also analysed [10]. The ER studies, by performing an interpretation of the rural world based in scientific and accurate principles, contributed with a wider and complete view regarding rural culture and different ways of life, not trapped in poverty but as part of a disappearing social and cultural context [13].

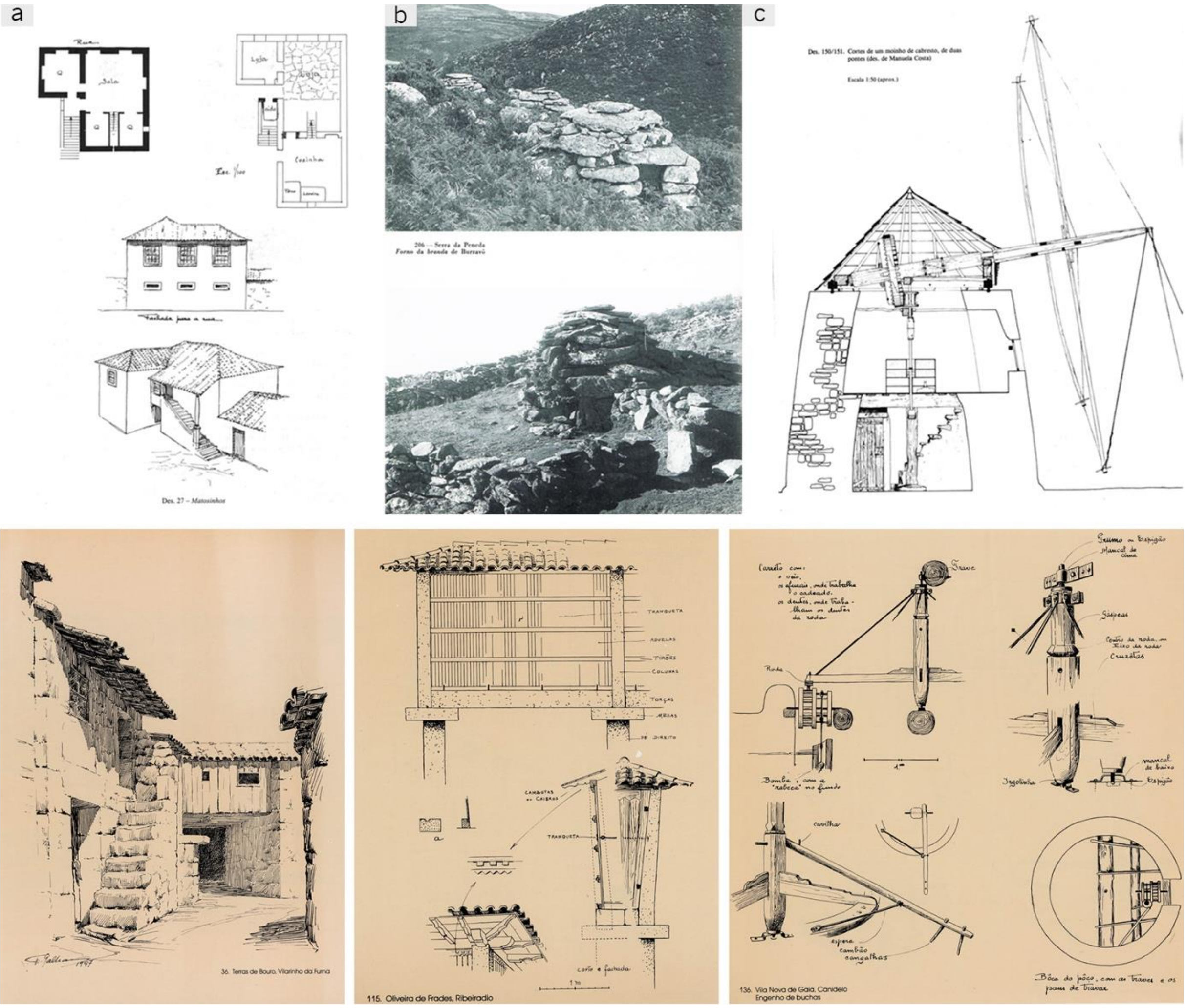


Fig. 3.10 – Above: images from several published studies from the ER: a – *"Maia"* house (Maia, Oporto) [14]; b – corbelled dome shelters (Peneda Mountain Range, Arcos de Valdevez) [10]; c – schematic section of a windmill [94]. Bellow: several examples of ethnographic drawings from Fernando Galhano [95].

3.6 The influence of emigration over the vernacular heritage

Records concerning migrations in the North of Portugal [16] date back to the middle ages. Research from the last decades show that these were and are always part of a wider and complex social and economic phenomenon, resulting from populations search for better living conditions [12,96,97]. Regarding emigration, its influence over the Entre-Douro-e-Minho way of life, can be divided into two distinct moments: *i)* the departure of emigrants, causing a population exodus and forcing the adaptation of local daily routines; and *ii)* the emigrants return, temporary or definitive, bringing foreign influences and lifestyles that over time influence the local way of life [12,14].

Referring to causes for migrations in the North of Portugal, Villanova et al. [12] pointed out to a very crystalized and centuries-old rural social structure with reduced social mobility, dependent of an agrarian economy with very low income and opportunities, that affected all rural social groups. Specifically addressing migrations of middle and higher rural social groups, they can be traced back to the traditional family based agrarian economy of micro and small-size property, insufficient to ensure the economic sustainability and prosperity of larger families [12,61]. For lower social groups, causes for migrations concern mainly the lack of opportunities and very poor living and working conditions [12,57].

According to Saraiva [11], emigrants with new economic capability and expertise gained working abroad, caused changes to local social hierarchy. According to the author, the most immediate effect of the return concerned the drastic diminishing of the gap between higher and lower social groups [11]. The newcomers would gain access to services and goods previously only available to higher rural classes (e.g. education, healthcare, new business opportunities). The introduction of new farming techniques and technologies, new economic activities were also strong outcomes [12]. For its visibility and status, the construction of a new house resembling the models seen at the foreign host country, capable of answering to its proprietors social and economic ambitions, was and still is the strongest sign of success [12]. According to Monteiro [97], the returned emigrant uses his house to show society the outcome of his sacrifices in a foreign land. Although in most cases, the new house incorporates some requirements needed to allow keeping the family agrarian traditions, the natural process of acculturation eventually led to significant changes to functions and purposes of vernacular buildings [11,12,97].

Researchers point out to transformation to farmhouses' symbolic value, giving it a new role in the settlement to express a new type of economic success, of improved living conditions and of a new and more urban lifestyle [12]. This new symbolism was achieved either by constructing new buildings with new morphologies and aesthetic values, but also by placing it at a more representative positioning in the settlement. Drastically upgrading and rejecting old and humbler vernacular buildings without higher social status, for being the symbol of a past of poverty, was also common [12,98]. As part of the rejection process, new materials and building solutions were favoured over vernacular materials and systems [12,14,62]. The strong Entre-Douro-e-Minho emigration, see Fig. 3.11, can be divided into two main periods [12,16]: *i)* the mid-19th to beginnings of the 20th century emigration to Brazil [96]; and *ii)* the mid-20th century large scale emigration to the centre of Europe [17].

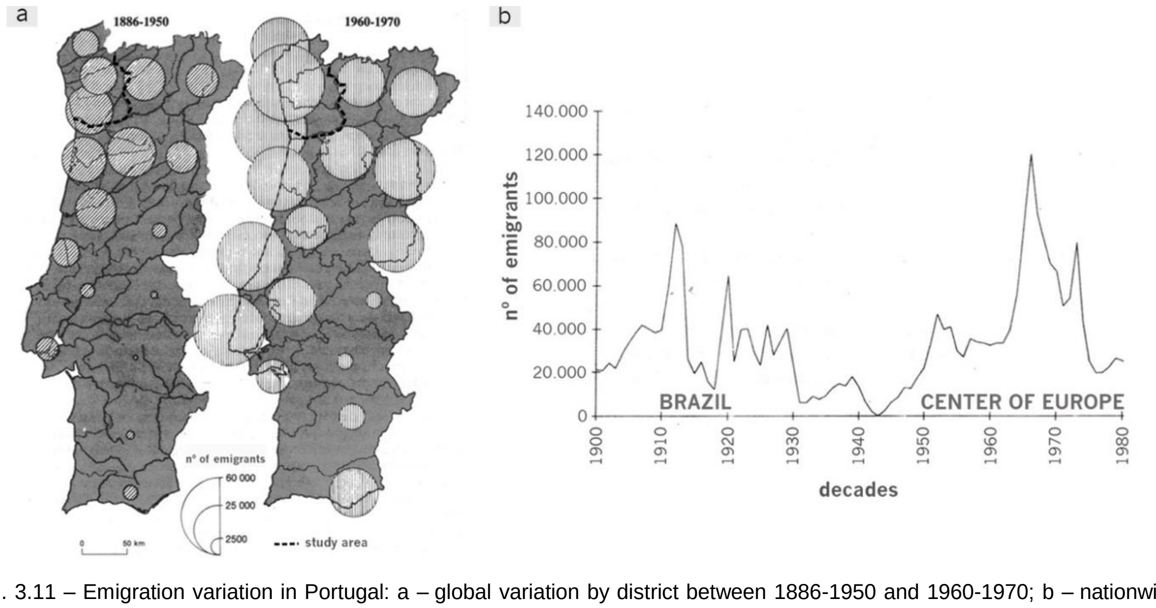


Fig. 3.11 – Emigration variation in Portugal: a – global variation by district between 1886-1950 and 1960-1970; b – nationwide variation between 1900-1980. Based in Brito et al. [17].

Previous and recent phenomena will not be addressed. Although very similar in their initial motivations and in symbolism given by emigrants to their new house, due to their different scales, the impact over the rural territory is significantly different [12]. Emigration to Brazil can be characterized by a strong rural exodus involving individuals from all social groups, that took advantage of Brazil's favourable economy in a period of strong structural changes in Portugal [96]. The investment and philanthropic action brought back by the emigrants that in fact achieved wealth there, known as the *"brasileiro de torna viagem"* (former emigrant in Brazil), decisively contributed to Entre-Douro-e-Minho turn of the century economic and social boom [61,97,99].

Small cities (e.g. Fafe, Póvoa de Varzim or Viana do Castelo) and larger urban centres (e.g. Porto and Braga) underwent a dynamic economic development that would lead to very intense urban renovation processes [14,97]. Becoming a new social, economic, and political player, Villanova et al. [12], points out that this emigrant's integration efforts were aimed at local elites, deliberately breaking apart from its low status rural roots in search of a position among nobility. In such context, the emigrant from Brazil became the *"brasileiro"*, a literary character created in the works of renowned writers of the time such as Eça de Queirós (1845-1900) or Camilo Castelo Branco (1825-1890). It impersonated a character with a negative image, built from specific *"clichés"* of the time, like the taste for exuberance and the *"nouveux riches"* behaviour [97]. The typical palace style *"brazilian house"* (Brazilian style house), is the main physical symbol of this character. Villanova et al. [12] points out the need for a full study of the *"brasileiros"* architectural phenomenon, due to scarce knowledge about houses built by non-wealthy emigrants or influences brought back by them. As pointed out by researchers on the topic, see Fig. 3.12, the *"brazilian house"* was a type of *"bourgeois"* (urban) or palace style house, based on different models of houses of European origin, first imported to Brazil and from there brought to Portugal, mainly between the mid-19th century and the 30's [97].

Fig. 3.12 - Examples of foreign models of houses: a – *"bourgeois"* style (Barroselas, Viana do Castelo); b – large estate or *"quinta"* *"brazilian"* house (Rio Côvo de St. Eugénia, Barcelos).

Although both vernacular and *"brazilian"* houses were built using the same vernacular materials, the new type of house showed a very pronounced urban character [14], either with new and improved construction technologies and quality materials, but mostly, for introducing in the countryside different morphologies and new sanitation standards. The *"brazilian"* house stood out from the vernacular houses or *"vilas rústicas"* (rural villas) [96,97], for its strong aesthetic exuberance, due to features such as the vibrant use of colours, complex volumetric compositions and the abundant use of decoration [14,61,97].

The second and still undergoing emigration phenomenon, directed to central European countries [12], for its scale and social impact, is considered as the most significant contemporary migration phenomenon of populations of the North of Portugal. Commonly known as *"casa de emigrante"* (emigrant style house) or *"casa à francesa"* (French style house), see Fig. 3.13, like the *"brazilian"* house, the type of house built by this emigrant is also a symbol of economic success. Nonetheless, Villanova et al. [12] points out that both emigration waves produced very distinct impacts and consequences. Studies from the 90's highlight the important social significance of the *"emigrant house"* and of its new industrial made building materials and technologies, among non-emigrants population [12].

Fig. 3.13 – Example of very common models of "*emigrant houses"* [12].

From a social point of view, Villanova et al. [12] refers to this type of house as the *"casa de sonhos"* (the house of dreams), through which the emigrant intents the reintegration and social recognition among its own community, not like the *"brasileiro"*. This new type of house, is also based in the importation of foreign models, acquired by emigrants either by direct contact in the host country or by access to reference projects and magazines [12,62]. Being humbler and more affordable than the highly elaborated and expensive *"brazilian"* houses, it was closer to non-emigrants' economic capability.

As the first, see Fig. 3.14, the *"emigrant house"* also has a strong aesthetic impact in the landscape, due to features such as a non-traditional placement recessed from the street, uncharacteristic volumetric compositions, the use of colours and facade tiles, or the use of decorative elements [62]. New buildings show internal organizations prepared for a more urban lifestyle, built with a taste for large-size buildings, with special care and investment put in the contact with the exterior of the house, in particular facing the main street [12,62]. According to Oliveira et al. [14], from a constructive point of view, with the *"emigrant house",* a complete break with the vernacular constructive tradition occurred. According to Villanova et al. [12], the massive introduction of uncharacteristic industrial building technologies and materials (e.g. concrete structures, new light structural systems or aluminium frames) beneficiated from the expertise acquired by emigrants abroad, most in the construction sector, and fast spreading through the self-help networks and self-construction agrarian tradition [14]. As a result, the construction market and associated industry underwent a significant development and specialization process from the 70's onwards, causing the almost complete abandonment of the vernacular materials and building technologies [14].

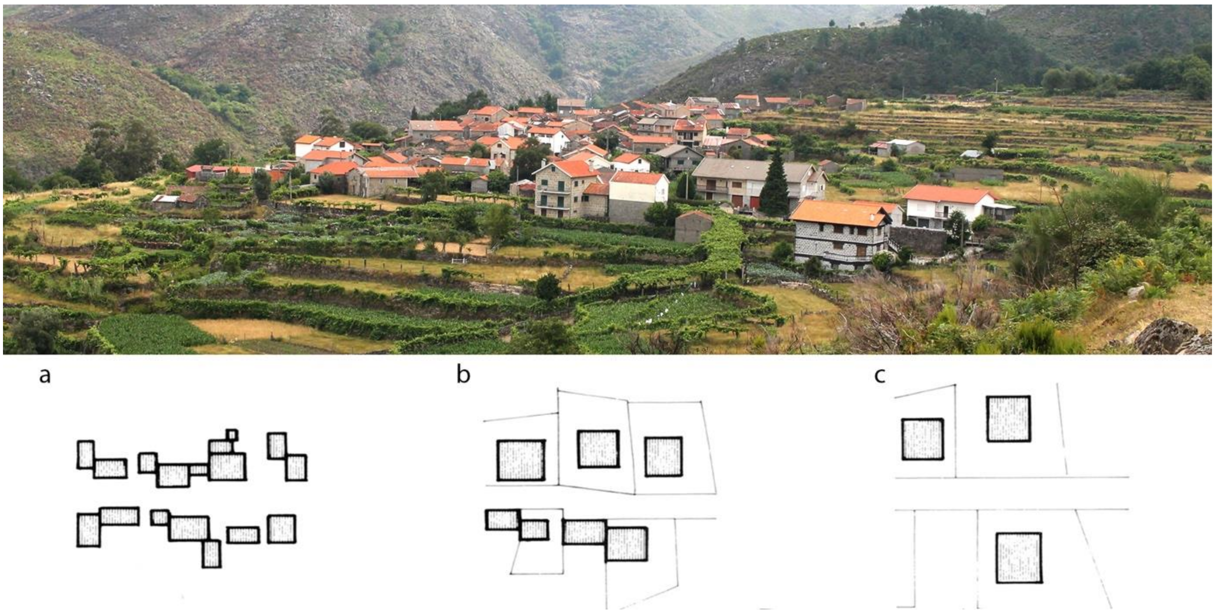


Fig. 3.14 – Above: traditional village with strong presence of uncharacteristic “emigrant houses” (Ermida, Ponte da Barca). Bellow: schematic of the placement of *“emigrant houses”* [12]: a – vernacular organization and reconstructed houses by emigrants; b – partially or fully isolated buildings (before the 80’s; c – fully isolated and recessed from the street (80’s onward).

According to several researchers [12,62], as the *“emigrant house”* gained status as role model for rural populations [57], in the opposite direction, vernacular houses and their building materials and technologies, acquired a negative image among rural communities [12,62,98]. As with *“brazilian”* house, also the *“emigrant house”* is targeted with a negative image, not only based on aesthetic criterions, but also due to their role in the loss of character of settlements and of the rural landscape [98]. According to researchers such as Ribeiro [16], Oliveira et al. [14] or Villanova et al. [12], this fact can be attributed to the past decades lack of public policies concerning the improvement of rural housing conditions, inefficient or the inexistence of administrative regulations, and lack of technical capacity among technicians and builders.

3.7 Final Remarks

The study of the rural world in Portugal started in the mid-19th century, evolving from a start defined by ideological interpretation of the rural realties, to studies based on extensive scientific methodologies, in latter mid-20th. In these studies, different readings, and levels of information regarding vernacular heritage can be found. Offering different perspectives, these studies are fundamental to the interpretation of still surviving vernacular heritage, being a first-hand testimony of a past way of life, nowadays almost lost. From the analysed studies, it is clear the strong relation between communities and their landscape and built heritage, in a relation marked by high levels of cultural diversity and strong authenticity and identity features. Proofs of the inventiveness of rural populations using local building materials and developing specific solutions to deal with climate and agrarian challenges, are also constant in these studies. Vernacular models’ flexibility and adaptation capability to context changes, and a dwelling design serving simultaneously as shelter but mainly as an agrarian tool, is also clear as a nationwide common basic feature of vernacular architecture. Recent studies regarding rural Portugal became focused on understanding the undeniable and drastic changes to the traditional way of life and of its multi-dimensional impact over the rural territory. Past decades emigration was again identified as the main source of change in the rural territory, either by putting pressure on more economically attractive rural territories, or by causing population exodus from the less attractive ones. Changes to the life standards, the denial of the symbols of the past harsh rural life, and the attractiveness of a contemporary and market based economy and corresponding way of life, led to the adoption of new models of buildings and of new symbols of success. Changes in the construction industry, redirected from the 60's onwards to answer to the need for industrial materials and non-vernacular construction techniques, gave a strong push to the high loss of vernacular constructive knowledge. Unappropriated legal standards and public planning were also identified as a major source of damage and loss of authenticity of both vernacular buildings and rural settlements. Further research is required to develop proper course of action to deal with the past decades' transformations in the Entre-Douro-e-Minho rural society, thus, to understand better how to reach a compromise between the protection of their vernacular heritage and answering to their life standards and social economic needs. A transversal reading of the above-mentioned studies underlines the importance of multidisciplinary methodologies applied to heritage preservation, as the most effective and accurate way, for the full identification of cultural significance of the endanger vernacular heritage [3,26].

Chapter 4

CHARACTERIZATION OF THE SURVEY AREA

Although human basic needs are identical to all, survival challenges imposed by climate, geography, and available natural resources, vary from territory to territory. In response to such challenges, human survival skills were perfected over centuries of trial and error attempts, to make the most of the territory potential, resulting frequently in context adapted agrarian strategies, that dictated the landscape occupation and communities social organization [14,63].

Addressing the rural territory, researchers adopted Ribeiro's [61] geographic model of continental Portugal, to explain and interpret the very rich and diversified Portuguese rural reality, including its vernacular heritage [13].

Based on geography, the author divided the territory into the Atlantic Portugal (North), subdivided into Northwest and Northeast sub-regions, and the Mediterranean Portugal (South). Later ethnographic research highlighted to the overwhelming diversity of sub-regions and specific identities existing among these two blocks' agrarian societies [13,14].

4.1 Geographical characterization

The Entre-Douro-e-Minho is located on the northwest of the Portuguese North region (NUTSII Euro region), being its territory administratively divided into the districts of Oporto, Braga and Viana do Castelo. According to Ribeiro [16], the Entre-Douro-e-Minho was the designation of the former territory management unit located between the two-main regional rivers, the Minho (northern border) and the Douro (southern border) [99]. This administrative region was later extinguished in 1832, being the territory divided into the Minho (North) and the Douro Litoral (South) provinces. These were also officially extinguished in 1976 and replaced by the present administrative organization of districts. Nevertheless, the old region and provinces identities are still a present reality among the local populations' cultural identity. For sharing common geographic and social features with Southern Galicia, to the north of the Minho river, and with the territory to the south of the Douro river, Bastos et al. [57] point to Entre-Douro-e-Minho wider territorial influence [57]. As shown in Fig. 4.1, the survey area remaining natural borders are [61,99,100]: *i)* the Atlantic Ocean to the west; *ii)* the Tâmega river to the southeast; *iii)* the Galician-Portuguese mountain range system to the northeast (Spain), and the east (Vila Real district) formed by the Peneda-Laboreiro (1416 m), Amarela (1362 m), Gerês-Xurés (1548 m), Barroso (1279 m) and Cabreira (1286 m) mountain ranges; *iv)* the Galician-Duriense mountain range system to the east and the southeast formed by the Alvão (1283 m) and Marão (1415 m) mountain ranges [61,99,100].

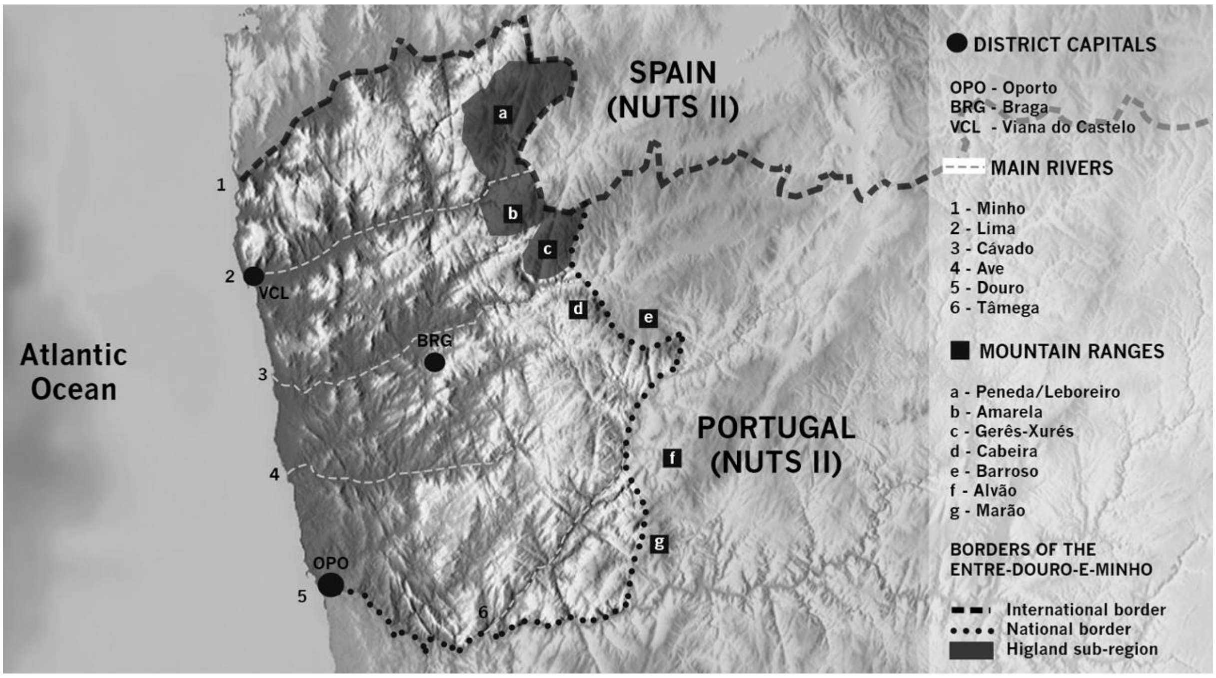


Fig. 4.1 – Borders of the Entre-Douro-e-Minho region, based in [101] and Maps for Free ®

Following Ribeiro's geographic tripartite model, see Fig. 4.2a, the survey area is part of the Atlantic Portugal, occupying the north portion of Northwest Portugal [15,61]. It is characterized by an Atlantic Ocean influenced climate, and a landscape shape configuration of natural amphitheatre [15,17,57], with predominant valleys, plains and smooth hills most bellow 200 m above sea level, that stretch from the mountain ranges (northeast to southeast), to west and south, see Fig. 4.2d and Fig. 4.2b [15,61]. Taking into consideration Continental Portugal's geography, the survey area shows a smoother topography and a moderate climate in comparison with the predominant mountain range territory and harsher Continental climate of the Northeast Portugal [15,61], yet radically different from the very large plains and valleys, and warm Mediterranean climate, of the Mediterranean Portugal [61]. Detailed geographic information is presented in Fig. 4.2.

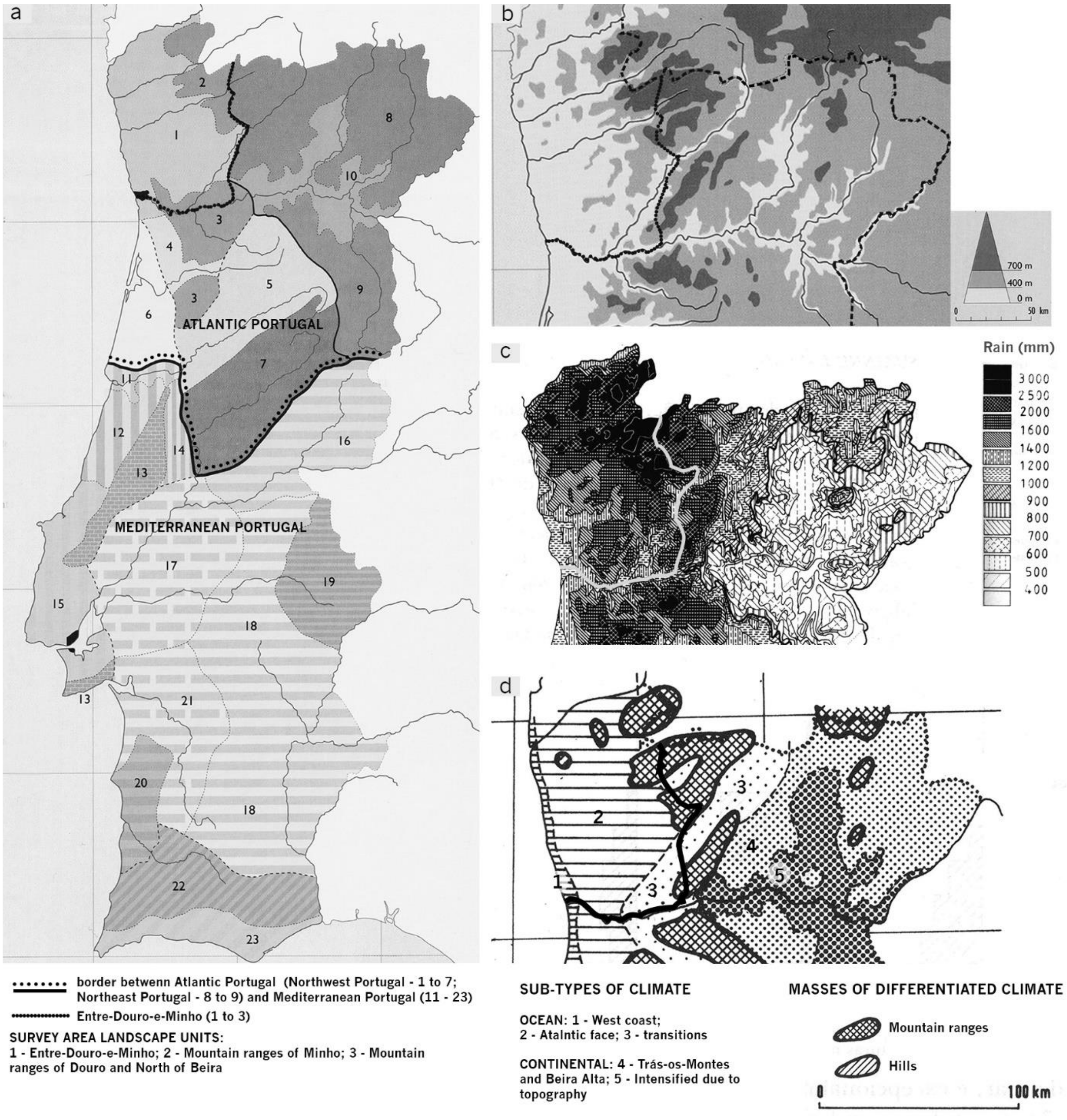


Fig. 4.2 – Entre-Douro-e-Minho geographic characterization charts: (a) Orlando Ribeiro Continental Portugal geographic model, based in landscape units (based in [61]); (b) orographic chart (based in [61]); (c) pluviometry chart (based in [15]); (d) climatic chart (based in [15]).

According to Ribeiro [61], see Fig. 4.2c, the Entre-Douro-e-Minho close proximity to the Ocean provides abundant rain and high levels of humidity, with an average variation from 1000 mm at lower altitudes to 3000 mm at higher altitudes, for a minimal duration of 105 days and with two dryer months (< 30 mm of rain) [15]. Fogs and rime are frequent during the cold season. Although snow is common in areas above 1000 m, humidity levels decrease from the coast inwards [15]. According to the author, see Fig. 4.2c, the always green aspect of the landscape, which favours irrigation farming and cattle, is due to high levels of humidity concentration in the region. Such is caused by the blocking effect of eastern mountain ranges over humidity propagation to Northeast Portugal, (from 3000 mm of rain per year on the mountain range northwest face, and from 1000 to 1500 mm on the mountain range northeast face [15]). Superficial water is very abundant, due to a vast network of waterlines, formed by larger east-west orientated rivers (Minho, Lima, Cávado, Ave and Douro), smaller rivers (e.g. Neiva, Homem, Este or Leça), and dense capillary network of streams, see Fig. 4.1.

Temperatures are moderated all year long, resulting in moderate winters (average of 8 ºC in January) and fresh summers (average of 20 ºC in August), with a temperature gradient of 0.4 ºC/100 m for minimal temperatures and of 0.6 ºC/100 m for maximum temperatures [15]. However, as shown in see Fig. 4.2d, climate becomes harsher in the mountain range areas due to topography. Analysing the described geography, two different types of landscapes were identified by authors in the survey area, each shaping specific agrarian cultural identity [11,14,57,61] (see Fig. 4.1):

i) The *“ribeira”* (riverside), from now onward referred to as lowland sub-region, also associated to the typical *“Minhota”* identity, covers the majority of the territory up to an altitude of 400 m, related to intensive family based polycultivation farming [11,61,102];

ii) The *“serra”* (mountain range region), from now on referred to as highland sub-region, that refers to human occupations found in the Peneda/Laboreiro-Amarela-Gerês/Xurés mountain range [11,100] territories, typically from 400 m to 1100 m of altitude, related to agro-pastoralism [11,60,61,102].

Establishing a frontier between the two sub-regions is not consensual due to a very strong agrarian cultural background shared by both sub-regional identities [11,61]. Authors such as Bastos et al. [57] or Saraiva [11] point out to several transition areas located at mountain areas around 400 m above sea level, (e.g. Agra mountain range), that shared features from both sub-regions, such as some forms of polycultivation, livestock in pastoral system or the use of farming terraces. Ribeiro [61], set a reference frontier marker at 700 m above sea level, based on the effects of natural conditions over typical regional cultivations of Mediterranean origin [15]. A resume is presented in Table 4.1 and the main cultivations distribution on the territory is presented in Fig. 4.3a. As shown in Fig. 4.3b, according to Lautensach et al. [15] and Bastos et al. [57], due to geography, property size and numbers, and associated productivity increases southwards into the former Douro Litoral province.

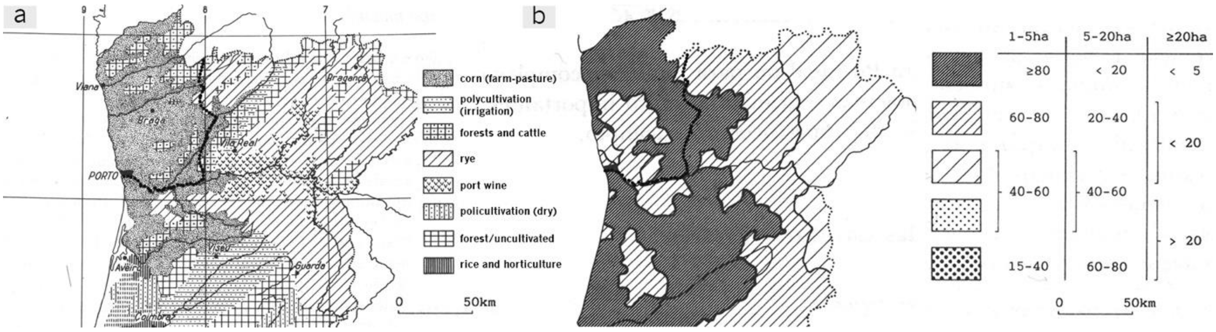


Fig. 4.3 – (a) Entre-Douro-e-Minho predominant cultivations based in [15]; (b) farm distribution according to size, based in [15].

Fig. 4.4 – Images from the Entre-Douro-e-Minho lowland (a and b) and highland (d and f) sub-regions: (a) Lima-Cávado rivers coastline; (b) coastline smooth hills (Póvoa de Varzim); (d) Vez river valley (Sistelo, Arcos de Valdevez); (e) terrace farming in Porta Cova (Sistelo, Arcos de Valdevez).

Table 4.1 – Loss of productivity of the most demanding regional cultivations (of Mediterranean origin) due to altitude [15,61].

< 20 m (dune area)	< 400 m	400 m to 700 m	700 m to 1100 m	> 1100 m
• Horticulture • Marine fertilizers (e.g. *“sargaço”* (*sargassum*) • Fishing communities	• Intensive production of all regional cultivations (Mediterranean origin); • Livestock (stabled)	• Loss of production capability of more demanding Mediterranean species (e.g. fige trees (*Ficus carica*); *Loureiro* (*Louros nobilis*) • Livestock (stabled and transhumance above 700 m)	• Loss of productivity or absence of the regional main species (e.g. corn (*Zae mays*); wine (*Vitis vinifera*); or pine trees (*Pinus pinaster*) • Mountains range cultivations such as rye (*Secale cereales*) or potatos (*Solanum tuberosum*) • Livestock and farming in mountain plateaus (vertical transhumance)	• Livestock in mountain plateaus (vertical transhumance)
“ribeira” or lowland - Intensive polycultivation		transition area	*“serra”* or highland - Agro-pastoral with vertical transhumance	

a) Lowland sub-region

As shown from Fig. 4.4a to c, and previously-described, the lowland landscape is shaped by the strong presence of water lines, smooth hills, plateaus, and large valleys. Natural conditions provide diversified and abundant farming resources such as forest resources, animal manures due to a strong cattle sector, and even marine resources such as the *“sargaço”* (*sargassum*) used as fertilizer [11,61,103]. Bastos et al. [57], described this sub-region for its strongly humanized territory. According to the author, through centuries of arduous work, lowland farmers turned less productive or unfertile land into farms, by improving the soil fertility by constantly adding natural fertilizers and building complex irrigation systems. Land availability was continuously increased by clearing forest areas, by occupying dune areas or by shaping hillslopes into farming terraces [61,65]. Over time, the territory was divided into a nebula of individual family-based farms, and the land used for intensive polycultivation, meaning that the same portion of farmland was used for several consecutive cultivations and pasture throughout the agrarian cycle. Concerning livestock, stabled large-size cattle predominated [61,65]. Regional agrarian economy was supported by the lowland large number of river and sea harbours, that allowed national and international commerce but also migrations [16]. Economic dynamics also resulted from the mobility allowed by partially or fully navigable rivers, and extensive coastline, both fundamental to support industrial and non-agrarian sectors such as the fishing industry [16]. According to Almeida [104], roads and associated commerce networks are reported since the Bronze Age. According to the author, the regional road network was improved in the Roman period, and later in the Middle Ages with the construction of bridges (e.g. Barcelos, Ponte de Lima or Ponte da Barca) and of new connections between the larger urban centres (e.g. Oporto, Guimarães or Braga) [104]. The interconnectivity of the territory was revolutionized during the 19th century with the replacement of pre-industrial road networks with new and improved roads, and in 1886 by the construction of the railway line of Minho, connecting the region to Galicia in the North and, through Oporto, to the South of Portugal [104].

b) Highland sub-region

As shown from Fig. 4.4d to f, and previously-described, the highland sub-region is defined by harsh mountain range landscape, with drastic territory elevation changes, shaped by steep mountains and narrow and deep valleys. The outcome was shortage of farmland and farming natural resources that led to the development of specific agro-pastoralist ways of life, that had in vertical transhumance a distinctive cultural identity feature [105]. Despite the strong humanization effort, landscape occupation density was low, and performed through spread and strategically located dense self-sufficient nuclei. These were formed by a main settlement, placed near pockets of farmland and farming terraces, connected through mountain roads and paths to each community individually owned mountain range plateaus settlements [102,106,107]. The latter were generally located above 700 m to an altitude of 1100 m. Different types of temporary settlements were built and used for livestock in pastoral system and for farming if possible, according to each mountain range specific geography and available resources (e.g. *“brandas”*, *“currais”* or *“brandas and inverneiras”*) [10,60,102]. According to literature, the adoption of such type of agrarian strategies was a common feature among most mountain range communities around Portugal (e.g. Estrela mountain range or Northeast Portugal), being specific in the Entre-Douro-e-Minho highlands for the development of a vertical transhumance strategies [58,63,102]. Regarding the highland cultural identity, a major defining feature concerns the common labour management system that allowed a vital rationalization of human and natural resources. Both sub-regions shared the same type of private and community owned property systems. However, individual farm work played a secondary role in these mountain range communities, with livestock management gaining a key role in their agrarian economy [58,61,102]. Due to the highland difficult orography, its mobility network was reduced to a minimal indispensable, being formed mostly by simple mountain roads and paths that frequently offered difficult travelling conditions, particularly in winter time. Although close to the lowland dense mobility network, few connections were available resulting in the severe isolation of the highland populations until recent decades, hindering the sub-region social and economic development.

4.2 Territory occupation and construction

Regarding human occupation of the territory, authors such as Ribeiro [61], Lautensach et al. [15] or Brito [17] considered Entre-Douro-e-Minho as a centuries-old case of success. Nevertheless, dense occupation in a reduced size territory led to a highly subdivided territory, with a very irregular agrarian mosaic landscape that imposed severe limitations to regional wealth creation [61], and to individual family prosperity [15,17]. Concerning human occupation, Martins [108] places the origin of the regional basic occupation layout in the megalithic cultures (around 4000 years) and in the Proto-Historic *“castreja”* culture (Northwest Iberian Bronze Age civilization - I millennium a.C. to the I millennium b.C.)

periods [17,61]. According to the author [108], in the following Roman occupation period (2th century a.C. to the 5th century b.C.), the remaining territory organization structural features were added, regarding its agrarian, administrative and urban structures, that prevailed almost unchanged until the 20th century. As shown in Fig. 4.5, in the *“castrejo”* and Roman periods, high density occupation takes shape [63,109], according to Brito [17], explained by the territory high farming potential.

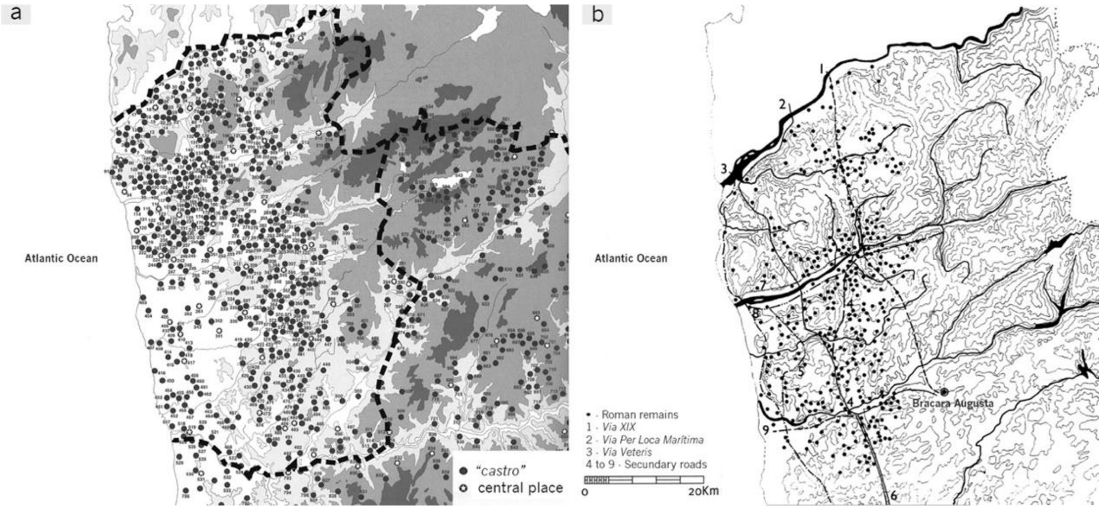


Fig. 4.5 – Entre-Douro-e-Minho territory occupation based in archaeological remains: (a) *“castreja”*, based in [110]; b – Roman located near the coastline, based in [111].

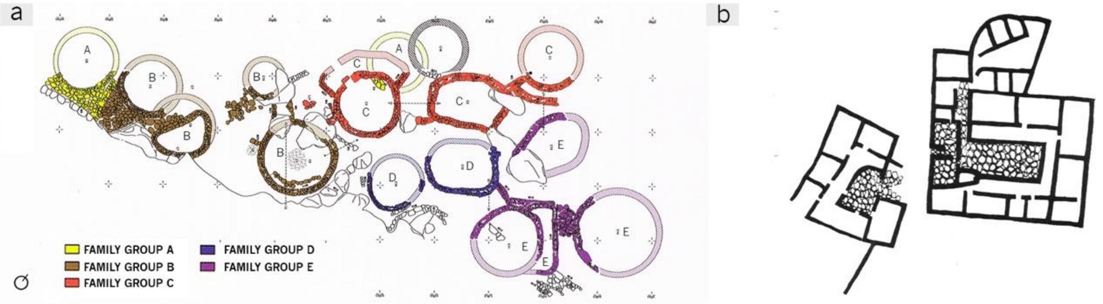


Fig. 4.6 – (a) examples of family groups of *“castrejos”* buildings in the *“castro”* of S. Lourenço (Esposende) [112]; (b) roman *“villae rustica”* in the Romanised *“castro”* of Padrão (Santo Tirso) [27].

According to Silva [113], it is during the *“castreja”* culture period that the first organized territory occupation took place. Based on archaeological evidences, the author [17,114] describes the *"castrejos”* as a agro-pastoralist society, that used marine and river resources, and maintained commercial contacts with Mediterranean civilizations for metals trading. As shown in Fig. 4.5a and Fig. 4.6a, the territory was occupied by establishing dense self-sufficient settlements, preferably near rivers or the coast, placed on hilltops or half-slope positions between 200 m and 500 m above sea level (e.g. Briteiros *“citânea”* in Guimarães, or Sanfins *“citânea”* in Paços de Ferreira). Very few known examples of coastal (e.g. S. Paio *“castro*” or Baroña *“castro”* in Galicia) or valley settlements (e.g. the *“castros”* of Roupeiros or Capela das Almas in Viana do Castelo) were discovered [111]. Almeida [111], based on the study of the Minho coastal territory, described a very vast nebula of settlements formed mainly by smaller *“castros”*

(< 1 ha) and larger and central *“citâneas”*, such as Sanfins (7 ha) or S. Tecla in Galicia (20 ha). According to the author [111], each settlement was at the centre of a territory influence area used for farming, being smaller settlements under the influence of larger ones. Regarding the Roman occupation period, centralized administration of the territory was established, based on a common administrative language, the Latin. As mentioned previously and shown in Fig. 4.5b, the construction of an inter-regional road network, or the first urban organization of the territory based in a system of larger administrative and political centres (e.g. *Bracara Augusta* (Braga), *Portus Cale* (Oporto) or *Aquae Flaviae* (Chaves)) and secondary network of smaller urban centres, named open settlements (e.g. Ponte de Lima or Taipas) [108]. According to Martins [108], this type of settlements were spread throughout the territory following the major roads. Rural and the *“castrejas”* populations of the Romanized *“castros”* could find in these settlements any needed religious and commercial support [61,104,108].

Simultaneously, some *“castrejos”* settlements evolved to *“vicus”* (small urban centres) such as the *“castros”* of Castle of Faria (Barcelos), St. Luzia (Viana do Castelo) or S. Lourenço (Esposende). Concerning the Roman agrarian organization, it was focused in the occupation of the valleys, through their subdivision into privately-owned agrarian production units of intensive polycultivation farming, named *“villae rusticas”*. Authors point out to this system as responsible for the introduction in the region of the concept of private ownership over the land [17,57,61]. Sampaio’s [115] turn of the century research regarding the organization of the rural territory, highlighted the important role played in it by the disintegration of the “*villae rusticas”* in the post-Roman period. According to the author, this process was fundamental to the creation of the Northwest occupation model of rural parishes and farmhouses. This conclusion was later disregarded by researchers based on the lack of strong archaeological evidences, the absence of the typical regular landscape mosaic shape configuration and of clear documental evidences [116,117]. Based on archaeological data, Martins [108] points out that the few known examples of *“villae rusticas”*, as shown Fig. 4.6b, were simple buildings of roman inspiration without typical Roman large agrarian estates specialized areas.

According to the author [108], evidences show a specific Northwest variation of the *“villae rustica”* system, organized in small and medium-size estates, property of indigenous populations and formed by scattered portions of farmland, resulting from the system adaptation to the soil high productivity but also to the territory size limitations. The author also highlights that both Roman and *“castrejo”* farming, and territory occupation were contemporary, being several hilltop settlements and their influence areas still reported in use in the High Middle Ages [108,112,118].

According to Ribeiro [61], the following centuries brought few changes to the Northwest human occupation layout. According to Brito et al. [17], population kept growing during Suebic, Visigoth and Arab rule. In the social, economic, and political stability that followed the post-*Reconquista* period, human occupation became increasingly dispersed, being the old hilltop settlements progressively abandoned. According to Ribeiro [63], the highland geography made the pre-roman occupation strategies and agro-pastoralist systems to prevail in time. From late 13th century onward, the consolidation of the Portuguese territory was enforced by royal power, and also included the Entre-

Douro-e-Minho. New settlements and municipalities were created (e.g. Caminha, Viana do Castelo or Castro Laboreiro), and changes were introduced in the territory management policies. This was achieved by assigning portion of territory to nobility and clergy orders administration (e.g. to Tibães or Alcobaça religious orders), and by creating legal frameworks to boost farming and commerce (e.g. the *"sesmarias"* law that reorganized the agrarian sector or the several new markets authorizations) [15,17]. Although a first considerable migration flow was reported in the 15th century, headed to the newly discovered Atlantic islands and new territories found during the Portuguese sea discoveries, regional population growth kept its rhythm, being the Entre-Douro-e-Minho occupied by 1/5 of the total Portuguese population [16,17]. As shown in Fig. 4.7, records from 1639 and 1732 show that the Portuguese population doubled from 1.070.000 habitants to 2.140.000 habitants, again with a very strong incidence in the Northwest region [15,17].

Regarding its causes, Ribeiro [61] points out to the substantial increase of income and availability of food stocks due to: *i)* the so called *"corn revolution"*, that resulted from the introduction of corn (*Zea mays*) cultivation in the Northwest (16th century), and led to an agrarian revolution based on this cultivation high productivity and new production needs; *ii)* the discovery of large reserves of gold in Brazil [27] that led to a period of strong economic and commercial development, with intense urban and rural renewal processes. Most of the existing religious (mainly of Baroque style) and vernacular heritage existing today was either built or deeply renovated in this period [14,17]. During the 19th century, population growth accelerated beneficiating of a new intense period of economic growth and the introduction of new cultivations such as potatoes *(Solanum tuberosum)*. According to Brito et al. [17], in this period, the human agrarian occupation of the Entre-Douro-e-Minho territory reached its maximum expansion regarding the use of mountain range and valleys territories, including a massive transformation of previously considered unfertile areas into new production areas (e.g. sandy coastline areas or steeper mountain range slopes) [63]. Despite the previously explained strong impact of emigration, population growth kept a constant rhythm until the 90's [17]. A synthesis regarding population growth from the 16th to the 20th century is presented in Fig. 4.7.

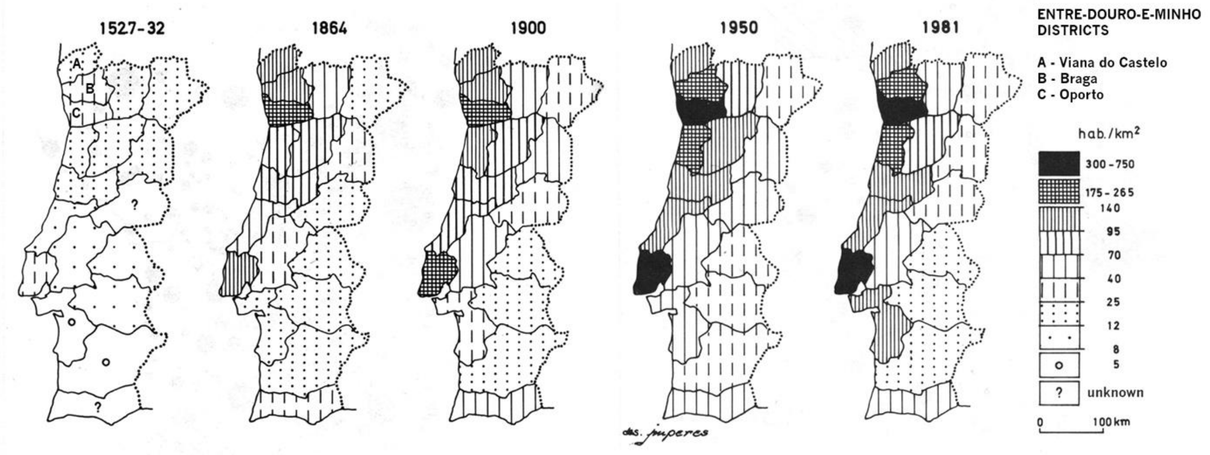


Fig. 4.7 – Synthesis of Portuguese population density variation by district, between the 16th and the 20th centuries [15].

a) The territory construction cell: the farmhouse

Regarding Entre-Douro-e-Minho landscape agrarian occupation, it depended of the following combination:

i) A mosaic of privately-owned property that had on the farmhouse estate its centre, see Fig. 4.8;

ii) The support of pockets of common or community-owned land (managed accordantly to community agreed rights of use) and public areas (meaning in this context with no specific claimed rights of use) used for pasture and to collect forest materials;

iii) All types of property integrated in either dense or scattered settlements [14,61];

iv) That covered the landscape with a vast nebula network of human occupation points, interconnected by roads and paths [27,63,104].

Fig. 4.8 - Example of a lowland group of farmhouses, also named *"casal"* (Paradela, Barcelos).

The typical exception to the above-mentioned organization, regarded groups or communities with specific trades or contexts such as fishing communities (e.g. Caxinas in Vila do Conde, or Matosinhos), communities dedicated to marine resources harvesting (e.g. the *"sargaço"* trade of Apúlia, Esposende, or Castelo de Neiva, in Viana do Castelo) [14,103], or dedicated to specific crafts (e.g. the ceramic artisans of Prado or Galegos, or of tiles in Barqueiros, all in Barcelos) [68,77,119]. The lowland type of farmhouse, also known as *"casa de lavoura Minhota"*, is described by Oliveira et al. [14] as a farming tool. According to Cabral [120], the Entre-Douro-e-Minho farmhouse must be interpreted as an economic and social enterprise, being the main physical cultural heritage symbol of the *"Minhota"* identity (tangible) and of its strong traditional family values (intangible) [120]. The common Entre-Douro-e-Minho farmhouse is generally presented by authors as a small or medium-size agrarian production unit, productive through family endeavour, with an estate formed by three main types of scattered properties [59,61,120,121]: *i)* an enclosed farmstead, formed by the family dwelling, kitchen garden, and several different types of agrarian premises, all placed around one or distributed through different farmyards; *ii)* farmland, generally used all yearlong; and *iii)* forest areas to collect all types of support materials for the farm (e.g. wood or vegetal materials for manures production). An example is shown in Fig. 4.9.

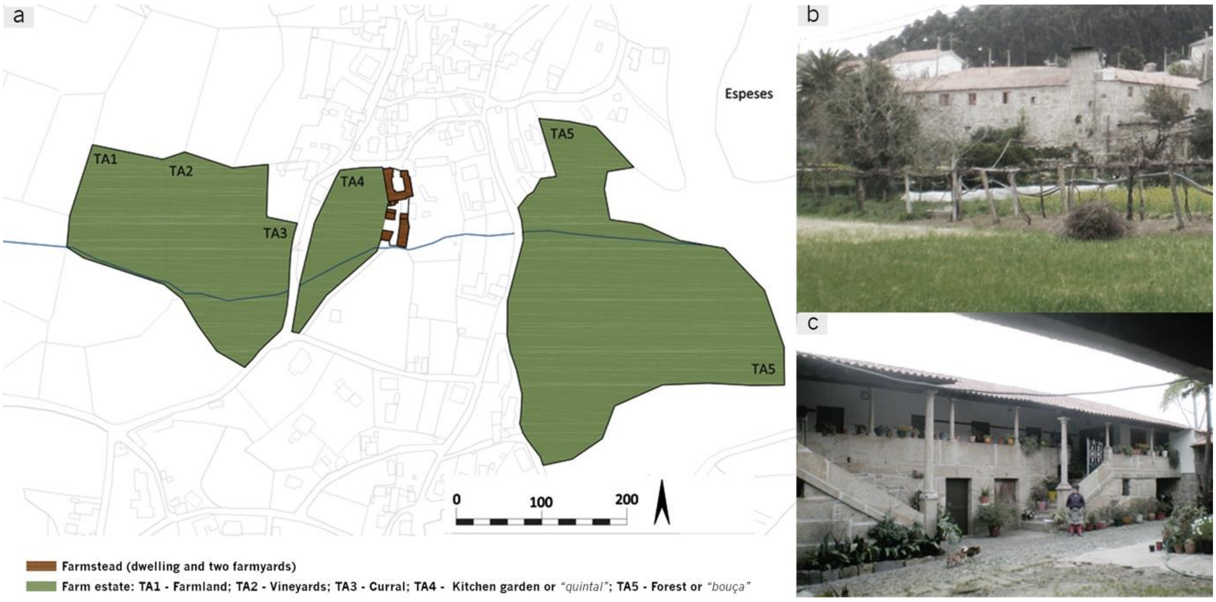


Fig. 4.9 – *"Casa dos Malheiros"* (Milhares, Barcelos), an example of a typical *"casa de lavoura Minhota"*, or lowland farmhouse [122]: (a) full estate; (b) external view of the farmstead; (c) view of the dwelling from the farmyard.

Concerning the farmland, it is described by Ribeiro [63] as used in the *"campo-prado"* (farm-pasture) system. In it, the same land is used throughout the agrarian yearlong cycle for different types of consecutive cultivations of dry (e.g. rye) and irrigation farming (e.g. corn), and for pasture in the remaining time [61,93,123]. Other cultivations such as wine, typically cultivated at the edges of the farms using the farm walls or trees as support, or vegetables, cultivated in kitchen gardens, or *"hortas"*, were also quite common. Concerning livestock, cattle was the main production of the lowland region (particularly as exportation assets), being livestock such as sheep and goats predominated in the highlands. Swine and chickens were part of each family domestic economy [57,61]. From livestock, animal origin sub-products were produced and used (e.g. milk and eggs). Manures were used as fertilizer. Bulls, horses, and donkeys were used as working animals (e.g. transport and to plough). Regarding their placement in the territory, as previously mentioned, farmhouses were part of a rural settlement, being the farmstead generally anchored to a road [104]. According to Almeida [104], being in the Middle Ages an essential tool to organize property in the absence of natural boundaries, the road became later a vital economic tool to the survival of the farmhouse economy. It allowed access to regional markets, or *"feiras"*, but also to urban centres and harbours, allowing trade and exportation of farming, livestock, and artisanal productions.

Regarding the lowland farmhouse, geography and agrarian strategies led to their dispersion throughout the landscape, either isolated or forming groups named *"casais"* (couple – a concept that refers to a type of family based agrarian enterprise) [117,120]. Due to the availability of land, the farmstead was built near or in a central position regarding the farm estate, therefore rationalizing work and travelling times and costs, but also a more effective protection of crops, livestock, and assets [14,57]. As a result, the landscape was transformed into a very dense pattern of walled farmland and forest areas (called *"bouças"* when private, *"baldios"* when common, or *"maninhos"* if public) [61,65,66].

Analysing the highland farmhouse, geography and shortage of land led to the context adaption of the lowland model of farmhouse, becoming the *“serra”* farmhouse (mountain range farmhouse) [14,59,121,124]. To maximize available land and protection against climate, farmhouses and rural houses were placed inside the perimeter of concentrated settlement, gaining group protection, and allowing a less defensive farmhouse layouts. The lowland farmhouse model undergoes a rationalization process that passes by the reduction of size, and as shown in Fig. 4.10, the relocation and regrouping of some of its basic elements (e.g. granaries, stables or threshing floors) to suitable areas of the settlement, allowing a more effective group management of work and resources [124,125].

Fig. 4.10 – Example of two groups (a and b) of individually owned small granaries, named *“espigueiros”* (Padrão, Arcos de Valdevez) [102].

In this way, farmsteads of larger farmhouses were reduced to small and very basic layouts, most to simple rural house’s configurations, being the road and public space used as farmyard [14,27,102,125]. Despite located inside dense settlements, farmhouses are at close distances from its farmland and farming terraces, whereas distant from its mountain range plateaus properties, required for vertical transhumance. Although of unknown origins, the use of such livestock strategies dates back to the 13th century [105], being the previously mentioned *“corn revolution”* referred to in literature has having boosted its use [102,121]. Livestock was moved up to the mountain plateaus during the warm season, freeing near village terrace pastures for grain production, and would be moved back down after the harvest, already in the beginning of the cold season [106,107]. In the mountain range plateaus, due to the very harsh conditions and long travelling distances, temporary support settlements were built, most in resilient stone corbelled dome structures, to shelter shepherds and farmers during their stay [10,124].

As for land ownership, the Entre-Douro-e-Minho hierarchy prevailed in the highland, with slight adaptations:

- *i)* Privately-owned property, being either isolated (e.g. the farmhouse or the kitchen garden) or forming groups of individual properties (e.g. stables or *“espigueiros”*);
- *ii)* Commonly-owned properties of groups of farmhouses (e.g. threshing-floors or common ovens);
- *iii)* Community-owned properties (e.g. common pasture areas or *“vezeiras”* (corrals));
- *iv)* Public areas (unfertile or unusable areas of the settlement its surrounding territory).

b) Rural settlements

Ribeiro [63] divides the Entre-Douro-e-Minho settlements typologies into two main distinct groups: *i)* the dispersed settlements typologies, with high representativeness in the lowland, resulting from the intensive polycultivation farming and land availability, almost inexistent in the mountain areas and highland [27,63]; and the *ii)* the concentrated settlements typologies that although existent in the entire region, are highly representative and considered by Amaral et al. [27] as the specific mountain areas type of settlement [27,63,102]. These typologies are synthetized in Table 4.2, being their distribution in the territory shown Fig. 4.11.

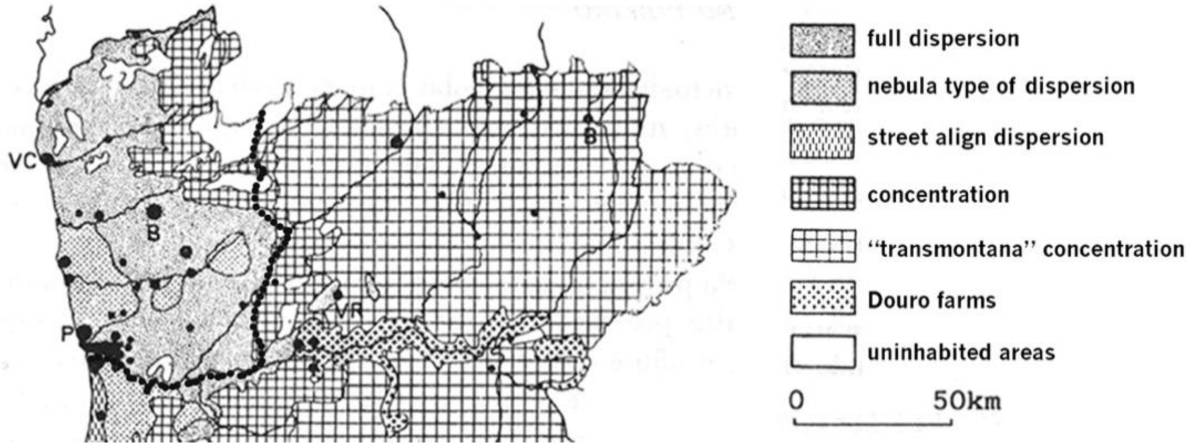


Fig. 4.11 - Variation of the typologies of vernacular settlements according to Lautensach et al. [15](1950's).

Ribeiro [63] highlights to the influence of geography and agrarian systems in both types of settlements typologies. From administrative and social points of view, rural settlements were organized accordingly to rural parishes, named *"freguesias"* (community of user of a parish) [120,121]. With a Parish Church [61,104], settlements gained a certain level of autonomy. Settlements could also show other centrality points resulting from nearby Catholic sanctuaries or monasteries (e.g. Senhora da Peneda, Arcos de Valdevez), nobility houses or public institutions (e.g. Paço of Giela, in Arcos de Valdevez, or the Castle of Faria, in Barcelos), or close proximity to main roads such as pilgrimage paths (e.g. the way of St. James), cross-roads, river or mountain range passages [104]. Analysing dispersed settlements, see Fig. 4.12a, according to Ribeiro [63], these were mainly the outcome of the placement of farmsteads among or near farmland, therefore resulting in very low density morphologies of occupation, formed by scattered buildings in a very subdivided landscape. The author distinguishes two sub-types:

i) Full dispersion settlements, in which farmhouses establish themselves isolated in the territory, without any specific type of organization, at the exception of the proximity to a road. This sub-type of dispersion was common in less densely occupied areas, such as larger valleys, or in areas of latter occupation, such as the coast [63];

ii) Nebula dispersion settlements, in which dispersed farmhouses formed small groups, more or less compact, also called *"lugares"* [121], that gained specific identity features resulting from strong neighbourhood ties among [63]. According to the author [63], these types of settlements can either be the outcome of dissociative or condensation mechanisms. In the first case, pre-existent concentrated settlement grows through the creation of new dispersed farmhouses that over time dissolve the settlement initial concentrated form. In the second case, through continued land fractioning with the creation of new farmhouses, an existent full dispersion settlement becomes denser with the formation of new groups of farmhouses.

Table 4.2 - Summary of the main features of the Entre-Douro-e-Minho vernacular typologies of settlements [63] (Fig. 4.11).

Main features	Main typologies settlements	
	Disperse	Concentrated
Higher representativeness	Lowland	Mountain areas and Highland
Natural conditions	High fertile soil availability (e.g. valleys, plateaus, or smooth hills)	Low fertile soil availability (e.g. mountains or mountain range)
Occupation density	Low and Very Low	High or Very High
Agrarian system supported	Intensive polycultivation	Agro-pastoral; vertical transhumance
Forms of occupation	Isolated or by small groups of farmhouses, named *"casais"*	Self-sufficient high-density nuclei of farmhouses and rural houses
Administrative organization	In parishes, named *"freguesias"*, with the centre in a Catholic Church or other institutional buildings (e.g. monasteries or nobility house)	
Settlements' organization	Scattered throughout the territory, with a main centrality (Catholic Church) and possible secondary centralities (e.g. main road, bridge, or crossroads)	Single or several nuclei spread around the mountain range, near suitable farming areas, with a main centrality (Catholic Church) in the most important or better-connected nucleus
Sub-typologies	• Full dispersion – farmhouses dispersion with no specific organization; • Nebula type dispersion – farmhouses form small groups, scattered in the territory (dissociative or condensed)	• Compact – farmhouses and rural houses align together along roads, in a very dense structure with reduced open space among buildings; • Condensate – groups of farmhouses and rural houses all aggregated in a less compact structure

Regarding concentrated settlements, based in the observations of Ribeiro [63], these can be described as larger aggregated nuclei of farmhouses, showing a clear distinction between built area and the surrounding farmland, anchored to a dense road network organized around a central point. Origins of this form of occupation can be reported to protection needs, such as settlements of *"castreja"* or Medieval origin [63], to benefits from the presence of a strong and dynamic central point or, like in the case of the highland, resulting from geographic constraints. Regarding the highland concentrated settlements, these could either show a single nucleus (e.g. Ermida, Ponte de Barca) or be formed by several self-sufficient nuclei, spread around the mountain range [27,63]. The Parish Church and the administrative centre were generally located in the most important nuclei (e.g. Sistelo in Arcos de Valdevez is divided into the Sistelo, Padrão and Porta Cova *"lugares"*, being the Parish Church in the first [102]). Ribeiro [63] identifies two different typologies of concentrated settlements that could coexist in the same parish:

i) Compact concentrated typology, see Fig. 4.12c, described as densely occupied structures formed by individual street orientated farmhouses and rural houses, showing a more urban character (e.g. Vilarinho da Furna, of S. João do Campo parish, Terras de Bouro; or Soajo, of Soajo parish, in Arcos de Valdevez), being open spaces restricted to small backyards and to common and public areas inside the settlement built perimeter;

ii) Condensate concentrated settlements, see Fig. 4.12b, with a lower occupation density organized in identifiable groups of farmhouses, with a higher presence of open spaces corresponding to kitchen gardens or small plots of farmland (e.g. Carralcova, of Soajo parish or Vilarinho do Souto, of Ermelo parish, both in Arcos de Valdevez).

Complementary to the above-mentioned typologies of settlements, Almeida [104] highlights to the formation of street orientated settlements or places in existent settlements, resulting from the aggregation of buildings and farmhouses placed and organized along main roads, cross-roads, bridges or river and mountain passages, see Fig. 4.12d. Therefore, communities were able to take advantage of the dynamics brought by travellers, by providing them with commercial and services areas, achieved by upgrading the typical farmhouse agrarian layout to include non-agrarian uses [126]. In existent settlements, this form of occupation would generally be the outcome of the passage of new main road that led to the over time spontaneous formation of a street orientated place (e.g. Necessidades, of Barqueiros parish, Barcelos [127]). Most of these mobility related occupations often evolved to become central areas with a certain level of urbanity, due to the concentration of commerce and services [104]. Over time, some became small urban centres (e.g. Trofa or Taipas) [27]. This form of occupation gained increased importance in the Entre-Douro-e-Minho territory construction from the 19th century onwards. It is associated to the latter occupation of the Northwest coastal region, or to the development of strong industrial or commercial areas along the main roads (e.g. in the Ave valley, along the EN 206, or the Cávado valley, along the EN 205) [27].

Along with the previously mentioned lifestyle changes, Silva [128] points to the role of strong mid-20th century industrialization to justify the radical changes to old vernacular territory occupation patterns [11,15,17]. This is particularly visible in territories of strong industrial implementation, such as the Great Oporto influence area (e.g. Maia, Matosinhos, Gondomar or Santo Tirso), but also around other important regional urban centres such as Braga, Guimarães or Viana do Castelo [128]. Regarding the growth models of the Entre-Douro-e-Minho settlements from mid-20th century onward, Silva [128] points to two identifiable processes: *i)* in areas of weaker industrialization, settlement show a clear rural structure with overlapping urban contaminations, visible in the presence of urban buildings anchored to a typical rural road and mosaic structure; *ii)* in areas of strong industrialization, the total absorption of pre-existent rural structures by the expansion of the urban area, visible by the existence of isolated farmhouses or small rural pocket in high density urban areas [128]. Brito [17] or Lautensach et al. [15], refer to this growth model as hybrid urban-rural or as transition territories of unclear boundaries, created from the subversions introduced in either rural and urban logics, by expanding non-agrarian economic activities, able to capitalize the rural populations dissatisfaction with the traditional way of life [128].

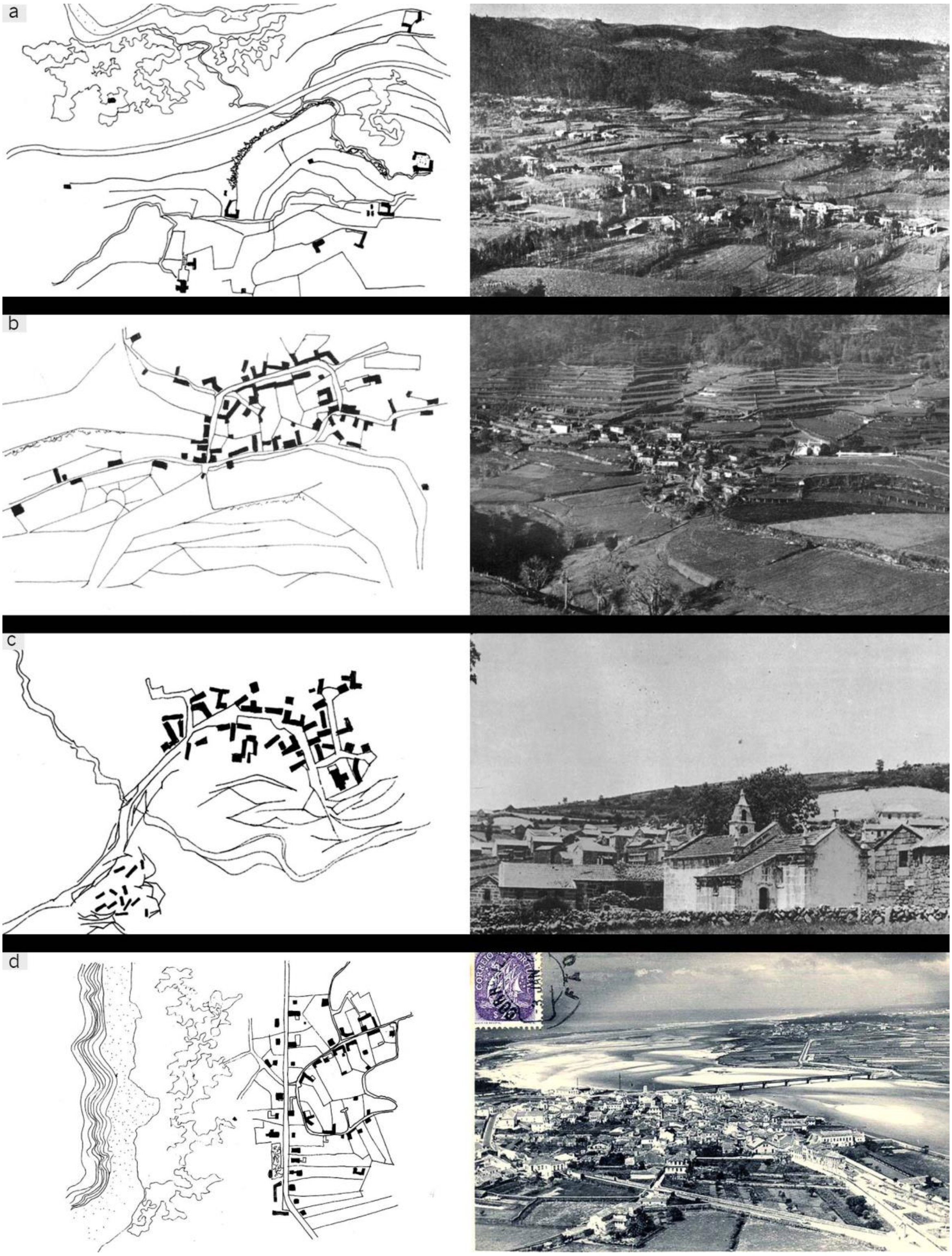


Fig. 4.12 – Schematic examples and images from Entre-Douro-e-Minho vernacular typologies of settlements, based in Almaral et al. [27]: (a) full dispersion (Balazar, Guimarães) [27]; (b) condensed concentration (Sobrada, Ponte de Lima) [27]; (c) compact concentration (Lamas de Moura, Melgaço) [27]; (d) street orientated (image from Fão, Esposende) [129].

4.3 Social and economic organization

According to Soeiro [121], the Entre-Douro-e-Minho society that endured without significant changes until the mid-20th century [14], was not homogeneous but shaped by their specific context. In general lines, it was described by anthropologists and geographers as a conservative society with a strong religious character, socially crystalized and with very low social mobility possibilities [11,121]. Being profoundly agrarian, social organization and family ties were decisively orientated to farming and to the land, as a fundamental condition for survival and prosperity [11,14,59]. Daily routines passed by intense farming and livestock labour, that defined a traditional way of life marked by isolation from external influences. Exceptions were the necessary travels to street markets, to the many Northern *“romarias”* (typical regional religious festivities based in pilgrimages), seasonal migrations or emigration [11,121]. Basto et al. [57] describes a rural population that reaches the first quarter of the 20th century with very high levels of illiteracy (masculine population – 48.6% in Minho and 40.4% in Douro Litoral; feminine population – 74.4% in Minho and 64.6% in Douro Litoral).

Regarding society lower ranks’ living conditions, the author [57] described them as very poor, being the highland communities (e.g. Castro Laboreiro [99]), identified by the authors among those with worst living conditions [13]. Although such examples were also common among lowland society’s lower ranks [57,77,78], according to Leal [13], these populations achieved better living conditions provided by this sub-region higher farming productivity, and the economic opportunities resulting from the proximity to larger urban centres. Traditional strict and very rational way of life dictated a very austere and sober existence to most Entre-Douro-e-Minho rural populations. Prosperity and living conditions were constricted by the territory excessive land subdivision. As previously explained, small-size property affected wealth production and economic sustainability, blocking social mobility of medium and upper social groups, and reduced its lower groups to survival farming and poorly paid salaried work [13,14,61,78].

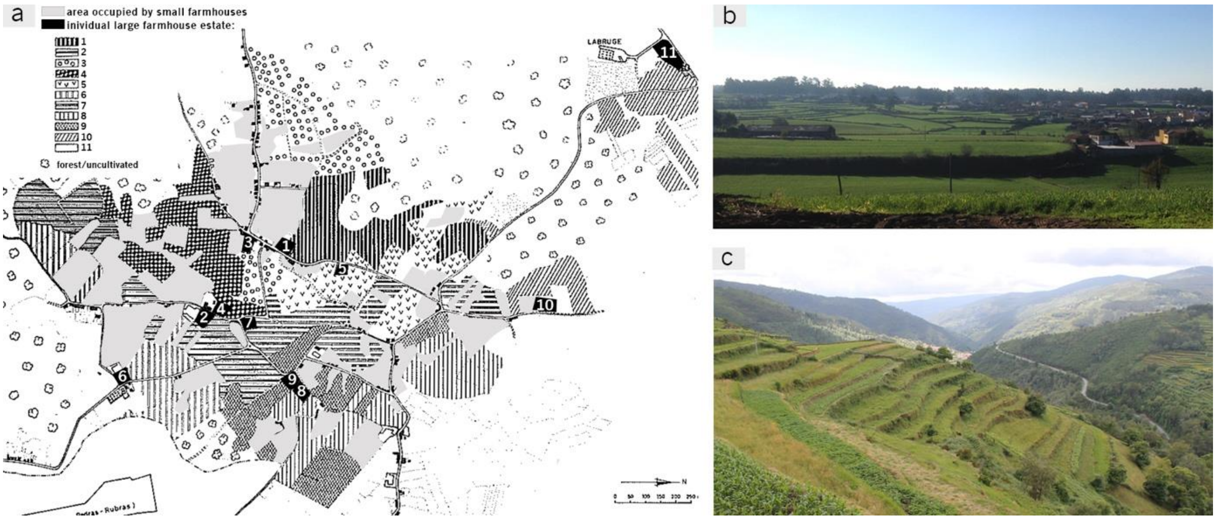


Fig. 4.13 –Example of land fractioning: (a) in the Aveleda and Labruge (Vila do Conde), based in [128]; (b) lowland occupation (Barqueiros, Barcelos); (c) highland occupation (Padrão, Arcos de Valdevez).

Therefore, in the Entre-Douro-e-Minho rural context, ownership over the land and securing its passage to future generations was the basis of the regional social structure [59,61,120,121]. According to Silva [128], see Fig. 4.13, such was achieved by ensuring the farmhouse protection against fractionation by marriage arrangements among families of the same statues, complex heritage and donation contracts and specific legal frameworks regarding property ownership transfers. Examples of land intense sub-division are presented in Fig. 4.13. As a result, the rural social pyramid was divided between landowners, and the ones that although having property, it was not a farmhouse. At the lowest levels were all the ones that did not owned any type of property [120].

According to Cabral [120], the farmhouse seen as family endeavour, played a fundamental role as a social enterprise of high symbolism, replacing the family as the holder of the social status. As for the typical Entre-Douro-e-Minho family, it is described by Dias [59] for its large-size and patriarchal organization, in which the women shared most of the physical work with the men. The author defines this particular type of family structure as extensive, for including the nucleus family (parents and offspring), but also other relatives and individuals related to the farm labour, such as domestic servants or agrarian workers [59]. As for the organization of the social pyramid, according to several researcher such as Cabral [120], it can be interpreted as followed [57,61,121].

iii) The proprietors' group (higher status), included all families with large estates that got their income by resorting to hired labour or from land leasing. In this group are also included the nobility, named *"fidalgos"* , religious orders estates, and estates from non-rural investors, also named *"capitalistas"* [16,130];

iv) The farmers groups, also named *"lavradores"* (from high to moderate status), include all families that owned a self-sufficient farmhouse managed through family-based labour. Silva [109] following an estate size criterion, distinguishes large-size or wealthy farmers (> 10 ha estate), from medium-size farmers (from 5 to 10 ha estates) and small-size farmers (2 to 5 ha estates). It was common for the farmers groups to lease land from the proprietors, most of the times including a dwelling and farmstead, in this case named *"caseiros"* [61];

v) Common peasants, or *"camponeses"* (low status), are families that could not maintain a self-sufficient farmhouse (owned or rented). In most cases, the small-size of their farms or kitchen gardens only allow survival farming, being the family income complemented by employing family members in other types of activities (e.g. seasonal rural workers or craftsman);

vi) Rural workers (lower or extremely low status), represented a group of families and individuals that did not owned any type of farm, and were hired by the other social groups. According to Silva [109], in this group were permanent rural workers employed in large estates, seasonally or temporary hired rural workers, or *"jornaleiros"* (hired by day of work), and domestic servants, or *"criados"* (domestic servants) employed and living in the employer's farmhouse. In this group, the rural workers that owned a house and a small kitchen garden had the highest social status in this group. On the other hand, the domestic servants, most of them without any kind of support

> outside the farmhouse, had the lowest status and shared their position with street vendors, gypsies, and indigents.

Analysing the community organization, each family represented by its farmhouse had a place in a wider social network, that through a status hierarchy was entitle to a share of rights and duties regarding the use of common resources and community properties (e.g. water and pastures). Concerning the lowland, Ribeiro [63] highlights that the success of every agrarian community was dependent of mutual assistance and of work exchange networks between farmhouses, becoming highly dependent of this system in certain stages of the agrarian cycle that required extra manpower. According to Soeiro [121], a system of economic dependence was established, see Fig. 4.14, having larger farmhouses at is head, offering support in exchange of extra manpower as part of marriage arrangements, land leasing agreements, or by hiring seasonal workers [61].

In the highlands, the common labour management system boosted community ties, that according to authors such as Dias [59] or Ribeiro [61] were in the mountain range communities generally stronger than in the lowland. Although Dias [58,131] pointed out these highland communities strong communitarian character, Silva [109] instead points out to a system of common work management. The latter highlights that for the remain social and economic features, they were the same as in the entire region and social status prevailed in the assignment of duties or rights of use over the land and resources [63,109]. Although sharing same basic principles, different types of common labour management systems could be found in the highland [102]. According to Cabral [120], in these communities, such as in the case of Vilarinho da Furna studied by Dias [58], a village council or similar, formed by representatives of the main farmhouses, would organize agrarian tasks and assign specific roles to each family. These tasks included common management of infrastructures, farming tasks and particularly, of tasks regarding the livestock management, being the remaining time used for each own individual farm work [58,121].

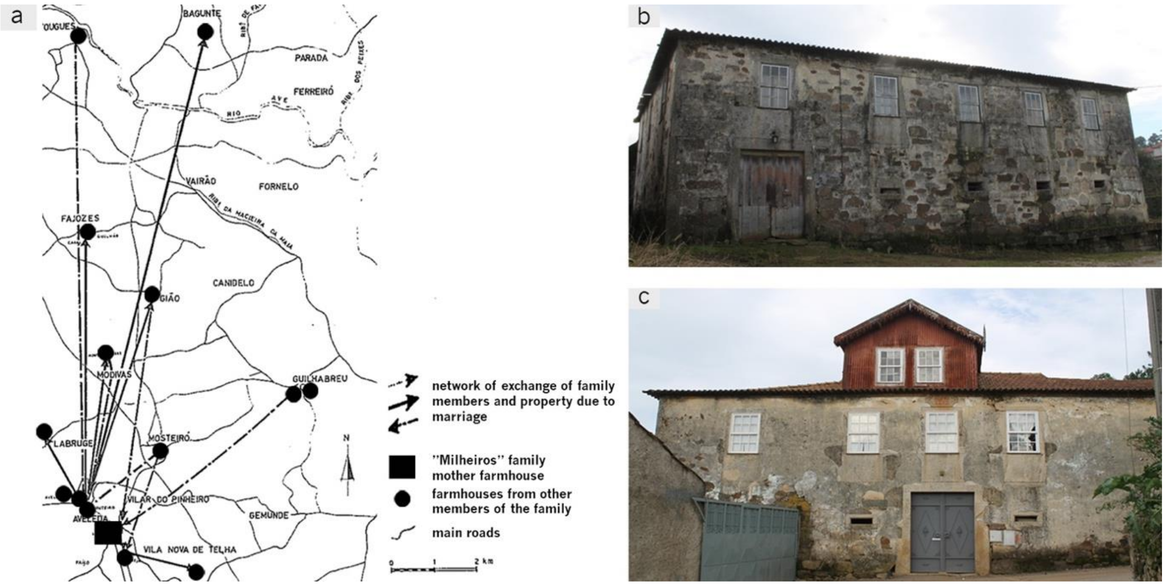


Fig. 4.14 – Example of a farmhouse support network: a – example of the *"Milheiros"* farmhouses network (Aveleda, Vila do Conde) based in [128]. Two farmhouses bounded by marriage: (b) the *"Capitão"*; and (c) the *"Barroso"* farmhouses (Paradela, Barcelos).

4.4 Final remarks

Geography is at the basis of the Entre-Douro-e-Minho large diversity of local identities and different types of vernacular heritage, that will be address in the following chapter. The centuries-old regional dense occupation helped to establish principles for a strongly agrarian society, that although sharing basic identity features, resulted into two different context regional identities. Near ocean valleys and plateaus with human occupation based on polycultivation farming, defined the specific lowland identity that due to its high cultural representativeness became the cultural heritage trademark of the Entre-Douro-e-Minho. On the other hand, the human occupation of the mountain range caused the regional identity to adapt and become the highland identity, based in agro-pastoralism, and the development of a very authentic and unique vertical transhumance cultural heritage.

Regarding vernacular heritage, geography and social organization resulted in a large diversity of forms of occupation and agrarian architectures. Dispersed and concentrated settlements were identified as the outcome and support for polycultivation and agro-pastoralism, being temporary mountain range settlements a genuine response to vertical transhumance strategies. Lifestyle changes and mutations to the traditional way of life brought profound changes to the Entre-Douro-e-Minho forms of occupation, that still require further research to understand its causes and consequences.

Based on this chapters' survey area characterization, specific regional vernacular heritage buildings features will be interpreted and analyse in the following chapter.

Chapter 5

MORPHOLOGIES AND TYPOLOGIES OF VERNACULAR HERITAGE

Analysing the rural architecture existing in the Entre-Douro-e-Minho region, it can be divided into three main groups [2,14,27]: *i)* vernacular architecture; *ii)* traditional architecture; and *iii)* foreign and contemporary architecture [12]. As for popular architecture, it is not addressed directly in this research as an independent group. Depending on examples specific features, they are either characterized as vernacular architecture or foreign architecture. Regarding vernacular architecture, see Fig. 5.1a, c, and d, these are highly representative in the Entre-Douro-e-Minho landscape. It is a group formed by buildings with a strong agro-pastoralist character, with a minority of buildings dedicated to other types of uses (e.g. traditional crafts or agro-pastoralist buildings with non-agrarian areas) [14,27]. Regarding categories, buildings from this group can be organized as [14,27,57]: *i)* rural houses; *ii)* farmhouses; and *iii)* production buildings that include rural infrastructures and temporary shelters. In this research, traditional architecture refers to buildings [132], see Fig. 5.1b and e, that although most share with vernacular building the same morphological, typological and construction features, are distinct due to their religious or aristocratic origin. Most were built using non-vernacular technical knowledge and followed non-local models. Among others, buildings from this group can be categorized as follows [14,27,133]: *i)* religious buildings that include a large number of parish churches, small chapels, sanctuaries and monasteries; and *ii)* nobility heritage buildings named *"paços"* or *"solares"*, of agrarian and non-agrarian character. As for buildings of the third group, excluding contemporary buildings and *"casas de emigrante"* (see Chapter 3) for their non-relation with traditional buildings techniques, the remaining buildings that may over time influenced the construction of vernacular buildings can be categorized as [12,14]: *i)* buildings of urban character located in transition rural/urban areas near larger urban centres or smaller rural urban centres; and *ii)* isolated urban style buildings located in rural context, such as the *"brazilian houses"* or institutional buildings. Although buildings from the second and third groups represent a minority of the built heritage in the rural landscape, their high status and for some, their strong symbolic role in the organization of the settlements, made them valuable and a symbol of identity among the Entre-Douro-e-Minho local populations. These buildings are mentioned for context purposes and to allow identify their influence over local vernacular models, but they will not be characterized.

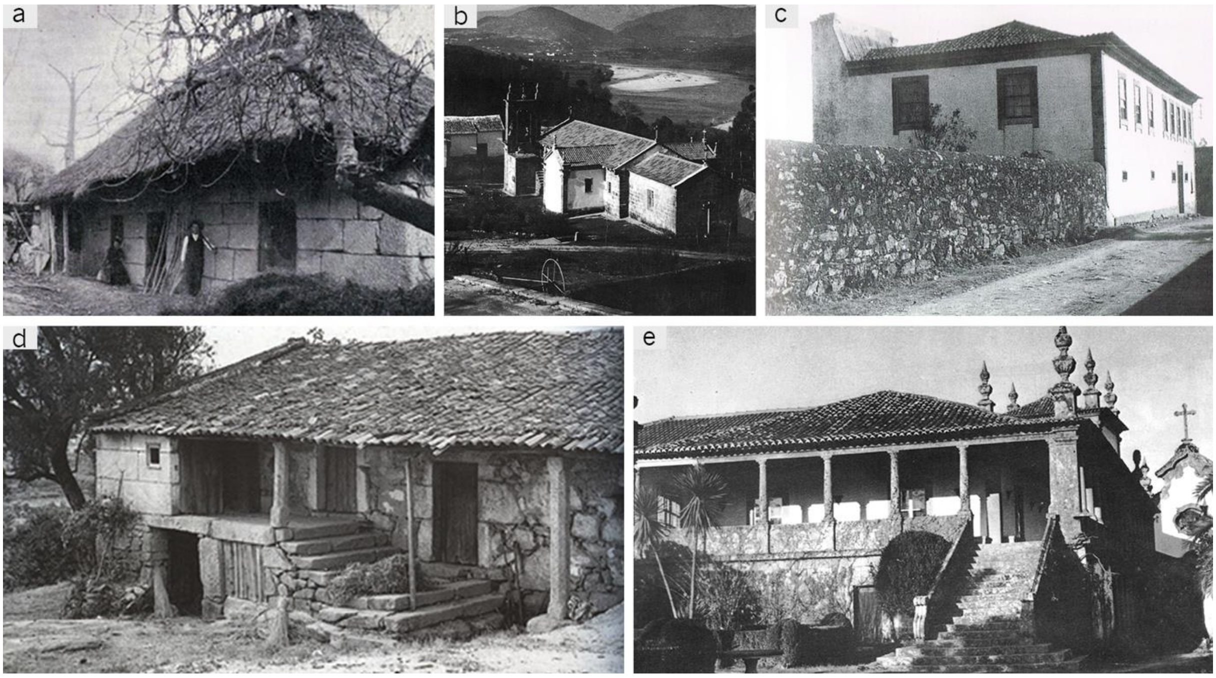


Fig. 5.1 – Examples of vernacular architecture (until mid-20th century): (a) small farmhouse (unk. location) [78]; (c) large farmhouse (Gemeses, Esposende) [14]; (d) rural house (Gondariz, Arcos de Valdevez) [14]. Examples of traditional architecture (until mid-20th century): (b) rural church (S. João da Ribeira, Ponte de Lima) [27]; (e) *"solar"* of Pomarchão (Arcozelo, Ponte de Lima) [27].

In this chapter, an overview regarding the characterization of Entre-Douro-e-Minho vernacular architecture is presented. It is based on a synthesis of exploratory visits results and literature review. Some constricts should be taken into consideration when analysing the data: *i)* the vast territory to cover; *ii)* most buildings being privately-owned property, posed restrict access to them; *iii)* the severe losses of character of most of the observed examples; or *iv)* the very advance state of ruin of the most authentic ones. Therefore, field observations focused on the most representative examples, and on collecting general characterization data through visual inspection. When possible, images and basic geometric information where collected.

5.1 Common principles of the Entre-Douro-e-Minho vernacular architecture

Being part of the same cultural background and sharing the same territory, most of the Entre-Douro-e-Minho vernacular architecture, shares the same fundamental basic principles. From the conceptual and functional points of view, Oliveira et al. [14] points out to vernacular heritage strong agrarian character, with high levels of specialization to the different needs of the yearlong agrarian cycle. Bastos et al. [57], points out the importance of farming to the common northwestern rural populations survival, that placed farming needs as a priority over the family comfort and living conditions. Oliveira et al. [14] highlights the importance of adding an ethnographic perspective to the development process of vernacular models and specific building traditions. According to the author [14], vernacular heritage was not exclusively the outcome of geographic and climatic determinism, being these, variables of a process of greater complexity. Oliveira et al. [14] presents the example of two different communities of the Póvoa de Varzim area that, although sharing the same geography and raw materials, gave birth to different models of vernacular buildings [14]:

i) Farmers, forming scattered communities along the territory, with a daily routine organized around robust stone masonry farmhouses, built with the expertise gained by handling the land's natural resources (stone, soil, and wood). Their vernacular architecture was the outcome of a stable and predictable way of life, resulting from its specialization to make the most of the yearlong agrarian cycle.

ii) Fishermen, that gathered in concentrated and more informal communities at or near the beach, known as the *"Poveiros"*, with a daily routine organized around small timber huts, later replaced by small masonry houses, both fully specialized in the trade of fishing, built with the expertise gained handling the timber fishing boats. According to the author, these fragile vernacular models were dictated by an unpredictable way of life, always dependent from unpredictable and treacherous ocean conditions.

Amaral et al. [27] describes Portuguese vernacular heritage as in a state of perfect harmony between buildings and their environment. That resulted in resilient and lasting morphologies and typologies, and in functional and optimized structures with undeniable flexibility and adaptability to context changes. Thus, according to the author [27], vernacular architecture was the outcome of strong and intuitive principles of rationality, functionality and adaptability, that resulted in simplified designs, austere aesthetics, and experience proven and adaptable construction process. According to the author, buildings' organization showed a rational and functional basis, identifiable in features such as the favourable use of simplified layouts, based volumetry and internal designs of regular and orthogonal shaped proportions. On larger buildings with larger gross area, space rational management use dictated the functional separation between farming and dwelling areas. Based on the same principles, the dwelling organization was optimized to make the most of the existent heat sources (fireplaces, ovens, and livestock), therefore making the kitchen a multi-functional area used to work and for the common family tasks but reducing to the indispensable minimal individual spaces used to sleep.

The territory occupation followed the same rational and functional principles. Rural houses and farmhouses were placed in the territory in the proximity to basic resources and roads. Their location aimed at making the most out of sun light exposure and gaining protection against intense winds (in this latitude, favourably by directing and opening buildings to the South and protecting them from the North). For practical reasons, it was preferable to place farmhouses as close as possible to the farmland, to better protect crops and to cut on travel distances.

Regarding vernacular heritage general aesthetic principles, according to Amaral et al. [27], rationality was at the basis of the typical *“minhota”* architecture, although other authors point to it as not being intentional but an outcome of the very harsh and very pragmatic Northwestern way of life [14,57]. From the very humble rural house to the traditional *“paço”* or *“solar”* (rural palace) [27], buildings showed the typical stronghold image, made of simple and orthogonal lines, with a volumetric of predominant horizontal proportion. In the typical *“minhota”* farmhouse volumetric organization, the large-size horizontally proportioned farmstead (walled compound) had its stronghold image reinforced by the vertical presence of the two-storeys dwelling building (main tower) and of the dry granary two-storey building (secondary tower). The very reduced number of openings in the farmstead facades, most of them simple ventilation openings, and the strong presence of the large-size oxcart portal completed this image. To this aesthetics contributed the overwhelming austerity of the farmstead facades. Being the image and symbol of the farmhouse, the dwelling buildings and sometimes the farmstead facades facing the road, were the only ones covered with render and painted in withe lime paint.

Amaral et al. [27] highlights to the residual or total absence of decoration in the majority of the observed rural buildings. As for its reasons, the rational use of raw materials in a context of shortage of resources, lack of technical skills, and the typical rural pragmatic effort management are presented in literature [14,27]. Whereas, as observed, structural elements such pillars, beams, quoin and jamb stones, lintels and roofs eaves were left visible, and worked as structural decorative elements. On more humble buildings, decoration could come as simple stripes painted around openings or at the top or bottom of the walls. On higher status buildings, elaborated elements such as cornices, bottom panelling, or decorative stripes, could be found, either made in stone, mortar or simply painted in oil paint.

Regarding vernacular buildings high resilience and adaptability to time and context changes, it was facilitated by the development of a building tradition based on known and durable building materials (stone, wood, and soil), and on construction techniques mastered by all farmers as indispensable requirement for farm management. Thus, much of the Entre-Douro-e-Minho vernacular buildings’ resilience is due to a very intuitive building process, passed through generations by direct empirical knowledge transfer, and by a technological uniformity that facilitated maintenance and any needed geometry adaptation [14,27]. According to Villanova et al. [12], vernacular buildings were examples of flexibility, able to typologically and morphologically adapt to new contexts, deconstructing the image of crystalized heritage often associated to this type of structures. As observed during the exploratory visits, reuse and adaptation of vernacular structures was constant as the property grew or was fragmented, by enlarging smaller structures or by their absorption into larger ones, or by larger structures being sub-divided into smaller ones, to accommodate new functionalities and smooth transformations to the agrarian reality, or new social realities.

5.2 Rural housing

Oliveira et al. [14] established a first typological categorization regarding rural housing, distinguishing the basic rural house, describing it as one-storey small buildings, frequently with a very simplified or single compartment organization. These houses could be found all around Portugal, and were according to the author [14] the most basic type of rural housing found at the time. Based on the author observations, the Entre-Douro-e-Minho vernacular houses can be divided into two distinct groups.

On the buildings of first group, from now on designated as *rural houses*, the dwelling occupation areas prevailed over agrarian areas, and existing privately-owned external areas were small kitchen gardens. According to Oliveira et al. [14] observations, at the lowland, the majority of these buildings were associated to lower ranks of the rural society and to survival farming. In the highland, rural houses were a prevailing typology, being fundamental to the concentrated settlements organization and to the agro-pastoralist economy. Regarding buildings of the second group, from now own designated as *“farmhouse dwelling”*, the rural house becomes part of the farmhouse organization, being another building (*“dwelling building”*) to consider in the farmstead layout design. With very few exceptions, buildings of both groups share the same main morphological and typological features, although distinct in their status, and social and economic contexts. According to Oliveira et al. [14], by the analysis of the organization and internal layout of the rural house, it is possible to establish the Northwestern vernacular heritage main authenticity and identity features [14,27,67,79].

From the organizational and morphological points of view, Oliveira et al. [14] established two main groups of rural houses: *i)* the rural houses of horizontal organization, or one-storey houses, known as *“casas térreas”* (ground-floor houses), in which all dwelling and agrarian compartments were organized at ground-level; and *ii)* the rural house of vertical organization, or two-storeys houses named by the author as *“casas bloco”* (container houses), in which the dwelling areas are moved to the upper-floor, therefore overlapping the agrarian compartments. Examples of layouts of rural houses from the first group are presented ahead in Fig. 5.2., whereas examples from the second group are presented for lowland houses in Fig. 5.3, and for the highland in Fig. 5.5 and Fig. 5.6. Images of examples of rural houses observed during the exploratory visits are presented ahead in Fig. 5.7.

Comparing both morphologies, the author highlights the advantages of the vertical organization: *i)* by concentrating several functions in the same portion of soil, its use for buildings is reduced; *ii)* by placing assets and livestock under the dwelling, these were better protected; *iii)* gaining higher observation position, the farmland was guarded in more effective way. According to the author [14], by moving the dwelling upwards: *i)* it gained protection against superficial water, thus reducing internal moister; *ii)* windows at the upper-floor facing the road, therefore improving internal lighting and ventilation; and *iii)* the natural heat of livestock placed under the dwelling, without their presence inside. Oliveira et al. [10,134,135] highlights to characteristic elements present in the Entre-Douro-e-Minho rural house, such as: *i)* the large balconies (*"varandins"* or *"varandas"*) or porches (*"alpendres"* or *"telheiros"*); *ii)* the large-size chimney (*"chaminé de fumeiro"*); or *iii)* the symbolism and importance given to the dwelling external access stairs.

Regarding the contact and access from and to the exterior, the dwelling opened favourably to the privately-owned property through windows, doors, and ventilation openings.

Smaller rural houses without privately-owned external areas, unavoidably showed openings and accesses facing the road, being doors the main source of ventilation and lighting in these buildings [14]. This case had higher representativeness in the compact concentrated settlements of the highland sub-region. The passage from the interior of the dwelling to the exterior was generally from the living room to the exterior, either directly or through a porch, a balcony, or a covered stair arrival. A secondary access from the kitchen to the kitchen garden, to the balcony or porch was also common [14,136]. Regarding internal distribution, access to the dwelling's different compartments was mostly from the living room (smaller houses), or through small connection corridors or halls (larger houses).

Concerning the design of the dwelling basic layout, it was divided into common (living room and kitchen) and private areas (bedrooms and alcoves). Agrarian compartments (e.g. pig stable, wood storage or hennery), could either be inexistent in very small houses, meaning that the agrarian uses were also part of the dwelling common areas, or independent compartment or adjacent building in larger houses. According to Bastos et al. [57] and Oliveira et al. [14], the number and individual use of the different compartments grew as the house grew in gross area. Regarding the main types of compartments typically found in the Entre-Douro-e-Minho rural house [14,27,57,126]:

i) The living room, generally the largest compartment of the dwelling, was its basic cell. On smaller houses (single or double compartment dwellings), it concentrated most of the family daily routines (common, private, and working routines). On larger houses with more compartments, freed from most of the daily routines, living rooms acquired a more ceremonial character (e.g. to great guests and for the Easter visit), with a higher level of attention payed to its construction (e.g. plaster or *"masseira"* timber ceilings) and decoration (e.g. the family oratory or ornamental timber frames) [14];

ii) The kitchen could either be an area inside the living room (smaller houses), be and independent compartment or be place outside and next to the dwelling building (large farmhouses). In the latter, when placed in a different level, it was connected to the dwelling through a service stair (0,8 m of width) [14]. It was generally the second larger compartment of the rural house, were the family gathered to take meals, to work and to be warm during the winter. According to Oliveira et al. [14], the chimney was a later innovation introduced to the northwestern kitchen. In its absence, ventilation and soot exhaustion were performed directly through the roof's voids. In these houses, it was observed the absence of ceilings. Therefore, according to Oliveira et al. [14], in the absence of efficient chimneys, placing the kitchen outside the dwelling, contributed to improve the internal air quality. According to Galhano [136], the fireplace and oven were the main equipment on vernacular kitchens, and chimneys could either be small openings in the roof or the typical *"minhota"* large-size *"fumeiro"* chimney [134];

iii) Regarding private spaces, used mainly for sleeping and to keep a few personal belongings, these were generally very small compartments (≅ 8 m^2 to 10 m^2). Alternatives were interior compartments that got light from the living room named alcoves (≤ 5 m^2) or cabinets with size of a bed (≤ 2 m^2) (e.g. named *"camaretas"* in the Póvoa de Varzim), built in timber frame structure and opened to the living room. [14]. Couples generally had a private and larger bedroom.

As observed, other types of compartments such as loom rooms or toilets were in most cases, later added to the main building. In the humblest houses, the toilets, or *"retretes"*, were either non-existent or an independent compartment, placed in the kitchen garden, away from the house. In the cases observed during the exploratory visits, toilets were small compartments that if in the upper-floor, were placed over the pigpen. In higher status houses or in urban influenced models, particularly from the 19th century onwards, these types of compartments became more frequent in the dwelling layout design [137]. In more humble houses, the toilet became part of the house from the mid-20th onwards.

As mentioned previously, the large-size porch (one-storey buildings) and the balcony (two-storey buildings) were fundamental to the Entre-Douro-e-Minho rural house dynamics. Both were generally built on the dwelling's facade facing South, to the kitchen garden or farmyard. These multi-functional areas were described by Oliveira et al. [14] as extensions outwards of the domestic space, providing the dwelling with an external connection space, a recreation and working areas. Simultaneously, the dwelling's most permeable facade gained improved protection against direct rain, excessive sun light and harsher climate conditions. Both were covered by an extension of the main roof, supported over stone pillars or masonry walls. The balcony pavement was built in timber beams and flooring. In the highland sub-region, solutions or shorter balconies facing the road, supported in timber and masonry cantilever structures, were frequent. In both sub-regions, the access to the balconies was through an external stone masonry stair, parallel or perpendicular to the facade. In the absence of balcony, the arrival of the stair to the upper-floor would be through a landing, covered in most cases. In these cases, stairs could also be placed parallel to one of the buildings lateral facades. In urban influenced or *"brazilian"* models, examples of the later type of stairs facing the road were observed during the exploratory visits [126]. Regarding specific rural housing typologies, Amaral et al. [27] points to a mixed dwelling/dry granary type of building. Designated by the author as *"casa sequeiro"* (dry granary house), see Fig. 5.4, it was the outcome of the transformation of porches and large-size balconies into fully operational dry granaries and grain storage area. In this type of building, that in some cases replaced the individual large-size dry granary building, both agrarian area and domestic space kept a close dynamic by sharing the same external covered space.

As reported by Oliveira et al. [14] both porches and large balconies were the first option to expand the dwelling, either by building into them extra compartments (e.g. bedrooms, loom rooms or toilets) or by fully transforming them into internal compartments by building an external facade. In the latter, the new compartment kept a double character of common/working and distribution areas. Based in the above-mentioned studies and on exploratory visits observations, in Table 5.1 and Table 5.2, the most representative Entre-Douro-e-Minho vernacular housing typologies are presented and characterized.

Table 5.1 – Typological and morphological synthesis of the Entre-Douro-e-Minho rural housing

Main morphological features	Smaller houses typologies			Larger houses typologies	
	Single-cell or Basic	Simplified	Full organized	Complex	"bourgeoise" or "brazilian"
Representativeness	All around the region, higher presence of two-storeys buildings in the highland	All around the region		Higher presence in the lowland, increasing to the south (Douro)	Higher presence near urban centres and to the south (Douro)
Average size (m^2)	Small (< 30 m^2)	Small (< 30 m^2)	Medium-size (< 120 m^2)	Large-size (> 120 m^2)	Large-size (> 120 m^2)
Storeys (average height in m)	One or two (< 2.4 m)	One or two (< 2.4 m)	One or two (from 2.4 m to 3 m)	Two (from 2.4 m to 3 m)	Two and a third recessed one (> 3 m)
Dwelling location in building	Ground or upper-floor (full occupation)	Ground or upper-floor (full or partial occupation)	Ground or upper-floor (full or partial occupation)	Ground or upper-floor (full or partial occupation)	Independent building (full occupation)
Volumetric organization	Single building	Main volume with a short number of coalescent volumes	Dwelling in the main building of the farmstead	Dwelling in the main building of the farmstead	Dwelling in the main building either in or independent from the farmstead
External areas (see Section 4.3 for farmhouse)	Non-existent or small kitchen garden	Kitchen garden or farmstead (small farmhouses)	Farmstead (small to large farmhouses)	Farmstead (large farmhouses)	Farmstead (single or multiple farmyards); independent yard or garden (*"quintas"* [63])

Table 5.2 - Basic layout features of the rural dwelling of the Entre-Douro-e-Minho

Layout design	Smaller houses typologies			Larger houses typologies	
	Single-cell or Basic	Simplified	Full organized	Complex	*“bourgeoise”* or *“brazilian”*
Organization	Common and private areas all sharing the same compartment	Divided into a common and private areas	Private areas fully separated from the common areas,	Different private common, and working compartments	Different private, common, and independent dwelling services compartments
Bedrooms or private areas (< 10 m^2 small indiv.; < 5 m^2 alcoves)*	All functions sharing the same compartment	One individual small or large or alcoves	One individual small or large or alcoves	Several compartments (including for employees)	Several types of compartments (e.g. master bedroom or handmaid’s bedroom)
Living room (very variable sizes)*	All functions sharing the same compartment	Sharing the compartment with the kitchen and/or private areas	Individual compartment (ceremonial character)	One or multiple compartment with several functions (e.g. Easter room or weaving room)	Several compartments with distinct functions (e.g. dining room or guests’ rooms)
Kitchen (% of the dwelling internal area)*	All functions sharing the same compartment	Sharing a common compartment; individual compartment (30% - 40%)	Individual compartment in the upper or ground-floor; in a coalescent volume (< 30%)	Individual compartment in the upper or ground-floor; main or secondary kitchen in a coalescent volume	Individual compartment in the main building, or in an independent building
Farming compartments	All functions sharing the same compartment	Inside the dwelling; individual compartments; annex or other buildings (if a farmhouse)	Independent areas; compartment in the same floor or beneath the dwelling; other buildings in the farmstead	Independent areas; some building beneath the dwelling; independent buildings in the farmstead	In independent buildings
Connection between compartments	None	None or through the living room, small porch, or balcony	Small corridors; internal timber service stairs (average 0.9 m wide); directly through the porch or balcony		Main and service corridors, halls, and stairs; directly through the porch or balcony
Main access	Directly from the street or kitchen garden; or through a masonry stair	Directly from the street or external area (porch); or from a masonry stair through a covered landing or large balcony	From the farmstead, directly through a porch; or from a masonry stair through a covered landing or large balcony		From the farmstead or private yard, directly through a porch; or from a masonry stair through a covered landing or large balcony

* data collected from the studies presented on Chapter 3.

Single-cell or basic rural houses were characterized by their very reduced size and single compartment layout organization, see Fig. 5.2a to c. Pavements in these buildings were normally in compacted soil. Facades presented a short number of openings, being lighting and ventilation ensured by the doors and small ventilation openings. As for external private areas, if existent were small kitchen gardens.

In comparison with the above-mentioned typology, the simplified rural house presents a dwelling layout divided into one private and one common compartments, in most cases, divided by a light timber frame wall. An analysis to Bastos et al. [14] observed examples, showing similar gross area and internal organization, simplified rural houses could be considered as an evolution of the basic typology, in which a bedroom was built for the use of the couple. An alternative layout with alcoves replacing bedrooms, was also common [14]. In these larger rural houses, it was common to find specific agrarian compartments, independent from the dwelling space. When in the same building volume, the access was through the exterior. Other common solutions were to build an adjacent volume, covered by and extension of the main building's roof or in a small independent building such as small a porch, shed or stable, built in the kitchen garden. As it was observed during the exploratory visits, this house was the typical dwelling typology of the smaller farmhouses.

According to Bastos et al. [57], living conditions of smaller rural houses were very poor due to the lack of private areas and of sanitation conditions, aggravated by these dwellings small-sizes and to the typical large-size families of the time. According to the author and the information collected during the exploratory visits, features such as the constant contact with manures inside the dwelling when using it for agrarian purposes, the lack of internal water supply generally reduced to a well, or sanitation infrastructures, increased sanitation hazards [57,67,79,126]. In these buildings, humidity was constant inside the poor ventilated buildings, due to the close proximity to soil humidity, to the traditional soil pavements in kitchens and cooking areas, and to the roof's poor water tightness [10,57,67,79].

As said, although existing in the entire region [14,27,57], two-storeys smaller rural houses morphologies were observed in the highland but seemed not a common solution in the lowland, see Fig. 5.3. However, during the exploratory visits at the highlands, the identification of examples of one-storey smaller houses was not frequent, therefore seeming that such typology was either not a common solution, or its examples were over time transformed into agrarian buildings.

On fully organized typologies, the design of dwelling's base layout counted with individual compartments to each domestic basic use (living room, kitchen, and bedrooms). See Fig. 5.2d and e, for one-storey buildings, and Fig. 5.3a to c and e, for two-storey buildings. In these dwellings, full separation between common and private areas existed. Alternative layouts showed a common compartment used simultaneously as living room and kitchen but preserving the individual bedrooms or alcoves design. At the lowland, this typology and the following ones are already quite common farmhouse dwelling typology.

Complex houses were the common large-size farmhouse dwelling typology, therefore property of higher status social ranks. See Fig. 5.3c, f, and g for lowland examples and Fig. 5.6 H1 and H2.

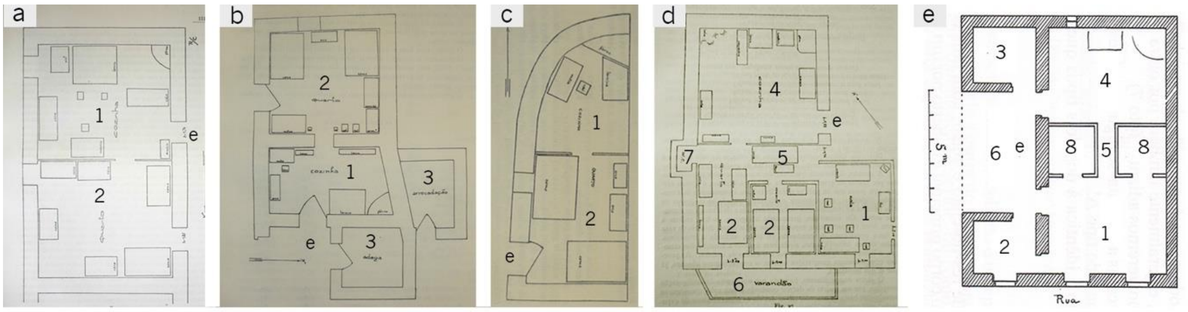
In comparison with the previous typology, its layout shows higher complexity and design diversity. As observed, several examples were the outcome of enlargement, adaptation, or subdivision of previously existent houses. The dwelling design would grow in the number of compartments, some with specialized functions (e.g. loom room, slating room, or toilets). Being larger, connection spaces such as narrow corridors, internal timber service stairs or even the construction of additional internal compartments were common. In these buildings large porches and balconies were specific identity trademarks [27].

Examples of more elaborated complex houses show a layout with a functional separation between the dwelling service areas and its domestic areas. These included the kitchen and its associated service compartments, and private compartments for the staff (bedrooms and resting areas). The service area formed an independent sector of the dwelling, with independent access to the farmstead and internal service connections to the domestic area. A secondary kitchen, to attend the farmhouse staff and to produce smoked sausages was also common in larger farmhouses [14,27].

The *“bourgeois”* or *“brazilian”* style houses can be described as based on adaptations of urban models and urban life style to the rural context. Examples can be found regarding all previously-mentioned typologies, although gaining stronger visibility regarding the higher status *“quintas”* houses, described by Ribeiro [63]. These were large-size urban style agrarian estates with specialized productions (e.g. the Douro valley Porto wine *“quintas”*). Regarding the *“brazilian”* house, according to Villanova et al. [12], further research is required to fully understand its humbler examples and their influence over the common vernacular house.

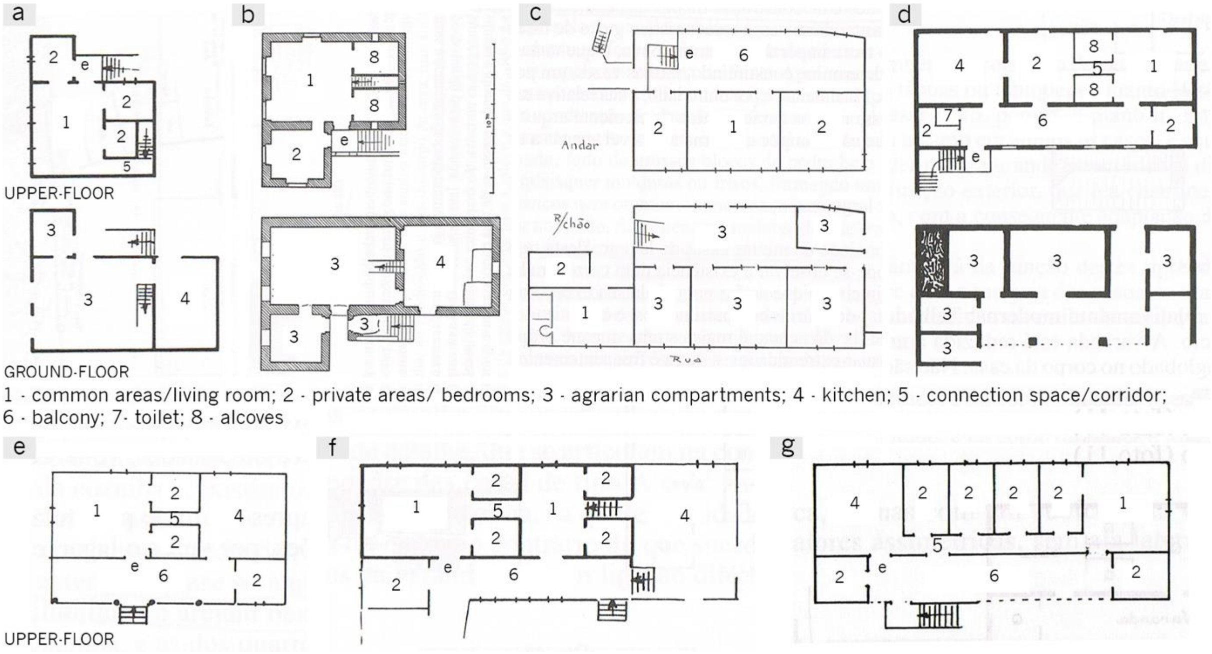
Although similar to complex house typologies, its internal design followed urban principles. In larger models, it was common to have the dwelling in an independent *“palace”* style building with no agrarian compartments. The house was normally placed in a yard separated from the farmstead, and with independent access to the road. Thus, the house gained a more ceremonial access, resembling the old traditional *“solares”* [27]. Regarding living and sanitation conditions, these were high standard buildings. Influenced by the 19th century urban hygienist principles, buildings design showed storeys with average heights of over 3 m and larger rectangular proportioned windows, to improve ventilation and lighting, and elevated and ventilated ground-floor timber pavements, to protect the house against soil humidity. Beside showing larger and more numerous compartments, these became functionally diversified (e.g. dining room, bathrooms, or office).

“bourgeois” or *“brazilian”* style houses were improved construction quality buildings, in some cases introducing in the rural world modern technologies and elements (e.g. cast-iron structures, the jutting short balcony or *“sacada”*), new aesthetics resulting from higher attention paid to details and decoration (e.g. use of strong and diversified colours, decorative plasters elements or facade tiles). The presence of a recessed and smaller third-storey built at roof level, named *“mirante”*, was a typical identity feature of these type of buildings.



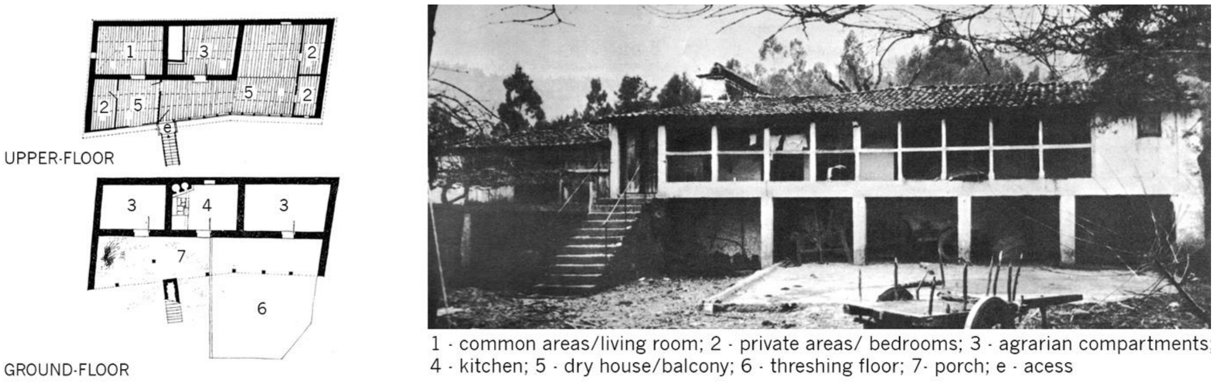
1 - common areas/living room; 2 - private areas/ bedrooms; 3 - agrarian compartments; 4 - kitchen; 5 - connection space/corridor; 6 - balcony; 7- toilet; 8 - alcoves

Fig. 5.2 – Literature examples of common lowland one-storey small houses: (a) simplified house (Passô, Arcos de Valdevez) [57]; (b) simplified house with external agrarian compartments (Vale de Bouro, Celourico de Basto) [57]; (c) simplified house (Darque, Viana do Castelo) [57]; (d) full organized house (Vale de Bouro, Celourico de Basto) [57]; (e) full organized house (schematic of a typical Maia house) [14].



1 - common areas/living room; 2 - private areas/ bedrooms; 3 - agrarian compartments; 4 - kitchen; 5 - connection space/corridor; 6 - balcony; 7- toilet; 8 - alcoves

Fig. 5.3 – Literature examples of common lowland two-storey houses [14].: a and (b) full organized houses (Barreiros and Moreira da Maia, Maia); (c) complex house (Mindelo, Paredes); (e) full organized house (Gemeses, Esposende) d and (f) complex houses (Gemeses, Esposende) (g) complex house (Gandra, Esposende).



1 - common areas/living room; 2 - private areas/ bedrooms; 3 - agrarian compartments; 4 - kitchen; 5 - dry house/balcony; 6 - threshing floor; 7- porch; e - acess

Fig. 5.4 – Literature example of a “casa sequeiro” (Carapeços, Barcelos) [27].

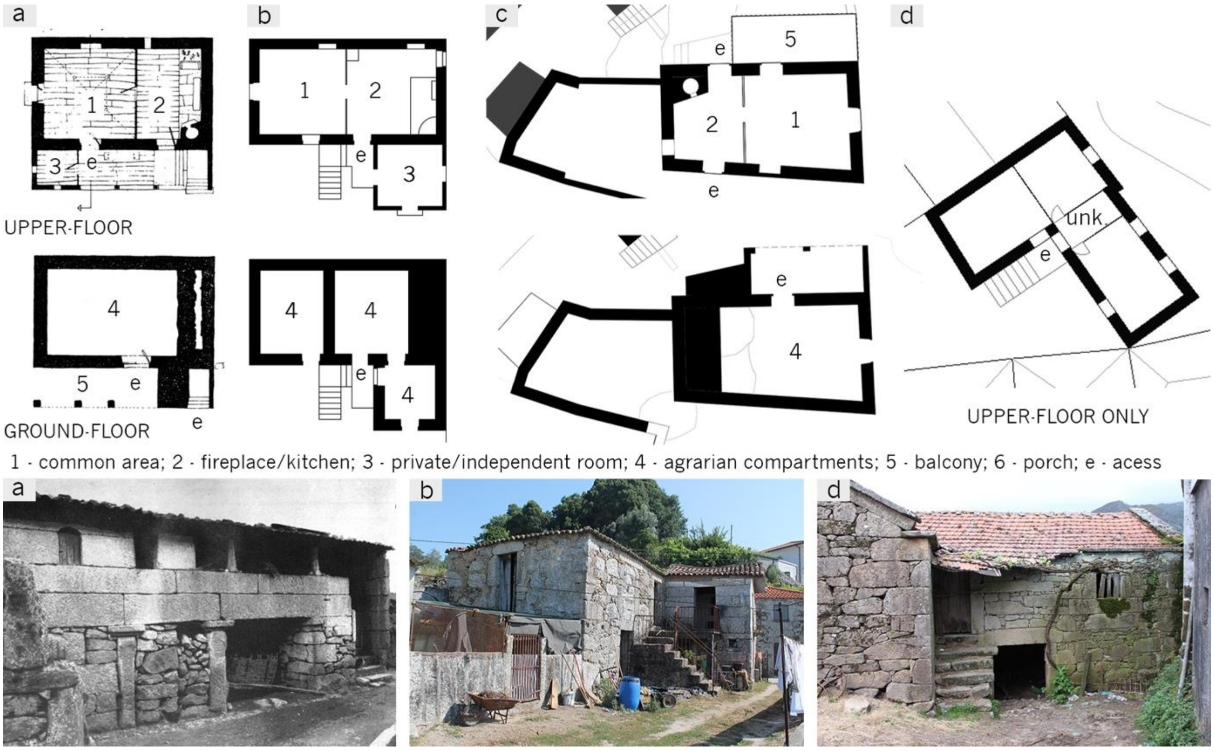


Fig. 5.5 – Examples from highland two-storey simplified houses: (a) Soajo, Arcos de Valdevez [27]; (b) Vale, Arcos de Valdevez (drawing by the author); (c) Vale, Arcos de Valdevez (drawing by Francisco C. Barros); (d) Padrão, Arcos de Valdevez [102].

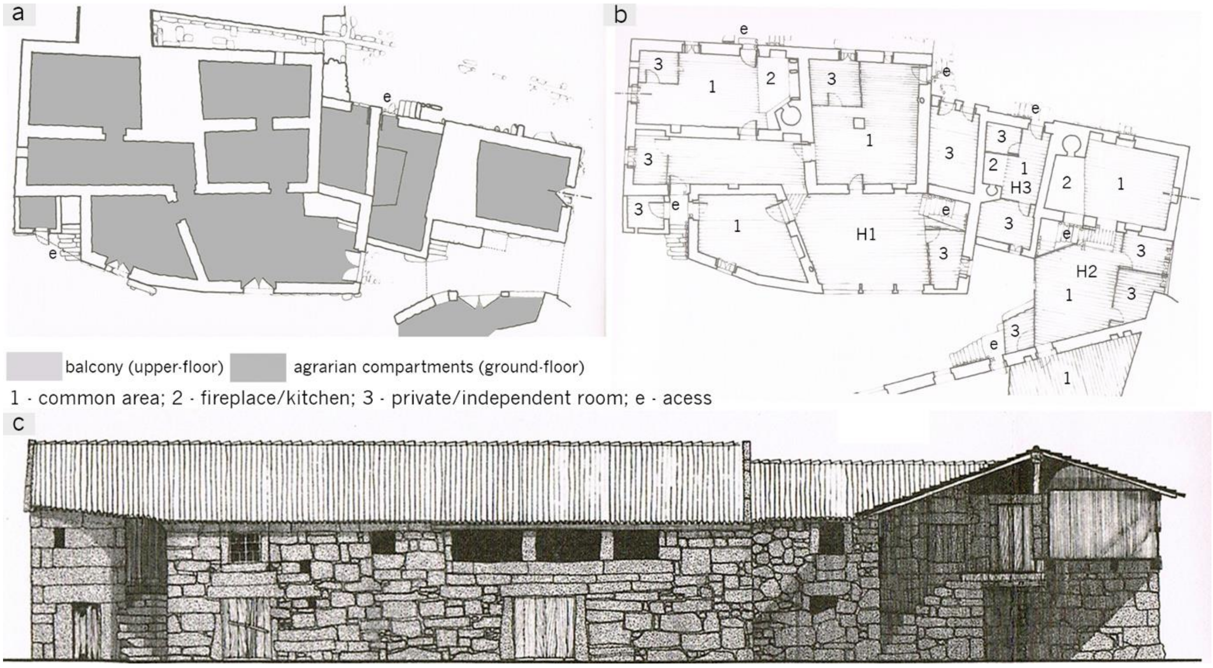


Fig. 5.6 – Literature example of a group of highland houses with two complex houses (H1 and H3) and a simplified house (H2) (Vilarinha das Furnas) [138]: (a) ground-floor; (b) upper-floor; (c) east elevation.

Fig. 5.7 – Examples of lowland small houses: a and (b) basic and simplified (Barqueiros, Barcelos); (c) composed (Balazar, Póvoa de Varzim. Examples of lowland large houses: (d) Vilar de Figos, Barcelos; (e) Fonte Boa, Esposende; (f) Apúlia Esposende; (g) Tamel de S. Pedro Fins, Barcelos; (h) Areias de Vilar, Barcelos; (i) Cristelo, Barcelos. Examples of highland small houses: j, l, and r – Ermida, Ponte da Barca; p – Lindoso, Ponte da Barca. Examples of highland large houses: k and m – Ermida, Ponte da Barca, n – Gavieira, Arcos de Valdevez; o – Padrão, Arcos de Valdevez; q – Cabreiro, Arcos de Valdevez; s – Ermelo, Ponte da Barca.

5.3 Farmhouses

The typical Entre-Douro-e-Minho farmhouse can be described as an agrarian production unit formed by: *i)* a dwelling; *ii)* an enclosed farmstead; and *iii)* a farmyard. As for the complete farmhouse estate (see Section 4.2), it was formed by the above-mentioned agrarian compound and all associated farmland and forest areas. Therefore, the farmhouse size and layout diversity and complexity were related to the estate size and production capability, but also from soil availability to build the farmstead. Based in these features, authors such Oliveira et al. [14], established a clear distinction between the lowland and the highland farmhouse. Examples of a typical lowland farmhouse and a typical highland farmhouse are presented in Fig. 5.8. On Chapter 4, context information regarding the role of farmhouses on the Entre-Douro-e-Minho landscape occupation was presented.

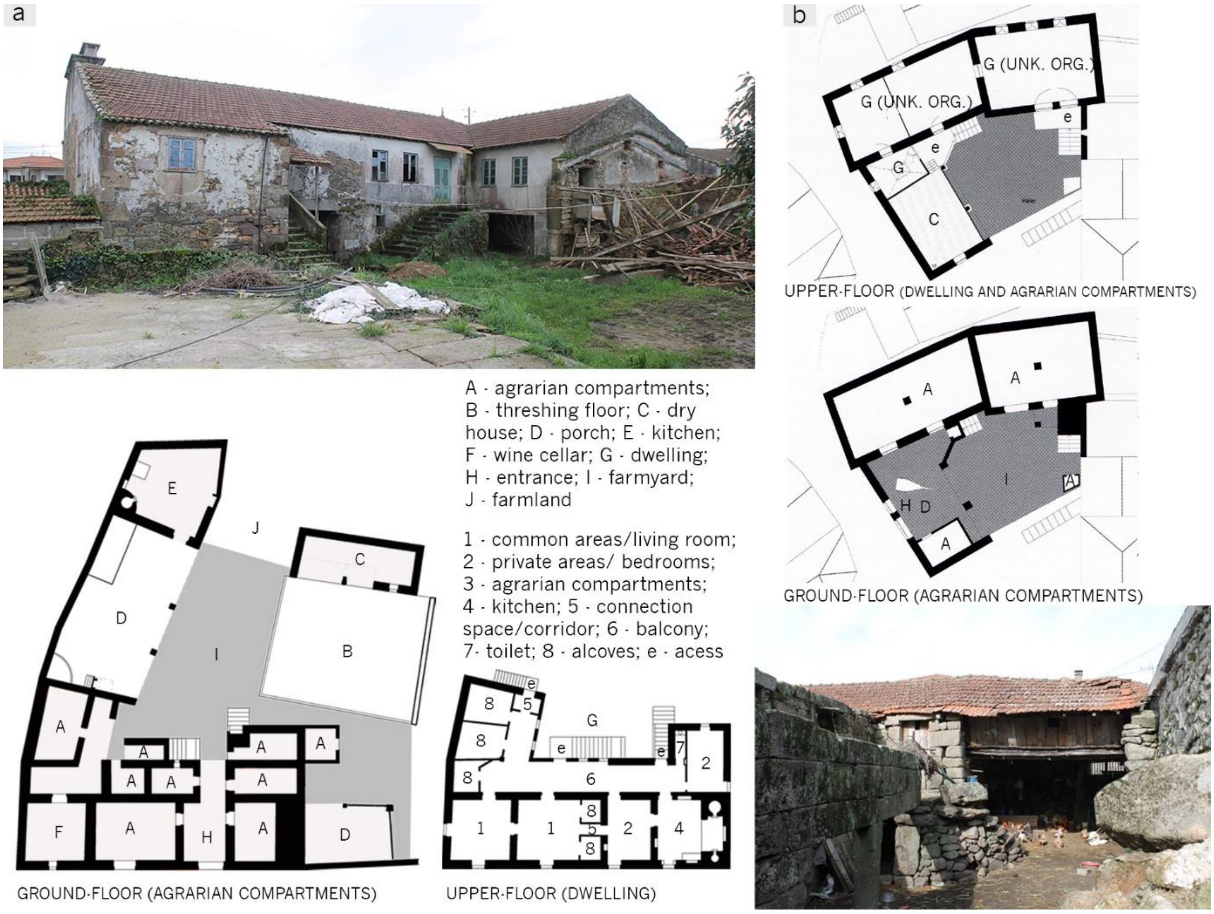


Fig. 5.8 – Examples of farmhouses: (a) lowland large farmhouse with a complex dwelling (Fonte Boa, Esposende) (drawing and image from the author); (b) highland farmhouse with a full organized dwelling [139] (image from a similar farmhouse).

In the first group, farmhouses are self-sufficient production units, placed isolated or forming groups, and integrated in dispersed or low-density concentrated settlements. Regarding design of the typical farmstead layout, it results from the combination of several different types of buildings (dwelling + agrarian buildings), placed around and facing the farmyard, and forming with perimeter masonry walls (≅ 2 m of height) an enclosed compound [10,27]. The farmyard played a double role, first as a protected working area, and distribution platform, that allowed working dynamics between the farmstead different buildings (generally without internal connections among them), and secondly as an access to and from the exterior (road + farmland) through the oxcart gates.

Regarding the design of smaller farmsteads, it could vary considerably from single *“block”* building configurations with all necessary agrarian compartments, placed facing the road at the edge of the farmstead, to simple *“L”* or opposite sides layout configuration [14,27,126]. Larger farmsteads presented a very characteristic courtyard layout of *“U”* or *“O”* configuration, that in larger estates could include farmyards, and secondary farmsteads to lease to smaller farmers (see Section 4.3). In all cases, the farmstead was a growing and evolving structure, being buildings added (most using the compound external wall for support load-bearing walls) or adapted as needed. Regarding farmstead base geometric configuration, it adapted to the edges of the property, being regular and most rectangular proportions favourable. Due to the small-size of property, even smaller in the highland inside the concentrated settlements, farmstead layout would assimilate the property boundary geometric irregularities in its design. Therefore, cases of very organic farmstead designs are frequent in contexts such as the mountain and the highland [140].

Regarding the role of dwelling building, a position near the road was favourable, either as part of farmstead road facade, or when over the lateral perimeter, with one of its lateral facades facing the road. Regarding farmsteads built at crossroads, it was common to place the dwelling building facing both roads. Other layouts with the dwelling building positioned away or inside the farmstead were not representative, at the exception of large estates (Douro Litoral region). The farmhouse agrarian buildings and installations were normally independent functional areas, either sharing or fully occupying a one-storey building. Among the most common ones are the porches, workshops, sheds, and distinct types of stables, fully opened to the farmyard or accessible through doors. Small windows and ventilation openings (vertically or horizontally proportion with ≤ 0.1 m of width) were common in these buildings. Storage areas for different types of production and materials were also frequent, either in open air areas (e.g. manures or fertilizers), under porches (e.g. wood or hay), or by using the available space beneath the roofs by building *“barras”*, light timber frame pavements, thus creating protected and ventilated areas to store goods such as potatoes and other types of vegetables. Other specific areas such as wine cellars or the cattle stables were located, if possible, under the dwelling. According to Dias et al. [93], grain production infrastructures, in particular the ones related to corn, were a vital element of the Northwest agrarian economy, becoming another distinctive identity and authentic element of regional culture. Several examples of such structures are presented in Fig. 5.9. Grain production structures were built in areas with good sun light exposure and were formed by [14,27,93]:

i) A threshing floor, or *“eira”*, built in granite slabs (most representative) or slate, with a taller perimeter edge (≅ 0.1 m) to help contain the drying grain, see Fig. 5.9c to g. The typical quadrangular or rectangular geometry, resulted from the requirements of the traditional flail-threshing technique, named *“malha”*. According to the author, primitive examples existing in soil pavement and with rounded shape, resulted from the use of animals for threshing;

ii) Sheds or porches adjacent to the threshing floor named *“casa da eira”*;

iii) A two or three-storeys large-size drying granary, called *“varandões”* or *“sequeiros”* (resembling a *linhay*), also built adjacent and fully opened with lifting doors to the threshing floor and to the farmstead, see Fig. 5.9c to g. Examples could vary from models with just ventilation openings in the remaining walls, see Fig. 5.9d,e and g, or with the remaining facades fully opened and protected with vertical timber slats, see Fig. 5.9c and f. The ground-floor had a similar use as the threshing floor shed, being the upper-floor used to store and dry grain. More elaborated examples had small granaries (*“espigueiros”*) built into them, see Fig. 5.9d and g. Access to the upper-floor were either through an internal timber stair or a lateral masonry one. Due to lower productions, large-size drying granaries were not common in the highland;

iv) Small individual granaries, named *“espigueiros”*, were individual grain drying and storage units, placed elevated from the ground over pillars with a capital to protect grain from rodents. These could vary from much elaborated ones with high construction quality, see Fig. 5.9a to g, to more harsh aspect ones with lower construction quality examples, see Fig. 5.9b and h.

Fig. 5.9 - Examples of grain production infrastructures seen during the exploratory visits: (a) two *“espigueiros”* placed over the road and facing a threshing floor (Paço Vedro de Magalhães, Ponte da Barca); (b) group of *“espigueiros”* placed around a common highland threshing floor (Ermida, Ponte da Barca); (c) *“sequeiro”* (Vilar de Figos, Barcelos); (d) *“sequeiro”*, with built in *“espigueiros”* on both sides, and threshing floor located outside the farmstead (Paradela, Barcelos); (e) large-size *“sequeiro”* and threshing floor (Sequeira, Braga); (f) isolated *“sequeiro”* with threshing floor (Vila Nova de Muía, Ponte da Barca); (g) isolated grain production compound formed by a large a *“sequeiro”* with built in lateral *“espigueiros”*, a large-size *“espigueiro”* and threshing floor (Rio Côvo de Santa Eulália, Barcelos); (h) group formed by threshing floor, threshing floor house and *“espigueiros”* (Arga de Cima, Caminha).

According to Oliveira et al. [14], the large farmstead oxcart portal, or *"porta carral"*, was one of northwestern farmhouses' main identity elements. It was the main, and in most cases, the only entrance to the farmstead. Regarding its location, according to the author, it could be placed: *i)* in the dwelling buildings under the dwelling, taking to an internal corridor (at least of 2 m of width) giving access to adjacent compartments and to the farmyard; or *ii)* placed under an internal porch, creating a covered entry area inside the farmstead. Gates simply placed into the farmstead external masonry walls without any internal covered area were not very frequent solutions. Solutions combining the oxcart gate and a lateral door (e.g. Agra mountain range) were also not common. Examples observed during the exploratory visits are presented in Fig. 5.10. According to Oliveira et al. [14], the basic geometric configuration of the *"minhoto"* oxcart gate was of rectangular proportion or with a top arch lintel. Regarding its different typologies, the author reported the following [14]: *i)* simple gates without any kind of external covered area, see Fig. 5.10a; *ii)* gates protected by a small external cantilever porch or by the extension outwards of the roof of the internal porch, see Fig. 5.10b; *iii)* recessed gates, creating a covered area under the dwelling or under the internal porch, see Fig. 5.10c; or *iv)* gates misaligned with the facade, thus gaining an external area covered by the roof of the porch. Elaborated gates were common on higher status farmhouses, see Fig. 5.10d, whereas non-conventional or monumental gates, were typical in estates belonging to religious orders or in *"solares"*, normally showing the family's coat of arms [27]. In later 19th century *"bourgeois"* and *"brazilian"* farmhouses, monumental and highly elaborated gates became common, as proof of status.

Fig. 5.10 – Images of typical Entre-Douro-e-Minho oxcart portals seen during the exploratory visits: (a) common portal (Barqueiros, Barcelos); (b) portal with porch (Balazar, Póvoa de Varzim); (c) recessed portal with porch (Barqueiros, Barcelos); (d) high status portal (Durrães, Barcelos).

A variation of the typical lowland farmhouse layout is identified as the result from the proximity to roads or areas with a large concentration of passing travellers such as near sanctuaries or important cross-roads. The resulting dynamics often led to the adaptation of the typical farmstead layout design to integrate the construction of commercial and service compartments [27,126]. These were built at ground-floor level, in the dwelling building, and had direct doors access to the road. The contact with the remaining agrarian and dwelling areas were reduced to the indispensable minimum.

Regarding the farmhouses from the highland, they can be described as a context adaptation of the lowland farmhouse organization. As explained on Chapter 4, to deal with soil shortage inside concentrated settlements, and for a more effective resources and common labour management, the farmhouse was transformed either by reducing the size of farmsteads or by using strategies of dispersion of its agrarian functions throughout the settlement [102]. As shown in Fig. 5.8b, in the first case and less representative, the farmstead is reduced to a basic layout, still organized around a farmyard that in some cases were not completely enclosed. The farmstead layout was formed by the dwelling, a balcony with *"sequeiro"* functions and with shed function underneath, and a few stables. As for additional stables, the threshing floor, and granaries, these are located elsewhere in the settlement.

In the second case, the farmhouse is simplified and shrunken to the dwelling building, using the road to replace the farmyard for accesses and agrarian works. In the humblest cases, it resembles a simple rural house. Therefore, as shown in Fig. 5.6, farmhouses and rural houses were built coalescent and aligned along the settlement's roads, giving them a primitive urban character, and being open and fully accessible from the public space. To replace the privately-owned farmstead, their agrarian buildings and related tasks were transferred to specific areas of the settlement [102]. Nuclei of commonly-owned agrarian buildings, formed by individual properties of each farmhouse of the group, were located in suitable areas of the settlement. Among them, the most characteristic are the nuclei of *"espigueiros"*, organized around a common or privately-owned threshing floors built on granite slabs or over a granite outcrop, and placed in a well-protected and ventilated area with high sun exposure [93,124], see Fig. 5.9b. Other typical nuclei were the groups of individual stables and storage areas, either individual or sharing the same building, see Fig. 5.11. These were placed at the edges of settlements and near existing roads that lead to nearby pastures or mountain plateau temporary settlements. By concentrating and moving stables to the limits of the settlements, large herds movements throughout the settlement were avoid. As part of the same dispersion strategy, isolated stables located among the farming terraces and in the mountain range plateaus were common and allowed an easier management of manures.

Fig. 5.11 – Examples of typical agrarian buildings of the highland settlements (common and privately-owned): (a) storage (upper-floor) and stables (ground-floor) building (Ermida, Ponte da Barca); (b) storage (upper-floor) and stable (ground-floor) (Lindoso, Ponte da Barca); (c) storage (upper-floor) and stables (ground-floor) (Penacova, Arcos de Valdevez); (f) group of *"espigueiros"* and common threshing floor (Lindoso, Ponte da Barca); (e) group of stables (Ermida, Ponte da Barca).

5.4 Production buildings and infrastructures

By reviewing literature (see Chapter 3), a wide functional and typological diversity of production buildings and infrastructures could be found in the Entre-Douro-e-Minho landscape:

i) To produce flours from grain, to transform cultivation such as flax or for timber sawing, using hydraulic or wind power, different types of mills where constructed, the first near water lines and the later in wind exposed areas [10,58,141];

ii) To store productions and tools, and to produce manures, all types of sheds were constructed in the farmland and near the coast [10,14,90,93,103], see Fig. 5.12b, c, h, and e;

iii) To manage livestock, different types of infrastructures such as masonry walls were built to help moving and controlling herds, being corral and stables built around the territory, in particular in mountain areas and in the highland [10];

iv) To implement vertical transhumance strategies, a vast network of temporary mountain range plateau settlements was built in the highland [10,60,107,131].

v) To manage wild animals, besides animal intrusion protection walls, stone masonry fish traps named *"pesqueiras"*, were built in rivers; to protect bee hives and honeycombs, protection walls against bears named *"silhas do urso"* were built; to protect livestock from wolfs, complex masonry wolf pit traps named *"fojos dos lobos"*, see Fig. 5.12d, were developed and built across the highland mountain range [10,107];

vi) To shape the territory and improve farming conditions, retaining walls and farming terraces were built [14,123]; reservoirs to manage water streams to feed mills, named *"açudes"*, and complex irrigation and water distribution systems and all sorts of management were constructed [92], see Fig. 5.12e and g;

vii) To move in the territory, the landscape was covered with a vast network of paved or dirt roads, and stone masonry bridges [10,14], see Fig. 5.12f;

viii) For all types of uses, different types of shelters were identified by Oliveira et al. [10] nationwide and categorized as simplified shelters when built in perishable materials such as straw and wood, circular or quadrangular base-plan shelters when built in masonry;

ix) To set, protect and manage property, farm walls were built dividing the mountain among its different communities, and shaping the lowland into its characteristic mosaic shape aspect [10,14,27,142,143].

Despite the severe state of ruin or the loss of most of the above-mentioned types of production buildings and infrastructures, an overview of the examples observed during the exploratory visits are shown in Fig. 5.12. For their representativeness, touristic potential, and landscape impact, this section will address in more detail the mills, the farm walls, and the temporary settlements built in the highland mountain range plateaus.

Fig. 5.12 - Examples of production buildings and infrastructures observed during the exploratory visits: (a) landmark (Gavieira, Arcos de Valdevez); (b) common threshing floor with the support for straw granaries named *"canastros"* (Vilarinho do Souto, Arcos de Valdevez); (d) wolf pit trap (Gavieira, Arcos de Valdevez); (e) masonry aqueduct (Barcelos); (f) granite paved rural path (Felgueiras); (g) common washing tank (Padrão, Arcos de Valdevez); (h) fishermen's sheds (Carreço, Viana do Castelo); (i) *"sargaço"* storage shed (Apúlia, Esposende).

5.4.1 Mills

Mills can be described as highly developed technological answers to help farmers deal with heavier and more demanding tasks. For their complexity, the construction and operation of such buildings required specific knowledge and skilled-labour. Depending on their purpose, mills could either be managed as commonly or privately-owned property of a *“moleiro”* (miller) that would provide milling services.

According to Dias et al. [141] the development of hydraulic and wind power mechanisms, represented a strong production upgrade, that regarding grain milling and flour production, replaced ancient Neolithic manual and animal powered systems [94]. Barreto et al. [144] points to the strong economic importance of such systems in pre-industrial Europe, in both agrarian and traditional industries context, being its buildings widely spread around the rural landscape. Although its precise origin is not known, Dias et al. [141] based in documental evidence, points to ancient Greece as the place of birth of the basic knowledge required to master such technologies. According to author [141], the first references to the use of hydraulic mills point to ancient Rome as its place of origin, whereas references to wind powered mills point to a Persian origin, prior to the 7th century. According to Dias et al. [141], grain milling for flour predominated in the use of mills. Later improvements to hydraulic systems led to substantial gains in power, allowing the development of mechanisms for other uses such as timber sawing, the preparation and spinning of flax or olive oil production (presses) [94,141]. From the mid-19th century onwards, the hydraulic mills technologies evolved regarding complexity, power and productivity output becoming in the Portuguese context, part of the industrialized world [144,145]. The used of traditional mills lasted until the mid-20th century, when their use declined almost to extinction due to the introduction of standards for flour production and electric powered systems [94].

A first categorization regarding Portuguese traditional mills was presented by Oliveira et al. [94], based on their propelling energy as: *i)* manual and animal power mills; *ii)* hydraulic powered mills of horizontal or vertical propelling wheel; and *iii)* wind powered mills. Regarding hydraulic mills and their propelling mechanism, according to Dias et al. [141], horizontal propelling wheel systems, named *“rodízio”*, were introduced during the Roman occupation period, while the vertical propelling wheel systems, named *“azenhas”*, were introduced during the Arabic domination period over the Iberian Peninsula (from the 7th to 15th centuries). Intense corn and grain production, and a vast water lines network, made both types of watermills widely present in the Entre-Douro-e-Minho landscape. As shown in Fig. 5.13, watermills can be described as very flexible structures, forming modular constructions that could vary from individual and isolated buildings, see Fig. 5.13a, to complex structures that combine both types of propellers and use them for different tasks, Fig. 5.13b. They could also be found on farmsteads placed near the river Fig. 5.13e. Hydraulic milling systems could also be installed in larger buildings.

As shown in Fig. 5.14, regarding size and typological diversity, watermills could vary from small to large-size buildings, and from very simplified to much elaborated geometries. Regarding their construction process, there were similar to all common buildings, except for the propelling wheel chamber, located at the inferior level or to the side of the building. Masonry structural reinforcements called *“quebra-mar”* were observed in watermills built in larger rivers to resist stronger water streams [145,146], see Fig. 5.15. Oliveira et al. [94] reported watermills formed by an upper-level built in perishable timber structures, reconstructed every year, over the propelling wheel chamber built in stone masonry, Fig. 5.13c. From Oliveira et al. [94] exhaustive inventory, the typical lowland watermills can be described as a rectangular shape gable roof building, with specific areas to accommodate the milling mechanisms (entirely built in timber elements), storage areas for grain and flower, and the larger ones, with a dwelling or a temporary lodging for the miller.

Regarding the system used to feed the propelling wheel with water, mills could either be fed directly by free running water or by conducted water. According to Dias et al. [141], watermills built near small or larger rivers were fed directly by free running water generally collected through the construction of small dams, named *"açude"*. According to the author, these mills achieved lower power outputs. When a suitable water line was not an option, water was conducted to the mill by an aqueduct or stone carved water canals named *"levadas"* (≅ 0.2 m x 0.3 m of cross-section), see Fig. 5.16c. According to the author [141], by using these systems to direct and control the water flow, a stronger power output was achieved, allowing to perform more demanding operations [144]. Oliveira et al. [94] reported several types of propelling wheels designs. Horizontal wheels were spin by a water flow dropped from above them. Regarding vertical wheels, these could either be spin by a water flow dropped from above or by a water stream passing at their bottom. In mountain areas, the slope was used to increase the water feeding potential through gravity, see Fig. 5.14c. Watermills would be aligned down slope and be fed by the same passing water. In these specific type of mills, the water flow was dropped over the propelling wheels by a vertical or with a strong slope masonry pipe, named *"cubo"* [147], see Fig. 5.16a. This particular element, gave the name to this specific mountain watermills [94,148]. As observed during the exploratory visits, see example in Fig. 5.16, the *"cubo"* watermills were small, rectangular shape buildings, distinct due to several different types of roofs. Observed examples vary from gable to single slope roofs covered in ceramic tile or straw, or roofs made of large stone slabs or corbelled dome structures. A third and very specific type of watermill, known as tidal mill, used the ocean tides to fill a reservoir, emptied during low tide to feed the propelling wells [94]. This type of watermill was common, being its examples located in the coast [94].

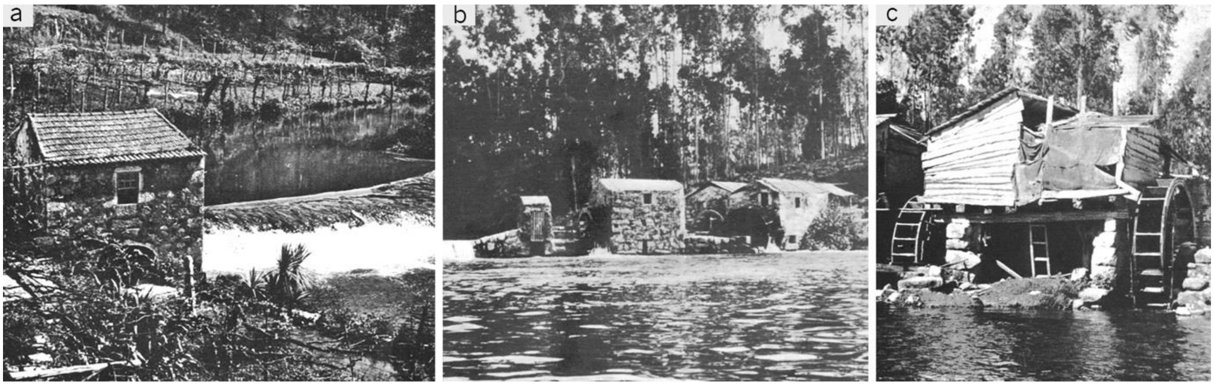


Fig. 5.13 - Examples of river watermills observed by Oliveira et al. [94]: (a) individual mill of horizontal wheel (Fontoura, Vila do Conde); b- large group of mills of vertical and horizontal wheels (Medros, Barcelos); (c) group of seasonal and temporary timber mills of vertical wheel (Perelhal, Barcelos).

Fig. 5.14 - Examples of watermills observed during the exploratory visits (in ruins or disabled): (a) large milling complex with combined vertical and horizontal wheel systems (Antas, Esposende); (b) schist individual mill of horizontal wheel (Rio Tinto, Barcelos); (c) example of a mountain range *"cubo"* mill of horizontal wheel, belonging to a group of several mills align down slop (Agra mountain range, Caminha); (d) individual mill of several horizontal wheels (Aguçadoura, Póvoa de Varzim); (e) large mill with several horizontal wheels integrated in a farmstead (Medros, Barcelos).

Fig. 5.15 - Example of a ruined watermill group built in the Cávado river on top of the small dam wall. These were mills of vertical wheel, with *"quebra-mar"* reinforcements. The image shows the two remaining mills (left and right), and the foundations of other two (centre).

Fig. 5.16 – Example of mountain watermill rehabilitated for museum, feed by conducted water system: (a) masonry pipe named *"cubo"*, that feeds the horizontal wheel; (b) view of the mills aligned down slope to maximize water strength and management; (c) water aqueduct, named *"levada"*, that feeds the masonry pipe.

Regarding windmills, according to Dias et al. [141], their higher complexity and dependence from a more unpredictable power source, made them less abundant than watermills. According to the author [141], this type of mill was an option for periods or areas with shortage of water, and its construction required areas with strong wind exposure, such as hill tops, slopes cleared from trees and obstacles, or the coastal dunes [94]. In the Entre-Douro-e-Minho, these typical tower mills were either built isolated or in groups, see Fig. 5.17, and were individual milling units, meaning that in each building there was only a propelling and grinder unit, see Fig. 5.17b [94,95]. Regarding their design, these were circular and two-storey conical buildings (average base plan diameter of 4 m) [94], built in load-bearing stone masonry walls, with timber frame pavements and stairs [94,95]. As observed by Oliveira et al. [94], with the exception of the granite circular grinders, all the elements of the milling mechanism were built in timber with metal connectors [94,95]. As for building's internal organization, grinders were located at the upper-floor, being the ground-floor used for storage and as lodge for the miller. The propelling mechanism was formed by an external vane made of a timber frame with textile or timber sails that captured rotational motion, and transferred it through a slightly horizontal axis, to an internal vertical axis attached to the milling mechanism [94]. The roof was built as a timber cap attached to the vane, and over wheels that moved on a masonry rail, built on top of the masonry walls. Using a tail pole, the miller would rotate and direct the vane to the wind. Regarding variations, a rare type of a smaller and lighter timber built and fully mobile windmill was observed by Oliveira et al. [94], see Fig. 5.17c.

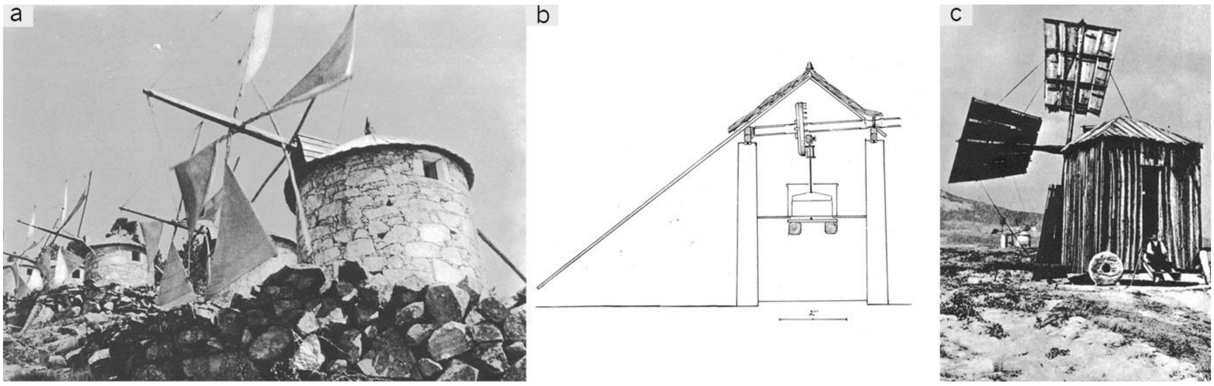


Fig. 5.17 - Examples of windmills observed by Oliveira et al. [94]: (a) wind mill alignment down slope (Abelheira windmills, Esposende); (b) cross-section of a windmill (Aguçadoura, Póvoa de Varzim); (c) mobile timber windmill (Caminha).

Fig. 5.18 - Examples of windmills in ruins seen during the exploratory visits: a and b - granite constructed mills (Monte of Fralães and Cristelo, Barcelos); (c) schist constructed mills (Barqueiros, Barcelos).

5.4.2 Farm walls

As observed during the exploratory visits, farm walls main authenticity and identity features are not only related to construction aspects but mainly with their function [3]. In fact, this fragile heritage cultural value comes from its centuries-old use as agrarian tool and its influence over construction features. Although seen as simple boundary walls, until the mid-20th century, farm walls were part of broad territory agrarian management strategies [66,143]. For their importance to the rural territory management, farm wall construction followed in most cases, community rules or legal frameworks established by municipal regulations. Among others, these rules imposed the mandatory delimitation of privately and commonly-owned property, or legally established suitable morphological features for specific uses (e.g. maximum or minimal heights) or the existence and use of gates and passages [65,66,149]. Requirements for farm walls maintenance and preservation were also common [150]. At the exception of the high standard and sometimes aesthetically elaborated farm walls that became common from the 19th century onwards in *“bourgeois”* or *“brazilian”* estates [97], for the common Entre-Douro-e-Minho farmer, function prevailed over aesthetics, balancing the cost/benefit in a more favourable way. Seeming very intuitive structures, similar to buildings load-bearing walls, although under less demanding structural work, farm walls were in most cases built by farmers, either using stone gathered from the farmland preparation process, or by reusing stone from demolished structures or by extracting it from the closest superficial rock outcrop [126,143]. Based on the exploratory visits, farm walls typologies can be organized into three main groups as shown in Table 5.3, sorted by functional criteria.

Table 5.3 - Main functional typologies of masonry farm walls [151,152].

Management		Protection		Terrain improvement	
Partitioning	Boundary	Animal intrusion	Full protection	Retaining	Terrace
Establishing different areas in the same property	Establishing the limit between different properties	Protection against wild animals and livestock	Full property protection against intrusion	Slight improvement of farm conditions	Increase of available farmlands

Partitioning farm walls were used to set different functional areas inside the same farm or commonly-owned areas, to manage livestock, different cultivations or working areas. Boundary farm walls were used to identify ownership, either privately or commonly-owned (e.g. farmhouses, farmland, forest areas. They were also used to define commonly-owned property belonging to a specific community (e.g. pastures and forest areas), or different ownerships inside larger properties (e.g. leased plots of land inside larger enclosed farmland areas) [57,66]. Farm walls against animal intrusion had a double function of protecting cultivations from passing herds, by confine them to roads and paths, or to keep livestock inside pastures.

For this specific typology of walls, community rules and legal frameworks established minimal heights and gates opening (to allow free pasture) and closure periods (during crop season) [65]. In the highland, this typology of farm wall is predominant and was fundamental in vertical transhumance strategies. When protection against robbery and intrusion was required, especially in cases of more isolated farmland and farmhouses, full protection farm walls were built. These were higher and improved masonry walls, with a higher construction cost, mostly observed in farmsteads and in large landowner's estates. Examples of such walls were also common inside concentrated areas of settlements, particularly along the major roads, like the *"Estrada Reais"* network (royal roads) or very specific roads such as the *"caminhos da missa"* (mass paths) [104]. Full protection farm walls were also common to protect specific production areas such as orchards or vineyards. As mentioned previously, being taller and stronger, allowed these farm walls to easily be transformed into sheds, stables and porches load-bearing walls, or to be used as support for vine tendone training systems, named *"latadas"*, either forming pergolas inside property or over public paths and roads [153]. Farm walls with retaining function, often combined with other farm walls typologies, were built throughout the region to correct the slope of natural terrain but also to make it suitable for irrigation [16,61]. To convert hills or mountain slopes into farmland, larger terrace walls were built. Although cases can be observed all around the entire region, intense farming terrace building was an identity landscape feature of the highland.

Analysing the above-explained typologies, one can conclude that farm walls uses depended on height. Therefore, higher farm walls allowed more uses, but also implied a larger built volume and higher technical complexity to ensure structural stability, resulting in higher construction and maintenance costs. Table 5.4 and Fig. 5.19 present the main morphological and most common building features for the typical Entre-Douro-e-Minho farm walls. Examples observed during the exploratory visits are presented in Fig. 5.20.

Fig. 5.19 – Schematic examples and examples of the most common farm walls typologies and morphologies: a and d - low partition/retaining farm wall; b and e - medium-height boundary/ retaining farm wall; c and f - high full protection farm wall (with support for vine tendone training systems). Images from examples located at Barqueiros (Barcelos).

Table 5.4 - Farm walls' morphologies and most common building features [151,152,154].

Building features	Low farm wall	Medium-height farm wall	High farm wall
Height (m)	< 1.0	1.0 to 1.5	> 1.5
Thickness (m)	0.15 to 0.40	0.4 to 0.6	0.4 to 0.6
Foundation	Non-existent or direct	Non-existent, shallow, or direct	Shallow or direct
Cross-section	Single-stone, single or double-leaf	Single or double-leaf	Double-leaf
Joints	Dry or mortar bonded	Dry or mortar bonded	Mortar bonded
Function	Management, improvement (retaining only)	Management; improvement; protection (animal intrusion only)	Management, protection, improvement
Location	Inside property; forest areas; forest paths	Farmland; farmhouses; secondary paths	Farmhouses, main roads, and paths

Fig. 5.20 - Images of different farm walls seen during the exploratory visits. In the lowland: (a) low boundary farm wall in granite (Póvoa de Varzim); (b) medium-height boundary (on the right) and high full protection farm wall in granite (on the left) (Barcelos); (c) high full protection farm wall in granite (Barcelos); (i) full protection high farm wall in schist (Barcelos). In the highlands: (d) low animal intrusion protection farm wall in granite (Peneda mountain range, Arcos de Valdevez); (e) medium-height boundary and animal intrusion protection farm wall in granite; (f) wolf pit trap high farm wall in granite (Peneda mountain range, Arcos de Valdevez); g and (h) low animal intrusion protection farm walls in schist (Agra mountain range, Viana do Castelo).

5.4.3 Mountain range plateau temporary settlements

The use of the mountain range plateaus in the highland for farming and vertical transhumance, constitutes one of the most authentic and important features of the *“serra”* (mountain range) cultural identity [10]. Although of unknown origin [131], references to the use of vertical transhumance in the region, or to very similar strategies, date back to the 13th century [105]. Attending to Oliveira et al. [10] research regarding primitive forms of vernacular agrarian heritage, the above-mentioned heritage was recognized by the author as a cultural expression of high level of authenticity an identity values, already severally threaten at the time (mid-20th century) due to abandonment. Although nowadays mostly unknown to the general population, this heritage was for centuries a fundamental piece of the highland vertical agro-pastoralist occupation of the territory, see Fig. 5.21 [124,125]. Sharing the same base vernacular architectural and building tradition, the observed temporary settlements, and buildings morphological and typological diversity, were a context adapted response to each mountain range specific context and challenges. As it was observed during the exploratory visits, the majority is in a state of full abandonment and without any type of maintenance, nonetheless, their quite simple and austere design, and construction fully in local stone, gave these buildings high resilience to the very harsh mountain range conditions.

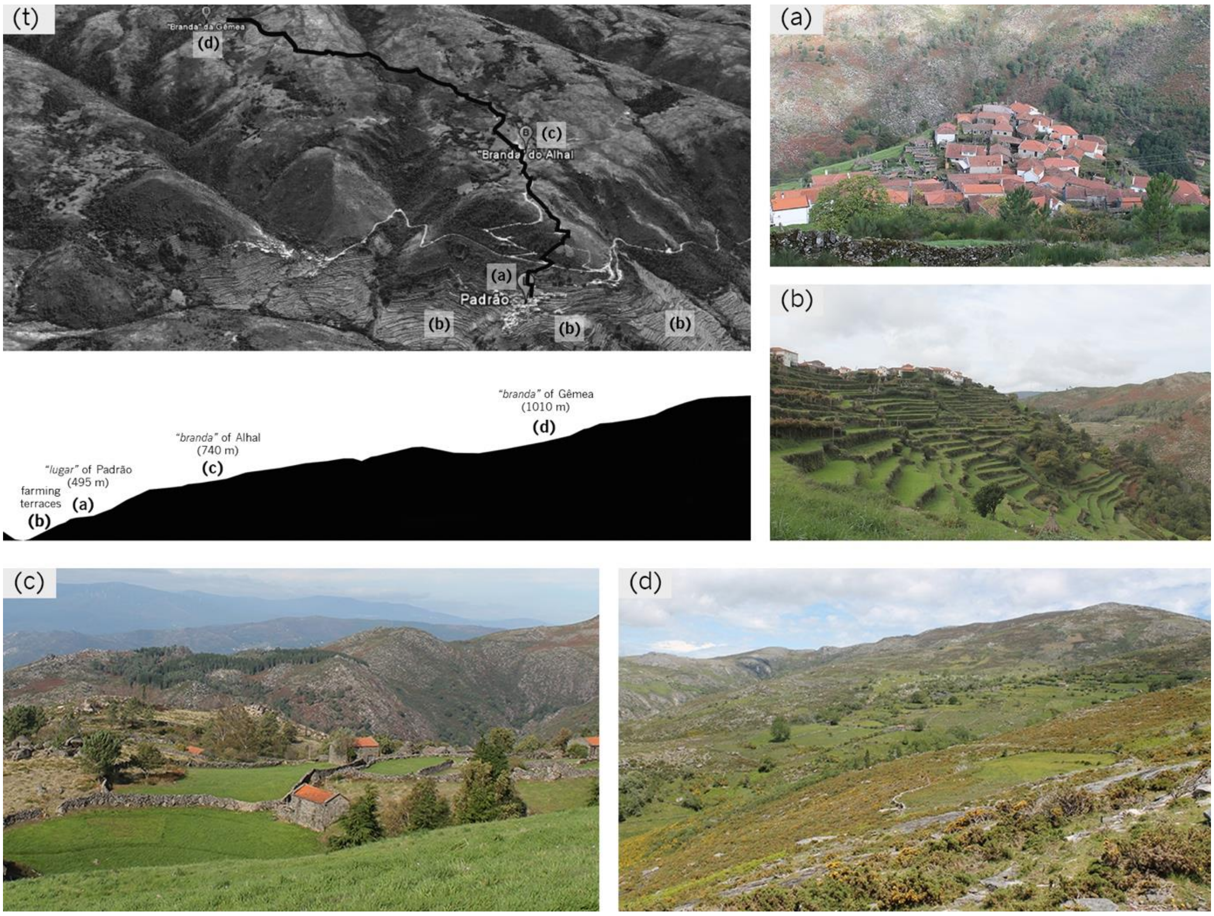


Fig. 5.21 – Mountain range occupation at the *“lugar”* of Padrão (Sistelo, Arcos de Valdevez): t – aerial view (Google Earth®) and cross-section of the territory (based in Barros [102]); (a) base settlement of Padrão (495 m of height); (b) farming terraces; (c) *“branda”* of Alhal (740 m of height); (d) *“branda”* of Gêmea (1010 m of height).

The temporary mountain range settlements could vary from simplified structures, used for shorter periods, to fully organized structures similar to the base settlement, used for longer periods of time for livestock and farming. Taking into consideration the staying period and type of economic use, several different typologies of temporary settlements built in the mountain range plateau are described and presented schematically in Fig. 5.22 (drawings and local designation by Fernando C. Barros [105,106,155]).

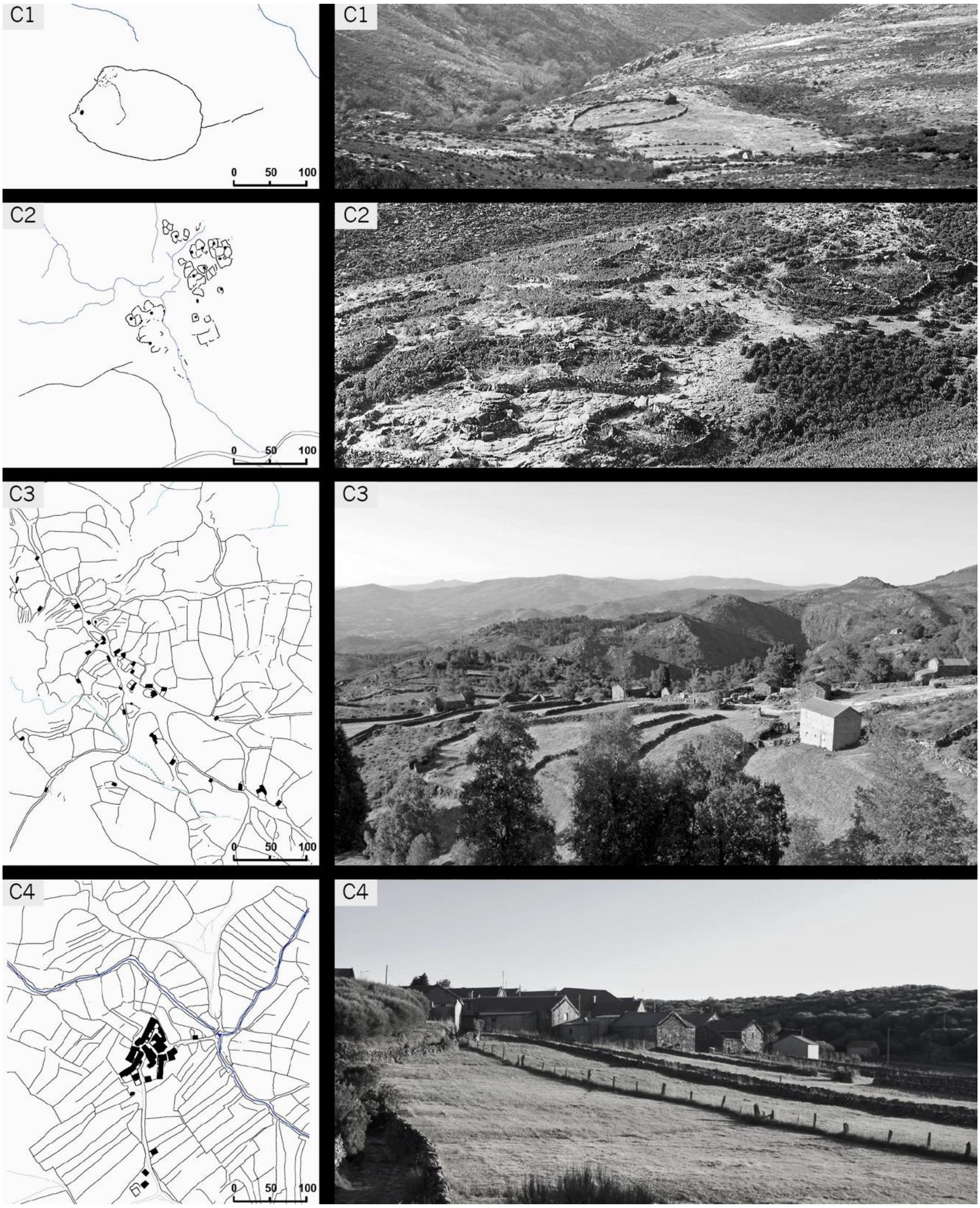


Fig. 5.22 - Examples of the different types of temporary mountain range plateau settlements: C1 – *"currais"* (e.g. Ermida, Amarela mountain range); C2 – *"branda de Gado"* (e.g. *"branda"* of Arieiro and *"branda"* of Burzavô, Peneda mountain range); C3 – *"branda de cultivo"* (e.g. *"branda"* of Alhal, Peneda mountain range); C4 – *"branda"* of Portos (e.g. *"brandas/inverneiras"* of the Peneda/Laboreiro mountain range system) [107,139,156–158].

Communitarian livestock settlements for pasture (C1), named *“currais”*, were typically found in the Amarela and Gerês mountain ranges, but less frequent in the Peneda/Laboreiro mountain range. It is a type of temporary settlement formed by a single nucleus of a commonly-owned large corral, built with a short height dry-stack farm wall and a one-storey small-size corbelled dome shepherds’ shelter, named *“forno”* or *“cabana”*. Livestock was grouped in the same herd and managed in turns by shepherds of the different families, in a system called *“vezeira”*.

Livestock settlements for pasture (C2), or *“branda de gado”*, found in the Peneda mountain range, differ from the *“currais”* for being formed by several individual and privately-owned corrals, forming nuclei named here *“bezerreira”*. In it, a one-storey small-size corbelled dome shepherd’s shelter, named here *“cortelho”*, was built. Although not frequent, a study case found at the *“branda”* of Seida (Soajo, Arcos de Valdevez), confirmed cases of nuclei with a smaller two-storey shelter [102]. In some cases, the *“vezeira”* system was used, although individual family livestock management was common.

Settlements used simultaneously for pasture and farming (C3), or *“branda de cultivo”*, were found at the Peneda/Laboreiro mountain range. The mixed used resulted from specific mountain range plateaus geographical conditions, only found in this mountain range area. The specificities of farming, which required more workforce and longer stays, lead to the construction of groups of buildings resembling a very primitive form of farmhouse organization, located each near their owned pasture/farmland. Therefore, the plateau was occupied by several nuclei formed by groups of buildings and walled pasture/farmland areas, anchored to a road network. Each individual group was formed by a two-storey shelter for farmers/shepherds, named *“cardenhas”*. Adjacent to it, several one-storey shelters used as stables for manures’ production to be used as fertilizers, named *“cortelhos”* were built. Each group had a privately-owned enclosed external area used as a small corral.

The main access to buildings could either by through each group private corral or directly from the road. Access to pasture/farming areas was through gates on the farm walls, or directly from inside the buildings. The farmland was prepared either by constant adding of manures to the soil, and by correcting their slope through retaining walls and terrace building. The construction of masonry irrigation networks (canals and wells) was fundamental to the settlement’s productivity. To allow controlling and managing herds, dry-stack single wythe (≅ 0.25 m cross-section) boundary and animal intrusion protection farm walls were built along roads and properties. To allow the mobility of the oxcart, fundamental for transporting farming goods, roads were paved with very rough granite stones or by hammer-dressing existing granite outcrops. An alternative morphology was observed during the exploratory visits and reported by Barros [139] at the *“branda”* of Bilhares (Ermida, Ponte da Barca). Inside a large corral, several small gable roof rectangular buildings were built aligned, forming paths. The cattle in these stables produced manures used to fertilize the surrounding farmland.

Prolonged stay pasture and farming settlements (C4), or *“brandas e inverneiras”*, were found at the northwest of the Peneda mountain range, being more specific of the Laboreiro mountain plateau [131]. In this specific system, according to Barros [106], settlements are used in turns as permanent dwelling, being the base settlement the *“inverneira”*, used for a shorter period of time during the colder months, and the *“branda”*, located at the mountain range plateau, used for the remaining months. In this specific case, the entire family and its assets would move from one settlement to the other. From the organizational point of view, the *“branda”* presented a simplified urban organization and nuclei of walled farmland with *“branda”* houses, used as dwellings during the warmer season. Corbelled dome structures are not common in this system of mountain range temporary settlement. In the *“inverneiras”*, communitarian ovens can be found [10,27], using a roof system built in large granite slabs supported over granite hammered-dress roof trusses.

Regarding buildings, the use of corbelling building techniques is a very distinct and authentic identity feature. Even though not exclusively used in this region, in comparison with other cases existing in Portugal, Oliveira et al. [10] highlights the morphological and typological diversity of the highland corbelled dome constructions. Origins of its use in the region are unknown [10,131], and according to testimonies gathered among the local populations during the exploratory visits (see Section 9.2), the use of such building technique has not been witnessed for the past century.

As shown in Fig. 5.23, observed examples varied from very harsh and primitive constructions built in cyclopean masonry with a single stone block roofing, to buildings with proper hammer-dressed stone blocks, with ashlar reinforcements in corners and openings.

Fig. 5.23 – Examples of different corbelled domes and construction quality of the highland vernacular heritage: (a) poor construction quality; (b) low construction quality; (c) improved construction quality.

According to examples from literature, some domes could be covered with soil [107,131]. Considering the smaller domes observed (number of layers inferior to 6 with the top of the dome bellow 2 m of height), the construction process can be considered very intuitive and simplified. Regarding the larger and heavier corbelled domes (number of layer superior to 6 with the top of the dome above 2 m of height), the used construction technique presents higher complexity due to the scale factor. Concerning average dimensions, examples can be found from very small buildings to large-size buildings, with Oliveira [107] reporting as the larger observed structure of his research, a two-storey corbelled dome shelter with 4.5 m x 3.5 m of base plan, with the internal top of the dome at 5.5 m of height. This building is located in the *“branda”* of Real (Cabreiro, Arcos de Valdevez).

Due to the loss of the empirical knowledge chain of transmission and the absence of documental evidence on the topic, the full understanding regarding such construction techniques is presently uncertain [10,124,131].

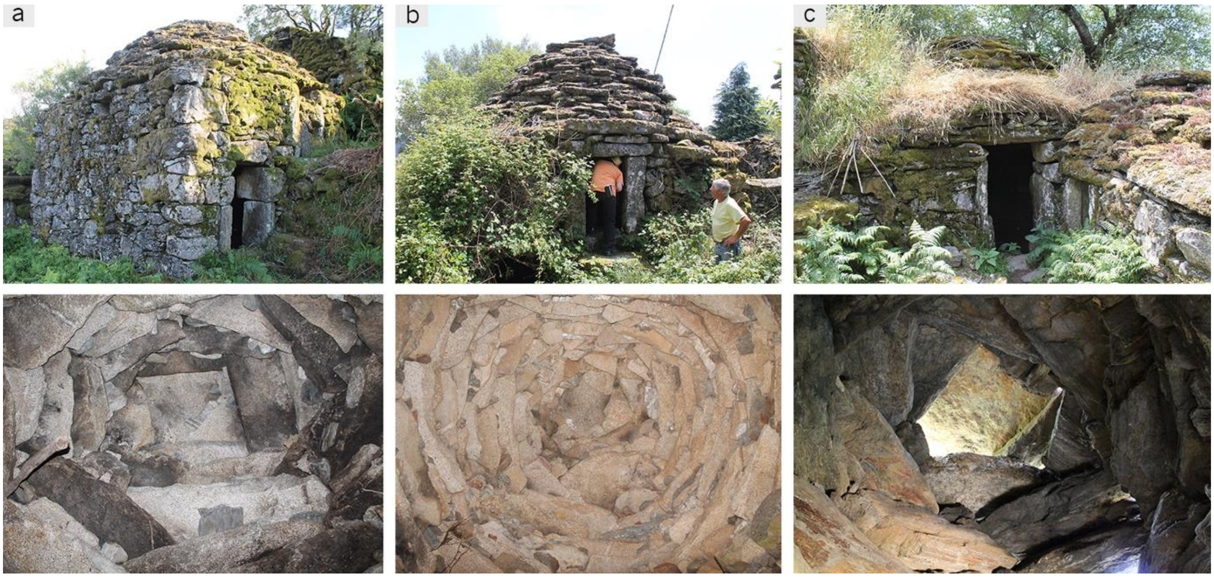


Fig. 5.24 – Examples of different rocks used for corbelled domes construction: (a) granite masonry in *"branda"* of Real (Cabreiro, Arcos de Valdevez); (b) mixed granite and schist masonry; (c) schist masonry (b and c are located in *"branda"* of St. António of Vale de Poldros (Riba de Mouros, Monção).

As for the building materials, as shown in Fig. 5.24, examples showed that masonry was built using local stone, either in granite, schists or by combining both.

Although misleading, most of the observed corbelled dome buildings of the highlands are associated with a beehive or cone shape appearance, see Fig. 5.24b. In fact, as shown in Fig. 5.24a, the majority show a rectangular and axial proportioned base plan geometry, being buildings with circular base plans a minority and restricted to smaller examples.

To this aesthetics contribute several construction features, such as the ones listed next: *i)* the high geometric irregularity of stone blocks and superficial masonry textures, that give these corbelled dome buildings a very characteristic primitive aspect; *ii)* the use of rounded corners to connect walls in corners; *iii)* in taller buildings, masonry walls built with a type of cross-section that diminishes in width as the wall rises, maintaining the vertical alignment by the internal face, but gaining a constant slope in the external face (see Section 9.2 for detailed constructive description).

However less common, improved construction quality corbelled dome buildings show an aesthetics of an orthogonal box, like any ordinary local building, but covered with a cone shaped roof, see Fig. 5.23c. According to Barros [124], corbelled dome roof solutions can also be found at the base settlements, being used in watermills or scattered buildings such as stables and sheds built in the farming terraces [102,106], see Fig. 5.27a.

Based on the study case and the exploratory visits observations (see Section 9.2), complemented with literature information [10,107,124], a morphological and typological overview of the highland corbelled dome heritage, either for isolated or grouped buildings, is shown in Fig. 5.25.

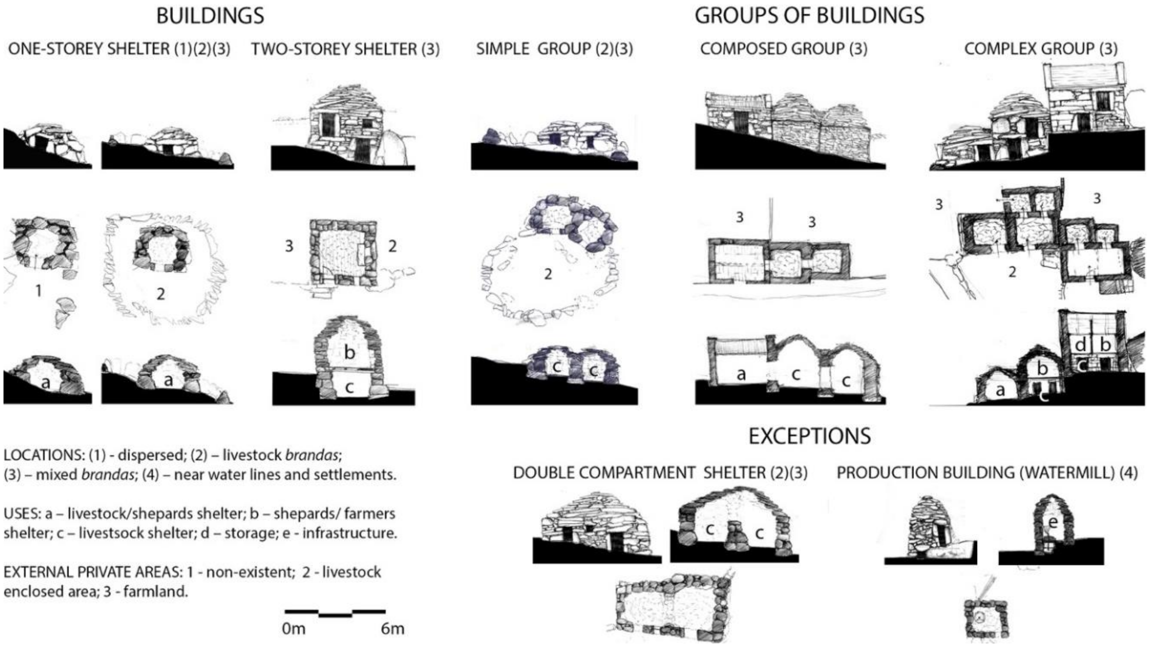


Fig. 5.25 – Schematic overview of common morphologies and typologies of highland corbelled dome buildings based in the case study *"brandas"* of Padrão (Sistelo, Arcos de Valdevez) [51].

Fig. 5.26 – Examples of corbelled dome isolated and grouped buildings (see Fig. 5.25): (a) small one-storey shelter; (b) larger one-storey shelter with dome covered with earth; (c) two-storey shelter; (d) simple group; (e) composed group; (f) complex group.

Fig. 5.27 – (a) example of corbelled dome watermill (Padrão, Arcos de Valdevez); b and (c) examples of *"branda"* houses still with original straw roofing (*"branda"* of Busgalinhas, Gavieira, Arcos de Valdevez).

One-storey shelters are the most representative corbelled buildings in the highland area (70% of buildings in *"branda"* of Gêmea) and were destined to shelter livestock or shepherds. When used by shepherds, these buildings were used as resting and shelter, being meals generally prepared outside, near the entrance. Geometrically, these buildings could vary considerably from small structures to large-size buildings. These could either be placed isolated in the territory, built inside a corral or with a small enclosed external area.

Two-storey shelters were buildings used during warm and crop season simultaneously as stable (ground-floor) and as shelter and temporary lodging for farmers/shepherds and storage (upper-floor). These types of buildings were only observed in the Peneda mountain range. To support a longer stay in the *"branda"*, the upper-floor had a fireplace that allowed cooking inside, and some, a small window. Due to the high percentage of voids of walls and domes, these were highly ventilated buildings, and did not have chimneys for soot exhaustion. The access was through external stone stairs, or directly if the entrance was at the terrain level. The upper-floor pavement was in timber, although some less frequent solutions of corbelling solutions or large stone slabs could also be found. As previously explained, two-storey shelters were normally part of groups formed by several one-storey shelters, meaning that these were less representative than the latter (13% of buildings in *"branda"* of Gêmea). Regarding their position in the group, they could either be aligned and accessible from the road or placed inside the external enclosed area. In these groups, it was common for buildings to have more than one entrance, and to have internal connections. The doors, with very few exceptions, were the only source of natural light of these buildings.

Two-storey gable roof buildings, or *"casas de branda"* (*"branda"* house) are considered a later addition to the built heritage of the temporary mountain range plateau settlements (17% of buildings in *"branda"* of Gêmea). These buildings were initially referred to by Oliveira et al. [10] as *"colmaços*" for their straw roofing [10], later replaced by ceramic tiles. Regarding their purpose, they appear to have functionally replaced the two-storey shelters for human lodging. These buildings were similar to the base settlement buildings, although showing inferior gross area and construction quality. Regarding their base plan geometry, these were rectangular proportioned buildings, being the upper-floor divided into a lodging compartment with a fireplace and a storage area, and the ground-floor used as stable. Regarding accesses, their role in the groups of buildings and connections to the remaining shelters followed the same principles of the two-storey shelters.

Regarding buildings and their location in the territory, these could either be found isolated or forming different types of groups, as shown in Fig. 5.26 and Fig. 5.27, distinct due to their complexity. Thus, one could observe during the exploratory visits: *i)* isolated shelters, with or without a corral, scattered in the territory or part of a temporary mountain range settlement; *ii)* simplified groups of two one-storey shelters associated to a corral; *iii)* composed groups formed by a short number of one-storey shelters and a two-storeys shelter or gable roof building, generally with a corral; *iv)* complex groups combining several one-storey shelters, a one two-storey shelter and one gable roof building associated to external enclosed areas and farmland. As observed, groups could have several one-storey shelters, whereas generally only presented a single two-storey shelters with/or a gable roof building.

5.5 Final remarks

As demonstrated in this chapter, vernacular heritage in the Entre-Douro-e-Minho show an extremely rich diversity of buildings and solutions to answer to survival needs. With a strong agrarian character, local vernacular architecture shares the same basic rationality, functionality, and adaptability principles. Although starting from basic layouts in which common compartments prevailed, as rural houses grow, the kitchen gains importance as working space, and the dwelling gains external covered areas that provide assistance to all tasks performed in the house. As for the private compartments, they are clearly secondary in the concept of the Northwest rural house. Therefore, as shown, the vernacular house of the survey area can be described as a very flexible structure, able to adapt to circumstances.

The same type of flexibility can be seen in the farmhouses, by the very wide range of distinct types of layouts shown by farmsteads. These can be described as rationally organized agrarian production units, that grew along with the farmhouse production output. The farmyard is the main connection and external working platform of the agrarian compound. The dwelling can either be the main and larger building of the complex or take a very humble place on it.

As expected, due to the context described on Chapter 4, rural houses prevail over individual farmsteads at the highland, showing a harsher aesthetics, and smaller proportions. Nonetheless, the same organizational and rationality principles found at the lowland are applied to the highland dwelling basic design. Limited for being inside concentrated settlements, a strategy of grouping and transferring to the public space of most of the typical tasks performed in the farmsteads, results on a very exquisite strategy of using common areas of the settlements to overcome the shortage of building area and to optimize labour and resources management. On both sub-regions, grain transformation and storage structures play a key role in the organization of the farmhouse and the highland settlement, becoming the *“espigueiro”* a regional trademark.

As for the production buildings and infrastructure, from simple walls to complex mills or elaborated temporary mountain range settlements, their morphological, typological, and constructive diversity is extraordinarily rich, proving how well the Entre-Douro-e-Minho populations knew their context and resources and their high inventiveness to make the most out of them.

Chapter 6

VERNACULAR BUILDING TECHNIQUES AND STATE OF PRESERVATION

Vernacular construction of the Entre-Douro-e-Minho found on stone masonry load-bearing walls, its key structural elements [14,154]. Vernacular buildings' basic structural layout can be described as formed by a structural box built with perimeter placed load-bearing wall, reinforced by transversal ground-floor partition masonry walls, both supporting the timber frame horizontal structural elements of pavements and roofs. Structural monolithic behaviour of buildings was improved by connecting vertical and horizontal elements and improving masonry fragile points.

The above-described structural system prevailed until mid-20th century. Afterwards was progressively replaced by industrialized building materials and systems based on concrete pillars and beams (prestressed) and ceramic tiles [14,159]. As seen during the exploratory visits, by showing higher durability, masonry load-bearing walls are frequently the last of vernacular building's elements to disappear. While standing, memory and ruined buildings' rehabilitation possibility is always possible. Therefore, the present section will focus on the characterization of masonry walls from a constructive and durability points of view. Regarding pavements, roofs and light timber frame walls, several studies can be found on literature on these topics [137,160–164]. As for the information presented next, it was mostly collected during the exploratory visits, by visual inspection and by direct contact with the populations.

6.1 Stone masonry load-bearing walls

Either part of buildings' structure or just as simple farm walls, vernacular masonry walls present the same basic mechanical principles, being all influenced by the same type of variables such as construction quality, geometric properties of building and structural elements, and the properties of the stone blocks used. According to Appleton [165], to load-bearing masonry walls is required: *i)* to resist to gravity loads of its building material's on weight; *ii)* to transfer own weight and vertical loads resulting from pavements, roofs and from the daily use of buildings to the foundation soil; and to *iii)* resist to unforeseen horizontal loads such as seismic actions, accidental shocks or inadequate structural behaviour of horizontal elements.

Therefore, according to author [165], typical load-bearing masonry wall's mechanical behaviour is characterized by a very low tensile and shear strength resistances, and a reasonable compression strength resistance [165,166]. According Lourenço [166], low tensile strength was in paste centuries a key feature in the design of buildings. As for compression strength, being vernacular masonry walls a composite element, they are highly dependent on the level of lateral confinement of external leaves. Other factors that affect structural performance are existing incoherent materials at the inner core, and the level and dispersion of internal voids [166]. Therefore, the stabilization and equilibrium of a masonry wall, a major safety concern of masons throughout construction [167], resulted from: *i)* a geometry based on heavy mass and thick cross-section; *ii)* building materials and their bonding conditions; and *iii)* general monolithic behaviour of the built vertical plane [165,168–170]. Being load-bearing walls heavy mass elements, its stone blocks' own weight cause an increase on walls' compression load, that act as stabilizing force, balancing vertical with horizontal loads [151,165]. According to Appleton [165], as cross-sections become less slender and inner cores' thickness increases, masonry walls are less prone to buckling. Therefore, by having larger inner cores and wider cross-sections, walls show improved resistance to tensile loads and cracking caused by horizontal loads [165].

Load-bearing wall's heavy mass design is also known for its influence over buildings' internal environmental conditions and protection against climatic agents [165,171]. High thermal inertia of heavy mass caused cold masonry walls to absorb heat from the warmer internal air, heated during the day by the fireplace, and to release it back when the air temperature drops below walls' temperature during the night [165]. Thick and composite cross-sections offered protection against wind, rain water or excessive solar exposure and heating [165]. Regarding humidity, thick cross-sections would absorb humidity during the cooler months and release it by evaporation in warmer month [171].

From a constructive point of view, to counteract possible instability on the vertical plane, masons interlocked bondstones, headers and stretchers stone blocks by overlapping them (kept in place by gravity and friction), and by forming misaligned vertical joints (to block vertical cracks spreading) [167], therefore achieving monolithic behaviour between wall's different leaves.

According to Binda et al. [172], such monolithic behaviour contributes to improve stress distribution. Nonetheless, due to compression, the inner core mortar infill expands horizontally (Poisson effect) and induces horizontal loads, pushing outside the external leaves. Properly bonded and linked external leaves counteract this out-of-plane behaviour, thus confining the inner core expansion and improving masonry wall's mechanical behaviour [173]. As a final note, structural performance and durability of masonry walls is strongly influenced by construction quality. As observed by Carocci [167] regarding masonries damaged by seismic events, masonries built according to what the author calls *"workman likely built"* showed less damage than others showing initial building defects.

6.1.1 Building materials

As for raw construction materials, rocks prevail by their high availability in the Entre-Douro-e-Minho natural environment. Soil was the most used raw material to make mortars [174]. The abundance of trees in the region, lower in areas above 700 m of height, made timber the selected material to make buildings horizontal structural elements, lighter structures, and frames.

Regarding mortars, these were mainly produced from granitic residual soil, locally known as *"saibro"* [126], but also from clayey soil with natural kaolin or higher percentage of clay [126]. To make mortars for all sorts of uses, soil was sifted to remove larger stones and dirt, and simply mixed with water. When used for bedding stone blocks, soil mortar allow a more uniform load transfer, and reduce significantly load concentration points [173]. However, due to its low bonding capability, preferential compression lines pass mostly by the overlapping interface of stone blocks and through levelling wedges [154,173]. Mixed with smaller stones and rubble, soil mortars were used to fill the inner core, originating an inner leaf with a high percentage of voids, poorly bonded to the confining leaves [175]. As observed during the exploratory visits, mortars decisively contributed to durable and stable cross-sections, particularly in masonries built with smaller and irregular stone blocks. As shown in Fig. 6.1a and b, the use of soil render painted with lime paint was common in housing buildings. At the mountain range areas, the use of renders was not common. In some cases, clay was used to fill masonry joints and, as shown in Fig. 6.1c, lime paint was applied directly over stone blocks, especially around openings.

Regarding pavements and roofs, and even frames and furniture, these were made of timber elements. Their construction quality could vary significantly attending to their level of complexity, being the simplest structures made by farmers themselves, and the more elaborated by builders and carpenters. Timber was collected from local species of trees such as the sweet chestnut (*Castanea sativa*), the maritime pine (*Pinus pinaster*), the oak tree (*Quercus robur*), the black poplar tree (*Populus nigra*) or the walnut (*Juglans regia*) [176]. Exotic woods from Brazil, although not a frequently used type of wood due to its high cost, was found in large-size *"brazilian"* houses.

Regarding transformed construction materials (artisanal production), despite artisanal clay bricks production in specific areas of the Entre-Douro-e-Minho (e.g. Barcelos), it was more valuable as commercial asset. Therefore, its use on local construction was residual (e.g. used to make chimneys or reinforce openings). On the other hand, ceramic roof tiles (e.g. Barcelos) were widely used on all types of buildings. Traditional *"lusa"* roof tile, over time replaced straw roofing (still reported until mid-20th century) [79,102]. As shown in Fig. 6.2a and b, both types of roofing materials originated roofs with smooth slopes, due to these materials low interlocking. As shown in Fig. 6.2c, highland buildings typically presented gable roofs. In areas with stronger winds exposure, roofs showed a large granite capstone over the lateral walls and above the roof's level, built to protect roofing materials from the wind. Later, the *"marselha"* roof tile was introduced and widely used for its higher water tightness and for allowing roofs with higher slopes [14].

Fig. 6.1 – Examples of the use of traditional soil renders and lime paint: (a) dwelling building of a farmhouse showing facades covered in *"saibro"* render and painted with white lime paint (Barqueiros, Barcelos); (b) rural house with lime painted *"saibro"* render on the kitchen walls (Vale, Arcos de Valdevez), (c) rural house without renders showing a white entrance painted in lime paint directly over the stone blocks (Ermida, Ponte da Barca).

Fig. 6.2 – Images of three gable roofs: (a) external view of a roof with *"lusa"* tiles (Vale, Arcos de Valdevez); (b) internal view of the structure of a gable roof covered with *"lusa"* tiles (Lindoso, Ponte da Barca); (c) detail view of a roof originally covered with straw replaced by *"marselha"* tiles, showing the granite wind protection capstone, and chimney built in *"lusa"* tiles.

Regarding rocks, as observed on the Portuguese lithological chart, see Fig. 6.3, the Entre-Douro-e-Minho is part of the northwest region of the Iberian Massif, and is located over an area of predominant igneous rocks (e.g. granite), with smaller pocket areas of metamorphic rocks (e.g. schists) [174,177]. For their different mineralogical compositions, building with granites and schists required from masons a certain knowledge regarding these rocks' handling and bedding to make masonry. Granite is referred in literature as one of the most abundant types of igneous rocks in the north of Portugal [178,179], being the predominant type of rock in the Entre-Douro-e-Minho region. With a wide range of different sub-types, granites are either present in the territory in smaller rock outcrops or in large massifs. Regarding its formation process, granite is the outcome of the cooling of magna (plutonic type) bellow the earth's surface (intrusive type), that emerged to the surface due to natural erosion [178–180]. Granite is described by Bell [178] as a coarse-grain type of rock (of megascopic texture with grain's size over 5 mm in diameter), completely formed by crystalline mineral materials (of holocrystalline type).

Regarding aspect, granites present non-glassy and granular texture with individual crystals. Concerning physical and mechanical properties, granites generally present a typical isotropic behaviour related to homogeneous and random mineral arrangement [178]. However, certain types of granites are known for showing preferred orientation or even a foliated structure, caused by certain types of minerals.

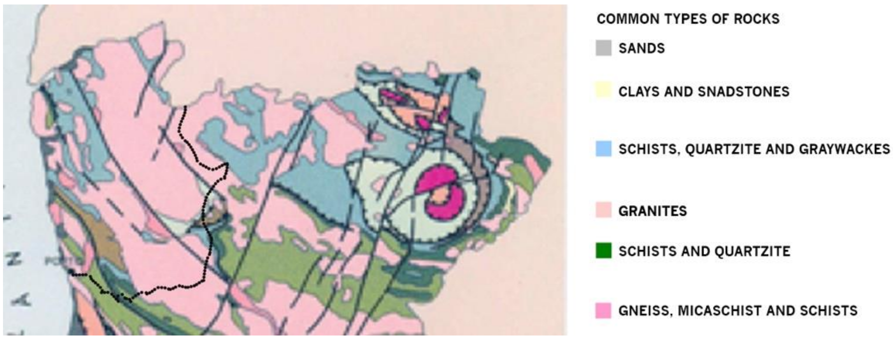


Fig. 6.3 – Detail of the Portuguese lithological chart, based on Barros [181].

According to Vasconcelos [182], Portuguese granites typically present a three orthogonal splitting planes structure, named preferred ruptures planes or quarry planes. According to the author [182], from the identification of these planes at quarry depends the success of the cutting operation, as each one has different ways of influencing stone block's end cut results. From the three, cuts following the rift plane allow achieving an easy splitting and smooth finish stone blocks [182].

Regarding schists, several types can be found in the survey area. Their use as masonry material is decisively influenced by intrinsic features such as: *i)* the metamorphic origin; *ii)* foliation; and *iii)* anisotropy [183,184]. Local schists were formed by regional metamorphism, a natural transformation process over existing rocks at solid state, related to deformation processes over large areas caused by pressure [179]. This process is influenced by a large number of variables such as pressure and high temperatures [178], and consists of several mineral recrystallizations that over time alter rock's microstructure [180,184]. Metamorphism is responsible for the existence of a large diversity of schists showing different physical, mechanical and chemical properties [183], visible in schist's different colours, textures and different levels of superficial hardness [179,180].

Resulting from the above-described formation process, schists are known for their strong foliated structure, with rocks exhibiting a typical planar structure that follows a preferred orientation and causes the weaker schists to easily split into different layers (delamination [36]). In some cases, such structure is clearly visible by rock's organization into parallel bands of distinct colours. Due to schist minerals specific shape, foliation is named schistosity [178]. Also originated from the metamorphic transformation process, schistosity is the outcome of the presence of inequant grain or grain aggregates of platy and lath-shape [183]. Foliation of schistosity is considered as well-defined if schists show a high percentage of inequant grains and a preferred planar orientation visible at naked eye, and splits into layers of less than one centimetre. However, it is considered as poorly-defined in all other cases [183]. The combination of all above-mentioned features is responsible for schist's known strong anisotropy [178,185].

Due to knowledge gained by experience, masons shaped and bedded schist stone blocks parallel to the rock's foliation. In this position and with its planar structure under compression, schists stone blocks are stronger and better protected from lamellar disaggregation and from water penetration through its foliation joints [182]. As seen during the exploratory visits, bedding schist stone blocks in other positions would induce over time lamellar disaggregation, therefore, was not common.

Interviews with local professional masons with vast experience on schist vernacular construction, allowed to understand that from their practical point of view, local granite is considered a stronger and durable type of stone when compared with the local schist, being easily shaped into larger blocks and ashlars. Due to granite heterogeneous composition and stiffness, it was used to produce elaborated and complex elements such as large-size lintels and beams, columns, or pillars, and with the appropriate skills, decorative elements, or balconies. For its higher strength and durability, particularly fresh granite (bluish colour), was also used for pavements. However, due to its granular fabric, very small units were highly irregular or too brittle to be used, being impossible to obtain thin smaller plate shaped wedges from local granite.

As for the schists, these rocks were considered by masons as weaker and less durable in comparison with the granites, particularly if exposed to water. Well-defined foliation schists typically showed inferior stiffness, therefore been easier to hammer-dressing on-site. Due to their characteristic foliated structure, it was easier to obtain very thin and small wedges. To diminish the risk of lamellar disaggregation during the cutting operation, stone blocks were shaped according to schists foliation into a typical horizontal shape (not higher than 0.2 m). For its limited height and brittle behaviour, to shape larger ashlars from local well-foliated schist was not common. Regarding poorly-defined foliation schists, these were similar to granites regarding the shaping of the stone blocks. However, according to masons, for being weaker and the difficulty on clearly identifying foliation orientation, made this schist less versatile in comparison with granites. Therefore, for showing a more brittle and unpredictable cracking behaviour during shaping and hammer-dressing, it was considered too fragile to be used for more elaborated stone elements or lintels.

6.1.2 Building elements

As clearly explained by Giuffré et al. [186], vernacular masonry walls were very adaptive for not being continuous structures, but instead, an assembly of overlapped stone blocks, kept in place by interlocking superposition and mortar joints. Therefore, according to the author [186], despite the hazard related to excessive loads, particularly those of seismic origin [154], masonry structures are easily disassembled for deep repairing, maintenance and to be adapted to context changes [186].

During construction, building materials were stored nearby to reduce travelling time and effort, being final shaping and hammer-dressing of ordinary stone blocks given at the construction site. As described by still working professional masons, as quality criterion in the selection of stone blocks, these were checked for the regularity and absence of voids in their surfaces. Stone blocks were also refused if showing areas of strongly different stiffness or excessive geometric irregularity. In this way, proper bedding was achieved and risks of tensile behaviours reduced [173]. Demolished stone blocks were typically reused in new constructions. Markers and guides were used to assist levelling stone blocks' rows and to set the path of new masonry wall under construction. Timber scaffolds, either supported directly from the ground or by a beam inserted in openings left intentionally in the fabric of masonry wall under construction, were used to build walls' over 1.2 m of height. After removing the scaffold, these openings would either be closed or left open for future maintenance.

The construction of masonry walls, either building's load-bearing walls or simple farm walls, was executed by portions or stages, described ahead. Fig. 6.4 shows a new schist farm wall under construction, and Fig. 6.5 shows schematic examples of the different construction phases.

Fig. 6.4 – High farm wall under construction, with details of schist stones blocks bedded into position (S. Pedro de Rates, Póvoa de Varzim).

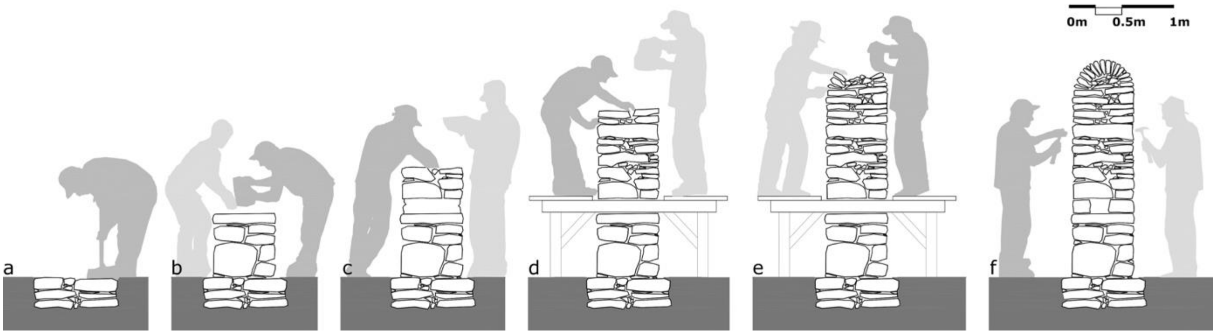


Fig. 6.5 – Different construction stages of a vernacular high farm wall: (a) foundation; b - placing a bondstone connecting both faces of the masonry wall); (c) construction until 1.2 m high, with openings to support the timber scaffold; (d) construction using a timber scaffold; (e) cap building; (f) pointing of masonry joints and scaffold's support opening.

a) Foundations

Foundations were built if the foundation soil showed poor loading capability. Wider foundations than the cross-section were built when a larger contact area was required to avoid concentrated loads on the soil [151,187]. From the practical point of view, wider foundation would also allow alignment correction along the new load-bearing wall's path, if needed [151]. Proper foundations were normally built on two-storeys or larger building. As for lighter structures such as smaller farm walls or in the mountain range temporary settlements, foundation's building could be expendable if the loading capacity of the soil was good enough to sustain load or when building directly on top of a rock outcrop [151], see Fig. 6.6c.

Therefore, three main types of contact with soil could be found in Entre-Douro-e-Minho masonry walls: *i)* shallow foundation, that were continuous foundations, wider than the wall cross-section (additional 0.10 m to each side) and about 0.6 m deep [151,164], see Fig. 6.6a; *ii)* direct foundation, in which the first layer of the wall was in direct contact with the soil, being built with carefully aligned larger stone blocks [151,164], Fig. 6.6b; and *iii)* without foundation, starting the cross-section directly from the foundation soil upwards [126,151,164]. In any case, existent rock outcrops on the wall's path would be integrated as part of the foundation [126]. Load-bearing walls that also had retaining functions would be built with a higher cross-section thickness on that specific stretch (over 0.6 m) but keeping the vertical alignment with the wall's main facade. In the case of masonry pillars or columns, individual shallow foundations were built.

Fig. 6.6 – Examples of different types of foundations found on load-bearing walls during the exploratory visits: (a) shallow foundation, 0.05 m wider than the cross-section (Barqueiros, Barcelos); (b) direct foundation with the first row of masonry made of large stone blocks (Barqueiros, Barcelos); (c) granite massif used as foundation (Lindoso, Ponte da Barca).

b) Cross-sections

The study of cross-sections and its characterization is fundamental to understand masonry walls structural behaviour [188]. Due to seismic effects on historical masonry over the past decades, important research was undertaken in Italy in order to better understand the morphology of masonry walls, including their cross-sections [167,186,189,190]. In Portugal, similar works on historical masonry walls were also undertaken [151,152,191]. These studies highlighted that bedding mortar is very important to improve structural stability and durability of masonry built with ordinary stone blocks [168]. Therefore, based in this fundamental building feature, the observed vernacular cross-sections were typologically divided into two main families of walls, namely walls built with soil bedding mortar and dry-stacked walls. Examples of both, built either in rubble and ashlar masonry were seen in the study area. As exception, examples of extremely poor construction quality cross-sections were seen where both types of cross-sections were combined. These were part of small agrarian support buildings or reconstructed farm walls that combined in the same superficial texture, several types of building materials and areas of large stone blocks with areas of small ones.

Due to high availability of suitable soil, mortar bonded masonry walls predominate at the lowland sub-region and some mountain areas. With lower availability of suitable soil an easy access to abundant rock outcrops for large stone blocks extraction, dry-stack masonry was the common cross-section building technique at the highlands and mountain ranges. However, dry-stack masonry was also used at the lowland when constructing with larger stone blocks or ashlars, or on small masonry walls with low performance requirements such as smaller farm walls at forest and pasture areas. Taking into consideration the type of rock used, it was observed that schists typical high geometric irregularity and mineralogical specificities, required mortar bonded cross-sections to make buildings and larger load-bearing walls, while dry-stack cross-section were restricted to smaller farm walls. As for granites, mortar bonded masonry predominated in the lowland, for all types of constructions. Dry-stack granite construction was predominant in the mountain and highland sub-region for both buildings and farm walls. Being a sub type of dry-stack cross-sections, Oliveira et al. [14] reported a later building technique using small and regular shaped granite stone blocks, named *“perpianhos”*, with average thickness of 0.2 m. This type of masonry unite was used either in new buildings or to build and add new compartment to existing ones. As the author [14] explained, it was a non-successful reaction of the local stone industry to the industrial clay bricks and concrete elements [12].

As explained on Section 6.1.1, the use of bedding mortar improved bond behaviour between stone blocks [173] and reduced the number of wedges used. As *“rules of art”* when building strong and durable multi-leaves cross-sections with bedding mortar, masons reinforced the bond conditions between leaves and inner core. Such was achieved by alternating stone blocks with different thickness and by turning their most irregular faces to the core, therefore, creating a more irregular leaves’ inner face to improve their bonding with the core filling mortar [154,191].

Regarding dry-stack walls, global performance was highly dependent on size of stone blocks and on regularity of interfaces, a requirement to reduce the number of wedges. Dry-stack masonries built with stronger large-size stone blocks or ashlars, with a reduced number of wedges and voids, showed improved structural behaviour. Ordinary dry-stack masonry built with small-size or highly irregular stone blocks, with higher amounts of wedges or voids, showed inferior interlocking between leaves and stone blocks. Therefore, seen examples of the latter, present characteristic lower structural performance and durability [166].

On both above-mentioned families of cross-sections, as previously said, global interlocking was dependent on friction between overlapping stones, and on physically connecting opposite leaves by placing bondstones [192]. Also known as throughout stones or bondstones, these specific stone blocks were placed at regular intervals to reduce the risk of buckling and detachment of leaves. Although for practical reasons, masons placed the heavier stone blocks on the basis of the walls, it in fact contributed to increase stability. In Table 6.1, common typologies and morphologies of vernacular cross-sections found in the survey are presented.

Table 6.1 – Entre-Douro-e-Minho common cross-section typology and morphologic features [154,171,193].

Typologies	Family	Leaves	Inner-core	Connections	Use
Single wythe	Dry-stack of single or overlapping stone blocks	One (> 0.15 m)	-	Friction (alternating horizontally and vertically placed stone units)	Farm walls
Single leaf	Dry-stack with wedges Mortar bonded with wedges	One (> 0.30 m)	- -	Overlapping layers of stone blocks and bondstones	Farm walls, retaining and smaller or larger buildings (if large blocks or ashlars)
Two-leaves	Dry-stack with wedges Mortar bonded with wedges	Two (> 0.40 m on farm wall; > 0.6 m on buildings)	Rubble infill or soil Soil mortar and rubble infill	Headers, stretchers, and bond stones; Opposite leaves not connected to the core (poor quality); or full interlock with headers, stretchers, and bond stones;	Farm walls and all types of buildings
Multi-leaves	Mortar bonded with wedges	Three (> 0.80 m on buildings)	Soil mortar and rubble infill	Three not connect elements (only by the infill mortar binding capability)	Large-size structures in buildings (e.g. large-size *“fumeiro”* chimneys or fireplace support massifs)
Mixed	Dry-stack	One or two (variable thickness)	Non and soil infill	Large bond stones and overlapping stone blocks	Very poor-quality buildings and highland mountain range temporary settlements

i) Single wythe cross-sections were, in simplified morphologies, the result from building a wall by aligning platy shaped schist stones or large stone blocks, also called *“pasta”* masonry. In the remaining cases observed, single wythe morphologies were built simply by pilling up stones. This type of cross-section was used to build smaller masonry walls, being the latter, the most common type of vernacular farm wall seen at the highlands;

ii) As for single leaf cross-sections were mainly used to build farm walls, or buildings if using large-size granite blocks or ashlars. Dry-stack examples showed a poor structural performance, particularly examples built in rubble schist masonry. Improved structural performance was seen in cases where joint mortar was used;

iii) Two-leaves cross-sections, either dry-stack (predominant in the highland) or mortar bonded (predominant in the lowland), were the typical load-bearing walls of buildings, used on both external structural box construction and ground-floor internal partitioning walls. Cases of two-storey partition masonry walls were not common, being such cases frequently the outcome of external walls that became internal with the growth of the building. Regarding the construction of facades, the external leaves were aligned from bottom to top, whereas the internal leaves were recessed at each floor level on an average of 0.1 m to 0.15 m [171]. By doing so, the total weight of the vertical structural element was reduced, representing a considerable saving on materials and construction time. The created recesses were used to support pavements beams [126]. Due to their important structural functions, these masonries showed improvements construction quality. Regarding two-leaves cross-sections used in farm walls, due to the lower vertical loads, typically presented lower construction quality. In both cases, global interlocking, connections, and fragile points were improved;

iv) Examples of multi-leaf masonry walls observed during the exploratory visits were in fact the outcome of walls thicker inner cores. Due to the thicker cross-section, leaves were not physically connected. Such type of masonry walls was seen in production buildings such as mills, and in rural houses to make the first level of higher masonry wall of large chimney (three-storey with ground-floor section of 0.8 m and final of 0.6 m), or the masonry massif to support the upper-floor fireplace slab;

v) As for mixed cross-sections, these were normally the outcome of overlapping in the same wall, single and two-leaves cross-sections stretches. It is a typical highland cross-section, used in very poor construction quality buildings and smaller corbelled dome shelters [106]. The latter was the outcome of using very irregular granite stones, resulting from combining smaller with large-size stone blocks. The examples seen at the lowland were a consequence of poor farm wall maintenance or reconstruction operations.

For examples of the above-mentioned cross-section see Section 6.1.2 (images) and Section 9.1.2 (sections and elevations).

c) Superficial masonry texture

Concerning vernacular superficial textures, it varies considerably due to multiple features such as the geometric regularity of stone blocks, or the regularity of joints and the bedding process [154]. Therefore, as shown in Fig. 6.7, observed vernacular masonry superficial textures varied from high quality textures, built with regular and homogeneous large stone blocks or ashlars, to very poor textures, built with very irregular stone blocks. From the exploratory visits, it was concluded that the overall superficial masonry textures quality was also affected by different construction phases or frequent over time deep maintenance operations. Other factors are related to materials' availability or the expertise of different masons [168]. During construction, masons paid close attention to avoid vertical joints alignments and to the regularity of the horizontal joints. As overall quality criterion, masons would also avoid as much as possible to leave opened voids on the superficial texture, by filling the gaps between the stone blocks with wedges and, in mortar bonded cross-sections, by using pointing mortar.

Regarding the joints, and following Roque [154], three main types of textures can be identified in the study area, clearly related to the geometry and type of used stone blocks. Among the three, the most common were the misaligned or random joints, see Fig. 6.7a, resulting from building with rubble masonry stone blocks with high geometric irregularity. Uncoursed or irregular joints, see Fig. 6.7b, showing horizontal and/or vertical alignments, resulted from bedding hammer-dressed stone blocks showing a predominant orientation. As less representative type of patterns, course joints following regular horizontal and vertical orientations, see Fig. 6.7c, were the outcome of using regular shaped stone blocks and ashlars. As for the bedding of stone blocks [154], it was performed randomly on rubble masonry and, when using very irregular shaped stone blocks, following as possible their main horizontal orientation. As it was seen, for single leaf cross-section, vertically positioned large-size stone blocks increase walls stability. In cases of single wythe or *"pasta"* walls, stone blocks could either be vertically or horizontally bedded, creating in most cases a very homogenous and repetitive type of superficial texture. Regular stone blocks and ashlar were bedded following regular horizontal and vertical orientations. In Table 6.2, a synthesis of the most common vernacular masonry superficial textures typologies is shown.

Fig. 6.7 – Different types of superficial masonry textures observed during the exploratory visits: (a) random joints (rubble masonry); (b) uncoursed joints (irregular shaped stone blocks); (c) coursed joints (ashlars or large regular stone blocks); (d) mixed joints (combining different types of schist and granite stone blocks).

Table 6.2 – Syntheses of common vernacular masonry superficial textures found in the survey area.

Arrangement	Masonry units	Bedding	Joints	Use
Monolithic	Single stone	Horizontal or vertical	One vertical or horizontal	Smaller farm walls
Random	Rubble (highly irregular geometries)	With wedges and with no preferred orientation	Irregular	All types of farm walls, poor-quality buildings
Uncoursed	Irregular shaped stone blocks	Following a preferred horizontal orientation (with wedges	Misalign horizontal and vertical	Farm walls and all types of buildings
Coursed	Regular shaped stone blocks and ashlars (with varied sizes)	Following a preferred horizontal orientation (with wedges) or forming align horizontal layers	Align horizontal and misalign vertical	Specific high standard farm walls and buildings (in granite areas or ashlar construction)
Mixed	Combining deferent types of masonry units (including several types of materials), bedding processes and types of joints		Very poor-quality buildings, most resulting from reusing buildings materials	

As for the representativeness of each types of texture arrangements, random and uncoursed masonry superficial textures were the most common typologies observed during the exploratory visits, whereas the monolithic were the less representative of all identified superficial masonry textures. Also, less representative, coursed superficial textures were used on improved quality buildings, being ashlar coursed textures common at the highland and on later lowland buildings. Mixed textures were observed on poor construction quality buildings, and normally resulted from the reuse of construction materials. This type o masonry is reported by Pinho [171] as showing a poor and unpredictable structural behaviour.

d) Reinforcement of fragile points and connections

For the sake of clearness, masonry fragile points are considerate all points of a masonry wall where an interruption on the continuity of wall's structural fabric is created [165]. Examples are openings (e.g. doors or gates) or intersection between different walls (e.g. corners). According to Appleton [165], due to the instability introduced by the creation of such points, to reinforce walls is fundamental to increase structural performance and durability. Connections between different walls and horizontal timber structures, improves building's structural behaviour, by increasing the level of interlocking between the different structural elements. [168,194].

When needed, openings are created into masonry fabric and improvements are applied on the edges, either by using large-size stone blocks, see Fig. 6.8d and e, or by building an edge by alternating headers and bondstones see Fig. 6.8c. A few cases of edges built with artisanal clay bricks were seen. Most common improvement solution was to use of large-size hammer-dressed jamb stones covering the full wall's thickness, interlocked to cross-sections by large headers, see Fig. 6.8d and f. Lintels were generally formed by two large-size hammer-dressed stone blocks placed over the edges, being the external lintel's bottom face an average of 0.03 m lower than the internal one, see Fig. 6.8c to g. Cases of both, or just the interior lintel, made in timber, were also observed. To protect lintels from excessive loads, shallow, flat, or triangular-shaped arches were typically built over them to divert load to the edges, see Fig. 6.8f. Cases of the use logs for the same purpose were also identified. In higher standard buildings, particularly *"bourgeois"* and *"brazilian"* houses, jamb stones and lintels were also used as decorative elements. In these buildings, the construction of granite *"sacadas"* (short balcony with the size of the door) was common.

In windows, a single wythe stone masonry parapet was built between the jamb stones, typically 0.2 m thick and 0.9 m high, over which windows timber frames were installed. As for openings size and shape, older buildings presented predominantly quadrangular shaped windows (< 1.2 m of side), while doors and gates showed an average height of 2 m. As previously said, later high-status houses (from the mid-19th century onwards), presented windows of vertical rectangular proportion (average 1.2 m wide) and taller doors.

As shown on see Fig. 6.8a and b, interlocking different masonry walls in corners was made by overlapping, from top to bottom, headers and stretcher quoin stones, that could either be large-size stone blocks or ashlars [154]. The same technique was used to interlock intersecting walls. On rare cases, metal connectors would also be used. Connections between timber beams and trusses and load-bearing walls was performed in most cases by simply embedding these elements into cross-sections, over regular and levelled stones to avoid excessive tension points [165]. Other more elaborated solutions included to support beams over cantilever stone supports named *"cachorros"*, or over built-in plate timber beam. On improved construction quality buildings, metal connectors were used to reinforce these types of connections [162,164]. Examples are shown in Fig. 6.9.

Fig. 6.8 – Examples of load bearing walls' fragile points improvements: a and (b) improvement of schist and granite different load-bearing walls on corners (Agra mountain range, Viana do Castelo; and Padrão, Arcos de Valdevez); (c) improvement of vertical edges with bondstones (Vale, Arcos de Valdevez); (d) improvement of vertical edges with large-size and irregular stone blocks and jamb stones (Lindoso, Ponte da Barca); (e) improvement of vertical edges with large-size schist stone blocks (Agra de Cima, Caminha); (f) lintel protected by an arch (Paradela, Barcelos); (g) lintel protected by a flat arch (Ermida, Ponte da Barca).

Fig. 6.9 – Examples of connections between timber beams and load-bearing walls: (a) pavement beam embedded into the wall (Barqueiros, Barcelos); (b) pavement main support beam embedded into the wall, and supporting secondary beams (Santa Maria of Bouro, Terras de Bouro); (c) pavement support beam supported over a *"cachorro"* (Santa Maria of Bouro, Terras de Bouro); (d) roof beam embedded into the wall (Barqueiros, Barcelos).

e) Finishing works

The finishing works on vernacular buildings included the protection of the top and faces of masonry walls against water penetration and biological colonization. The top of load-bearing walls is a point of instability (lower compression) and a durability problem (rainwater infiltration). Therefore, masons improved its stability by increasing the compressive load over the top rows and by blocking access to water. To do so, the most common solution was to build a final row of larger and heavier stone blocks. On improved quality buildings, above such raw, a top lintel or cornice was built. These masonry improvement elements created suitable surface for walls' interlocking with roof's timber structural elements, but also allowed a more effective transfer of roof's load onto the walls. Roof's eaves were constructed on top of these elements. As for farm walls, except for monolithic or single wythe cross-sections, capstones were built in a large diversity of materials and geometries, as shown in Fig. 6.10's examples. These could vary from a simple final row of larger stone blocks placed as headers or stretchers, to very aesthetic elaborated capstones.

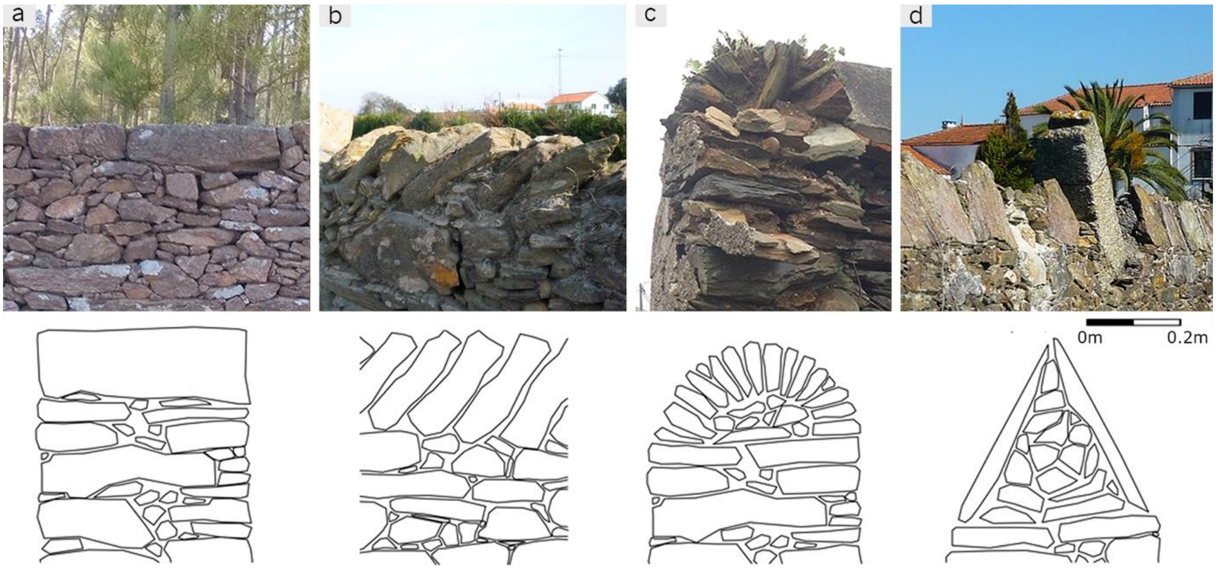


Fig. 6.10 – Examples of different types of capstones identified at the lowland schist farm walls (Barqueiros, Barcelos): a - large blocks placed horizontally; b - blocks placed with a constant slope; c - fan-shaped capstone, built with mortar; d - blocks forming a triangular capstone.

Regarding the protection of faces of masonry walls, as previously-mentioned, the most basic finishes were pointing with soil mortar and inserting thin spalls and wedges into the superficial textures' voids. Spalls and wedges were carefully hammered into place to avoid crushing them and the surrounding stone blocks.

Except for buildings constructed in ashlar masonry or regular stone blocks with narrow joints, most buildings facing the main roads were covered with soil renders. On improved quality construction, the typical granitic soil render (< 0.04 m of thickness) was improved with a final layer of lime-soil mixed mortar (< 0.01 m thickness), see Fig. 6.11d. Internal dwelling or commercial and services compartments also had render. On both cases, renders were painted with lime paint, a process named *"caiação"* [14,195]. White was a quite common colour, although yellows, reds, blues and greens were also used, see Fig. 6.11a. Lime paint had the double function of aesthetically improving buildings and protecting renders from biological colonization, due to lime caustic action on biologic agents [14,195].

As shown in Fig. 6.11b, several observed high-status farmhouses houses presented painted bands and decorative elements. In these houses, it was a common practice to paint a darker band (using oil based ink) at the basis (average 1 m of wide) and at the top of the facades (average of 0.2 m of wide) to protect walls and paint against dirt and rain water drops [127], see Fig. 6.11c.

On *“bourgeois”* and *“brazilian”* houses, it was common to use facade tiles with several different shapes and colours [12].

Concerning the dwellings’ internal walls and ceilings [195,196]:

i) Light frame walls, used either as internal partitioning walls or as structural external walls, were built with the *“tabique”* technique, and were covered with plasters and painted with lime paint [164];

ii) Timber panelled partitioning walls were painted with lime paint;

iii) Ceilings, typically not existing in kitchens of the humbler buildings, were made of timber beams and boards. These could either be horizontal or in *“masseira”* shape built in simple painted timber panels. On higher status houses, *“bourgeois”* and *“brazilian”* houses, ceilings were built in *“tabique”* covered with plaster and with plaster decorative elements, see respectively Fig. 6.12b, c, and d;

iv) Timber pavements were only polished and waxed, see Fig. 6.12a;

v) Frames and other timber decorative elements were polished and painted with oil-based paint.

Fig. 6.11 – Examples of renders and painting: (a) “saibro” yellowish and reddish render (Laúndos, Póvoa de Varzim); (b) white lime painted renders with painted yellowish frames and bands (Balazar, Póvoa de Varzim); (c) façade showing a lower darker band (Barqueiros, Barcelos); (d) example of a thick render with inner layers in *“saibro”* render, and an external layer of lime render (Barcelos).

Fig. 6.12 – Detailed view from the interior of visited vernacular buildings: (a) view of a bedroom (Fonte Boa, Esposende); (b) *“masseira”* ceiling without paint (Barqueiros, Barcelos); (c) flat ceiling built in painted timber panels (Barqueiros, Barcelos); (d) plaster *“tabique”* ceiling with a plaster decorative element at the centre (Paradela, Póvoa de Varzim).

6.2 Durability and damage overview

High structural performance and over time durability are not the outcome of one isolated feature, but from a combination of multiple variables that include construction features, environmental variables and human uses and interventions.

To build a durable masonry wall, masons paid attention to the choice and handling of building materials, but mostly to build accordantly to what is referred by several authors as *"good practice rules"* [173]. From the users point of view, a proper use and maintenance of buildings and masonry walls was required [165,168,197]. According to Roque [154] damage on masonry walls can be divided between structural damage, affecting the stability and safety of buildings, and non-structural damage, related to material's natural durability.

Regarding damage of the second group, it can be caused by excessive tension resulting from structural damage, but generally is the outcome of materials' intrinsic properties, and their adaptation to the surrounding environment (weathering) [198].

As for damage of human origin, it is related to variables sub as original conception and construction mistakes (e.g. damage during construction or masons different skills), or unappropriated uses, but also caused by abandonment or poor maintenance [154,169,173]. In Table 6.3, a resume of the most common types and causes of damage, identified during the exploratory visits is shown.

Table 6.3 – Common damage causes and types found during the exploratory visits [36].

Damage causes			Damage types	
Human actions	Structural	Non-structural	Masonry walls	Materials
• Lack or poor maintenance • Conception mistakes or poor construction • Poor interventions • Improper use changes • Changes to interior living conditions • Accidents and impacts	• Seismic events • Soil and foundation settlements • Geometric tension and compatibility • Loss of monolithic behaviour between structural elements • Load-bearing walls loss of monolithic behaviour (leaves detachment) • Unforeseen or excessive loads (in-plan/out-of-plan) • Unforeseen changes to the structural balance	• Excessive tension • Natural decay • Weathering and environmental agents (e.g. moister, temperature, wind, etc.) • Biological colonization • Mechanical, physical, and chemical incompatibilities between building materials	• Cracks, fractures and opening of joints • Compatibility joints • In an out-of-plan deformation • Partial or full desegregations • Buckling; • Partial or full collapses; • Deformation of timber elements	• Cracks, deformations, expansions, crushes, schist lamellar breakdown, material detachments • Abrasion, erosion, granular disintegration by powdering or sanding • Superficial deposits (e.g. crusts, film, or patina), salt damage (e.g. efflorescence and sub florescence), colour changes • Bedding mortar disaggregation • Superficial changes due to biological colonization (algae, lichen, moss, plants) • Rooting of timber elements; failure of connections

6.2.1 Structural damage

Concerning damage of structural origin, it represents the higher danger risk to vernacular buildings, due to the catastrophic consequences of the rupture and collapse of structural elements, normally causing the ruin of buildings. As for structural damages on vernacular load-bearing walls, they are often the result from excessive vertical and horizontal loads of multiple origin. Foundation deformations or changes in the use of building that can result on unpredictable loads, are among its most common causes. Other factors such as poor construction quality, loss of leaves interlocking or monolithic behaviour between different structural elements, are also common causes for structural damage [154,169].

Regarding excessive loads, seismic hazard represents a major threat. Earthquakes, like the ones seen in Umbria (1997), L'Áquila (2009) or more recently in Nepal (2015), show the high destructive power of these natural events over heritage buildings [186]. Several studies performed in post-earthquake scenarios showed masonry buildings' high vulnerability due to lack of safety measures of vernacular building processes or, the lack of improvement of fragile points [169,173]. Collapse mechanisms originated from seismic actions cause failure modes that can lead to immediate catastrophic collapse of masonry structures.

They are also known for causing damage that will evolve over time and are difficult to identify when there are no records of such events. Historically, the Entre-Douro-e-Minho has no significant records of seismic actions, being part in a region of low seismic hazard. Such fact explains why no specific improvements or buildings design features concerning seismic retrofitting, were identified during the exploratory visits [199].

Analysing on-going researches, masonry walls presenting low construction quality, built with poor levels of interlocking or poor quality improvement of fragile points, such as most of the majority of the Entre-Douro-e-Minho rubble or dry-stack masonries, present a medium-high seismic hazard and are vulnerable to brittle collapse mechanism [154,194].

Regarding cases of damage of structural origin, see Fig. 6.13 ahead for seen examples, cracking and partial or full ruptures (by opening of joints and disaggregation) were identified on walls showing deformations (out and in-plane). Causes were mostly related to walls foundation settlements or loss of monolithic behaviour, but also due to excessive loads resulting from changes to building's structural equilibrium (e.g. added levels or deformations on timber structural elements).

It is noteworthy the severe risk of ruin resulting from cases of collapsed timber pavements and roofs. As for the latter, it was the most catastrophic type of damage observed during the exploratory visits, either for risks to the safety of building's users, but also for the high level of destruction caused. In most cases, such type of damage immediately turns a building into a ruin. Besides the mechanical impact damage caused on load-bearing walls by the collapsing timber structures, walls become highly exposed from both sides to environmental agents. As observed, under such levels of exposure, over time decay leads to masonry walls disintegration and collapse [126].

Cracking on load-bearing masonry walls, were often observed damages of structural origin, generally resulting from opening of joints, either following diagonal (foundation settlements) or vertical paths (excessive tension), see Fig. 6.13a. On the most severe cases, it was seen that walls would fracture into different sections, some collapsing due to out-of-plane deformation, see Fig. 6.13g. On walls with renders, see Fig. 6.13b, visible cracking was normally a symptom of such type of damage. Rubble and dry-stack masonry built with smaller stone blocks showed higher susceptibly to such type of damage.

As for walls deformation, it was seen that vernacular masonry show a high capability to adapt to deformation and reach new balance, as shown in Fig. 6.13e. This process was found either in cases of excessive out-of-plan deformation of the entire vertical element or of is individual leaves (due to buckling) and by the presence of crushed and loose wedges and smaller stone blocks in walls' texture. Other types of diagonal cracks and opening of joints were common near poorly reinforced openings edges (geometric tension cracks), near timber beams and trusses embedment point, see Fig. 6.13c, or as compatibility cracks between poor interlocked walls, see Fig. 6.13f. As observed, farm walls showed higher sensitivity to such type of deformations. Cases of buckling and load-bearing walls' leaves detachment can be pointed out to poor interlocking, see Fig. 6.13d. Cases of structural damage caused by evolving severe material damage related to stone blocks natural decay or weathering were also observed.

Fig. 6.13 – Some example of structural damage seen during the exploratory visits: (a) multiple cracks caused by the opening of joints (Paço Vedro de Magalhães, Ponte da Barca); (b) vertical cracks on facade with render (Laúndos, Póvoa de Varzim); (c) partial disaggregation and collapse due to push-over load caused by a roof beam (Fonte Boa, Esposende); (d) partial disaggregation of masonry superficial texture (Vale, Arcos de Valdevez); (e) high farm wall out-of-plane deformation (Barqueiros, Barcelos); (f) deformation and opening of joints crack on farm wall corner (Barqueiros, Barcelos); (g) out-of-plane deformation caused by the loss of monolithic behaviour and deformation at the base of the wall (Laúndos, Póvoa de Varzim).

According to Barros [181], masonry superficial texture and leaves deformation and disaggregation may also result from internal horizontal loads, caused by settlements of the inner core materials and internal water pressure. The author [181] also reported cases of individual leaf deformation and detachment caused by eccentric loading over a single leaf, unable to individually support it. In the most severe cases, excessive deformation leads to partial disintegration and collapse of the deformed leaf, with the consequent reduction of the walls' cross-section. In these cases, the inner core becomes exposed to environmental agents.

6.2.2 Non-structural damage

According to Binda et al. [200], regarding the structural analysis of historical masonry, at the exception of a few cases of wall's built with regular stone blocks and joints, historical masonries mechanical behaviour cannot be directly correlated with its individual building elements. However, according to Binda et al. [168], although materials damage is generally seen as not posing and immediate hazard to the structural safety of buildings, if not attended to in time, can evolve to structural damage [160,165,198]. As observed during the exploratory visits, excessive tension imposed over the material, is responsible for causing from simple cracks to full fractures with losses of material, or for splitting larger stone blocks in smaller ones [36]. Examples of some of the seen non-structural damage are presented on Section 9.1.1, and on Section 9.2.4.

Cases of stone blocks' disaggregation caused by crushing were a common type of damage seen. In the case of schist stone blocks exposed to excessive tension and crushing, lamellar disaggregation is frequent [126,184]. Along with materials' natural durability and resistances, environmental conditions contribute decisively to increase decay and to reduce their mechanical performance.

Weathering damage mechanisms are a consequence of the interaction of rock's minerals with local climate. According to Aires-Barros [198], this is a dynamic process of physical, chemical and biological origin that tend to act simultaneously over rocks, either in their natural state or as masonry elements. Therefore, according to the author [198], causes for damage can either have an endogenous or exogenous origin, and damage can either be of physical origin, through disaggregation, or of chemical origin, by decomposition. Concerning such type o damage, masonry without renders and with larger and opened joints, present lower protection against different environmental agents, in particularly to water [198]. During the exploratory visits, weathering effects seen on exposed masonry stones were overwhelming, causing superficial changes, particularly visible in schist masonry due to this rock's rich colour patterns. Observed damage included from different types of deposits formation, to discoloration (e.g. crusts, film or patina formation), and mechanical damage with material loss (e.g. cracks, superficial disintegration or material detachments) [36]. Salt and frost weathering are analysed on Chapter 8.

As for the observed biological damage mechanisms, these are of simultaneously biophysical and biochemical origin [198]. Micro-organism such as germs and fungi colonise stones' surfaces that are not protected by render and penetrate existing imperfections. Along with aspect changes, the organic acids produced by these species are known to cause chemical damage on rocks [198]. With the increase in size of the colonising specie, mechanical damage occurs by the penetration of roots either into stone blocks through small imperfections and superficial cracks (e.g. lichen), or into masonry walls superficial textures voids or joints (e.g. larger vegetal species) [174]. Species such as bushes or nearby trees, by their size and large roots often cause push-over actions on masonry walls, leading to their collapse.

As seen during the exploratory visits, damage caused by biological weathering is responsible for all sorts of superficial changes on stone blocks, see Fig. 6.14a, including a certain level of superficial disaggregation. Colonization of renders and mortars causing disaggregation was identified as resulting from the presence of moister [201], either due to rising dump or by its accumulation in render imperfection.

The colonization of masonries by plants or other large-size species is the outcome of soil deposits' formation and water accumulation at the top and in superficial textures' voids, see Fig. 6.14b. As observed, over time disaggregation and collapse are the most expectable outcomes. Dry-stack masonry, especially when built in smaller schist stone blocks or single wythe, are highly susceptible to large-size species colonization. Therefore, penetrating roots were identified as causing the disaggregation of cross-sections, foundations, and corbelled dome structures.

Nearby colonization by trees or bushes represent a structural threat, to both stronger and more fragile walls. These species are known to cause to push-over actions that overtime lead wall's to deform and eventually to collapse, see Fig. 6.14c. Animal actions can also cause damage, either physical damage by abrasion or contact, or chemical damage by contact with animal excrement [198]. This type of damage was observed in areas with close contact with livestock such as stables or corbelled dome livestock shelters.

Fig. 6.14 – Examples of seen non-structural damage caused by biological colonization: (a) micro species colonization on exposed granite wall showing a large structural crack (Ermida, Ponte da Barca); (b) several smaller and a large-size specie colonizing abandoned rural house (Vila Nova de Muía, Ponte da Barca); (c) collapse on dry-stack wall caused by tree (Paradela, Barcelos).

Concerning timber structures and frames, it was observed that constant presence of moister and poor ventilation, particularly on abandoned and without use buildings, leads to severe biological colonization (e.g. fungi or insects), causing losses of cross-section and deformations [160], see Fig. 6.15a and b. The rotting of timber elements was a common type of damage identified in buildings with severe presence of moister, in many examples related to lack of maintenance [160], see Fig. 6.15c. As observed and shown Fig. 6.15d, such type of damage frequently evolves to severe structural damage, caused by the combination of timber elements deformation, joints failures and the rupture of the connections to the load-bearing walls [160,164].

Fig. 6.15 – Examples of damage seen on timber structures: (a) insect colonization on pavement beam (Barqueiros, Barcelos); (b) rotting of timber pavement due to infiltration from the roof (Barqueiros, Barcelos); (c) decaying roof structure due to the loss of the roof tiles (Tumio, Paredes de Coura); (d) building in ruins due to collapsed roof (Vila Nova de Muía, Ponte da Barca).

6.2.3 Human caused damage

Although in most cases not being the direct cause, as observed during the exploratory visits, the over time effect of human actions over Entre-Douro-e-Minho vernacular buildings frequently resulted on structural and material damage. As explained in Section 3.2, the mid-20th century changes to the rural way of life [12,14], caused significant changes in the way rural populations saw and used their buildings. From the contact with local populations during the exploratory visits, as previously-mentioned, it was noticed the strong will not to adapt, but to radically transform or replace owned vernacular buildings for new and more contemporary buildings. At the exception of the high status buildings, it was seen that humbler vernacular buildings either underwent a systematic destruction and replacement by new building, or underwent profound upgrades that compromised their identity [126]. It is noteworthy, the difficulties felt during the exploratory visits in the lowland, to find examples of smaller rural houses and farmhouses. Fig. 6.16 shows three of the most common types of such destruction and losses of authenticity and identity, observed during the exploratory visits.

Fig. 6.16 – Examples of human caused damage over vernacular heritage: (a) state of ruin caused by abandonment (Arcozelo, Ponte de Lima); (b) loss of authenticity and identity of vernacular building due to poorly planned changes (Padrão, Arcos de Valdevez); (c) "branda" loss of identity due to the introduction of foreign models and building materials (*"branda"* of Gorbelas, Arcos de Valdevez).

Along with other factors such as an unappropriated legal frame work, poor preparation and severe loss of traditional constructive knowledge from behalf of technicians and builders, a widespread phenomenon of illegal and uncontrolled construction related to easy access to industrial building materials, increased drastically the above-described phenomena. [12,14,16].

Form the exploratory visits, it was concluded that a considerable share of the observed damage and durability issues are the outcome of maintenance problems. According to literature on the topic, proper maintenance is a major contributing factor to durability and longevity of buildings [186,202]. As observed in more isolated areas, the strong rural exodus and the ageing of the remaining population increased significantly the number of vernacular buildings abandoned, uninhabitable and unusable, that deprived of maintenance, will become ruins. In the remaining territory, either in buildings without or still in use, a general panorama of neglected or poorly performed maintenance, in most cases using inappropriate materials and building techniques, was identified. Regarding the latter, such type of maintenance aggravates severe losses of authenticity and identity.

Identified structural damage of human origin, is often caused by poor interventions such as the removal of structural elements, by adding or replacing vernacular structural elements by new structural concrete elements (e.g. slabs or entire new storeys), or simply caused by excessive loads related to changes in uses [161,186,203]. As for the above-described interventions, when in concrete elements, often result on adding unforeseen loads to vernacular structures, that negatively alter buildings' structural equilibrium.

According to Binda [204], concerning common practices for seismic retrofitting of historical buildings in Italy, the risk of structural damage in face of seismic events grows in cases of improper use of contemporary building materials and techniques, when performing rehabilitation interventions in historical buildings. The lack of technical skills performing such interventions, and of knowledge about material and structural compatibilities significantly increase such hazards [169]. Changes to the use of soil and to its compactness, either by added loads from new nearby buildings or landfills construction, or related to changing water table levels, often originate typical geometric compatibility and settlements crack patterns [203]. Other identified human caused for damages, were poor initial construction quality, conceptions and design mistakes or over time poor repairs [154,167], see Fig. 6.17c.

As shown in Fig. 6.17a and b, the previously mentioned lack of knowledge and technical skills using vernacular and new materials and building techniques, was identified as source of systematic material damage, caused by physical and chemical incompatibilities between new and original materials. Other causes were the frequent replacement of vernacular mortars and lime paint, by concrete base mortars and synthetic and plastic paints. These add potentially damaging chemicals to stone blocks, and act as a barrier to masonry internal humidity evaporation. Seen damage varied from soil mortars disaggregation to superficial cracks, and chemically caused disaggregation on stone blocks, see Fig. 6.17a and b [205]. Authenticity losses and damage were also identified as resulting from the inappropriate introduction of new infrastructure, see Fig. 6.17c, such as electric and water infrastructure.

Among these, a stronger impact resulted from upgrading vernacular buildings with contemporary kitchens and sanitary installations. When poorly performed, these interventions often caused water leaks and infiltrations with devastating consequences to soil mortars and timber elements [126]. Attempts to improve internal environmental conditions by replacing traditional timber frames with aluminium or PVC frames, or by adding thermal insulation without taken into attention to necessary ventilation conditions, were identified as causes of damage. As observed, changes on dwellings internal hygroscopic and thermic balances resulted in higher levels of internal humidity and moister, causing deformation and rooting of timber elements, disaggregation of soil renders and the constant presence of fungi and molds inside dwellings [161], therefore reducing the internal air's quality.

Fig. 6.17 – Some of the typical example of poor intervention on vernacular buildings found during the exploratory visits: (a) the use of incompatible materials (Barqueiros, Barcelos); (b) the insertion of metal elements on stone blocks (Ermida, Ponte da Barca); (c) new infrastructures poorly introduced (Balazar, Póvoa de Varzim); (d) unsuitable reinforcement solutions (Antas, Esposende).

6.3 Final remarks

Using the exploratory visits as a source of information, it was possible to obtain a global overview regarding the Enter-Douro-e-Minho vernacular building tradition. As expected, typical regional structural system of load-bearing walls supporting timber pavements and roofs, is the prevailing structural system in the analysed vernacular architecture. Observed exceptions were the use of corbelling techniques at the highland's temporary mountain range settlements, and very specific cases where stone slabs replaced timber pavements (e.g. the fireplace slab) or were used as roofing solution (e.g. waster mills or communitarian ovens observed in the Laboreiro plateau). For its availability, granites and schists were the main masonry load-bearing walls' building materials.

Stone blocks were used either for dry-stack or mortar bonded masonry construction. Building masonry with schists required extra attention to these rocks' natural foliation. The use of soil for mortars was common if possible. The use of lime was restricted to availability or economic capability.

Availability of wood made it the main material for pavements, roofs, but also for the construction of light frame structures such as partition walls, ceilings, and all sorts of frames. Ceramic products of artisanal origin such as roof tiles were widely used and replaced straw roofing solutions.

From the exploratory visits, it was clear the regional diversity of vernacular cross-sections, superficial masonry textures and finishes solutions. As seen, extra care was put by masons on improving load-bearing walls structural performance and durability, by improving walls' fragile points and connections between buildings' different structural elements.

As for the identified damage, field observation revealed local vernacular masonries high deformation capability, proving being able to sustain severe deformation and structural damage without collapsing. However, structural cracks and partial collapses were a common type of observed damage. For the severity of its consequences, the rupture and collapse of timber roofs often caused the ruin of buildings and, although taken longer, the rupture of the load-bearing walls. As for material damage on stone blocks, granites showed higher resilience. Schists showed lower structural performance related to its strong foliation and risks of lamellar disaggregation, but also to higher susceptible to salt damage.

Being the survey are predominantly a rural environment, observed biological colonization on masonry is overwhelming. Human actions seem the strongest and most devastating cause of damage on Enter-Douro-e-Minho vernacular architecture. Such circumstance can be point to severe lack of maintenance and abandonment of rural buildings, but also by the low value recognition given to humbler or lower status rural houses and farmhouses. Therefore, the lack of technical skills, illegal construction and very poor interventions were identified as another major cause for severe damage and loss of authenticity and identity on the observed vernacular buildings.

As a final note, results from the exploratory visits show that most of the existing Entre-Douro-e-Minho heritage is endangered and facing the loss of their cultural value, either due to ruin caused by abandonment, but also by facing destruction when buildings are still in use, due to lack of knowledge and technical skills, strong real estate and touristic pressure handled without any kind of control or care.

Chapter 7

EXPERIMENTAL CARACTERIZATION OF STONES FROM VERNACULAR BUILDINGS

As previously mentioned, preservation good practices require to properly know heritage materials from a technical point of view [49]. By doing so, better, and precise damage diagnosis can be achieved, and therefore, more effective solutions can be designed and implemented. Whereas international quality standards such as the EN (European Standards), ISO (International Organization for Standardization) or the ASTM (American Society for Testing and Materials) allow precise knowledge regarding standard materials behaviours, such a knowledge is scarce for vernacular materials. To acquire the same level of knowledge, and therefore promoting compatibility between new and vernacular and reducing potential sources of future damage, represents a challenge to industry and researchers [206,207]. According to scientific literature, several different types of testing can be used to determine materials physical and mechanical behaviours [193,208]. Such experimental procedures may be categorize between on-site and laboratorial testing, and can be complemented by advanced mathematical simulations [193,209,210]. Nonetheless, the use of such advanced tools poses difficulties on their applicability to vernacular heritage. On one hand, the use of some procedures requires inflicting a certain level of damage, unacceptable on highly valuable heritage. On the other hand, the level of investment involved overshoots the economic capability of common interventions on vernacular heritage buildings.

By applying simple non-invasive techniques or NDT (Non-Destructive Testing), it is possible to analyse building's parameters such as humidity levels, materials superficial integrity and all types of visual data such as visible deformation and damages. Regarding mechanical parameters, it is possible to apply some NDT techniques (e.g. geo-radar, x-ray, dynamic identification, or real-time monitoring) to estimate strength, flexural or tensile resistances. However, invasive techniques or DT (Destructive testing - e.g. uniaxial and diagonal compression testing, or the removal of specimens for laboratory testing) are still required to determine with scientific precision such resistances.

To overcome such difficulty, the replication of existent elements under laboratory conditions is a common solution (e.g. using specimens of materials, small wallets, or masonry panels). Although laboratorial replication of real conditions is considered as a reliable alternative, results must be interpreted with care for being a limited simulation of real parameters. As a compromise solution, less invasive techniques such as flat jacks and tube-jack techniques are being developed to collect on-site mechanical data. Sonic-based analysis are also extensively used and developed to better understand materials under their natural service environment [211,212].

Growing data libraries regarding vernacular materials and construction systems, mostly collected in recent decades, are used as support for mathematical simulation techniques, that along with on-site information (e.g. through visual inspections or dynamic identification data), helps to replicate and to study structural behaviours. With the use of advanced survey techniques such as laser scanners, the level of geometric and detail accuracy of models allows deeper knowledge of heritage architectural features, and the creation of advanced mathematical structural models [213,214].

Regarding testing in non-monumental or vernacular buildings, the cost for such elaborated techniques often makes them not an option. As a counter measure, the use of existing scientific and technical data libraries regarding similar materials and construction solutions may be an option.

Therefore, to assist technicians and researchers in the effort of preserving and rehabilitating the Entre-Douro-e-Minho vernacular heritage, representative types of rocks used for centuries as masonry materials were experimentally characterized. To set an example of the potential of using experimental techniques and the type of technical data required to assist vernacular heritage interventions, representative materials were collected from two case studies: *i)* schist farm walls built in ordinary schist masonry with soil used as mortar, typical from the lowland; *ii)* granite from the corbelled dome shelters, built in dry stack masonry, typical from the highland (see Section 9.2 for further information). The case studies were selected not only for the specific preservation challenges they represent, but also for the very scarce scientific literature on their building materials.

The design of the experimental campaign presented in the following sections was based on literature examples [175,181,182]. Due to the very scarce scientific and technical knowledge on the topic, and the growing industry investment around vernacular architecture rehabilitation, the knowledge produced during the experimental campaign, described herein, contributes to the ongoing research on the topic, and to the growth of this sector of the national economy.

7.1 Experimental campaign

From the most common types of rocks used for centuries to build masonry, schist and granite blocks were collected and tested at the LEST – Laboratory of Structures, University of Minho, to determine basic physical and mechanical properties. Durability assessment for both types of rocks will be presented in the following chapter. Special attention was given to determine the existence and influence of foliation or preferred orientation over these rocks performance and natural resistances [174,178,179,184,215,216]. For their known influence over rocks natural durability and resistances, water absorption behaviours were analysed for both types of rocks [174,178,179,184,215,216]. Due to the scarcity of reliable technical information, a strong effort was put into the characterization of the Entre-Douro-e-Minho schists, with special attention paid to the influence of anisotropy over their physical and mechanical performance [178,181].

Representative granite and schist large-size stone blocks were recovered either from case studies demolished materials (farm walls) or from nearby (corbelled dome shelters), and sawn into laboratory specimens, see Fig. 7.1. As quality criterion, damaged stone blocks were rejected, either on-site or later if damage was detected during specimen's preparation process. In these cases, a spare stone block would be used to replace the damaged one. To ensure reliable comparison between the different analysed parameters, each large-size stone block was cut into the several different types of specimens used throughout the experimental campaign (see each testing for specimens' sizes and quantity).

Due to the average size of stone blocks used and available in the study area, for the specific geometry of the prismatic specimens used for flexural testing, these were sawn from additional stone blocks of the same types of rocks used to saw all the other remaining specimens. Therefore, no correlations are presented when analysing the tested rocks flexural behaviour.

As shown in Fig. 7.1, specimens were cut using a diamond blade saw, and according to their natural bedding orientation, following existing foliation or preferred orientations, as required by the criteria specified on the NP EN 1926:2000 standard [217].

On well-defined foliation XL and XR schist, and for being clearly distinguishable to the naked eye, foliation orientation was defined by visual inspection. On poorly-defined foliation XA and XM schists, foliation directions were confirmed by using UPV. Regarding GA and GE granites, a preferred orientation was identified and confirmed by UPV. According to each testing specific aims, specimens of each stone block were tested in both normal (N) and parallel (P1 and P2) directions to foliation, as shown in Fig. 7.2.

Fig. 7.1 – Examples of 50×50×50 mm^3 specimens of each different type of rock tested (see Section 6.1) for rocks geological characterization.

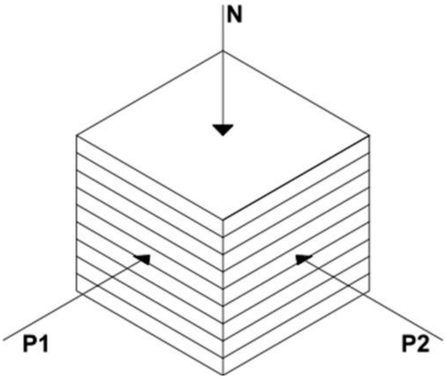


Fig. 7.2 – Schematic representation of specimens' anisotropic directions according to foliation based in NP EN 1926:2000 [6].

Regarding the tests performed during the experimental campaign, their selection took into consideration a suitable cost/benefit ratio between investment/data output and the level of information required for a simple preservation and rehabilitation intervention. NDT techniques were used for rocks physical characterization, whereas indispensable DT techniques were used for mechanical characterization. The implementation of the experimental campaign followed the same basic procedure for all specimens. First, all specimens were tested for physical characterization, and afterwards, uniformly divided into groups to be destructively tested for different mechanical characterization or durability assessment. Therefore, each source stone block, corresponding to a specific type of rock, was tested throughout the entire experimental campaign, except for the previously mentioned exception. In this way, a more accurate and complete overview regarding rocks global characterization was achieved.

However, rocks are known to be affected by a very wide range of variables that range from natural and mineralogical features, to the influence of pre-existing weathering effects. (e.g. heterogeneous mineral organization, areas exposed to environmental agents in masonry or natural cracks or voids). Therefore, based in preliminary experimental results and literature, it was considered that due to the nature of the material, a maximum coefficient of variation of 25% would be considered as an acceptable range. Outliers identification and statistic treatment was based on ASTM E178-02 [218].

To be noticed, the tested rocks are certainly weathered materials as they are materials under service conditions and exposed to environmental agents for decades or centuries (unknown dating). Therefore, such results must be interpreted with care. Common weathering changes may be related to surface and colour changes, porosity or mechanical strength performance losses [178]. Since no vernacular stone quarry is still operating (most since the mid-20th century), it was not possible to collect non-weathered rock specimens, any attempt to rate with precision these rocks for their weathering level become unfeasible.

7.2 Physical characterization

Bell [178] highlights that natural durability of rocks is not an exclusive outcome of the action of weathering agents over rock masses, but in fact, decisively influenced by rocks intrinsic features such as the area of internal surface created by the mineral arrangement and type of grain, texture, porosity, natural strength and internal discontinuities [179,219,220].

Regarding porosity, it is influenced by features such as mineral heterogeneity and the bonding and closeness between grains [219]. On rocks, Bell [178] points out to higher levels of porosity as directly responsible for lower densities and strengths, therefore, for higher deformability. Taking into consideration the effect of weathering over porosity, Bell [178] points to grain break-up caused by weathering, as directly responsible for higher porosity levels, particularly on rocks highly exposed to water and salts [178,179,216,221]. Also related to porosity, rocks capillary dynamics is regulated by pore size, geometry, distribution and interconnectivity [179,216,219,220]. Therefore, porosity also plays an important role on rocks water absorption, desorption and internal mobility [179,216,219,220], being pore size distribution responsible for capillary absorption, saturation and drying. Buj et al. [220] points out the percentage of pore throats inferior to 0.1 μm, for their strong influence over water saturation degree, critical content and retention. Mineral composition is referred to by the author [220] for influencing fluid transport dynamics.

Water is addressed in literature as responsible for directly causing mechanical (e.g. frost damage, granular disaggregation or clay swelling) and chemical damage on rock masses (e.g. by transporting salts that cause efflorescence and subflorescences) [178,179,216,221]. Water is also known for providing conditions for biological weathering (e.g. micro to large-size species colonization) [178,179,216,221].

According to Charola et al. [221], water penetrates by capillarity due to a combination between superficial tension of the liquid, capillary and water attraction. According to the author [221], water penetrates through infiltration as vapour, due to hydrostatic pressure and natural permeability of rocks. These phenomena rely on atmospheric conditions (saturation and pressure) and temperature differentials (between air and rock surfaces) [179]. Moister capillary absorption is further described by Winkler [179] as the outcome of electrostatic attraction in capillaries under 0.1 μm, in which water's H^+ ions (positive) are attracted by pore walls (negative). The intensity of the charge decreases as porous increase in size. Charola et al. [221] points out that once inside, water can migrate as moisture through interconnected porous, or as vapour by diffusion. In the first, water can transport salts, and in the latter, it can be retained by hygroscopicity, thus forming ice crystals at specific lower temperatures.

The critical moisture content of a rock is defined as the transition point between both above-described mechanisms [178,221]. As shown in Fig. 7.3a, Winkler [179] highlights to water mobility capability, either on horizontal or vertical direction, reaching twice as far in the first. Due to drying and atmospheric absorption under suitable temperature and pressure conditions, according to the author [179], water mobility is directed outwards. Capillary rising from the ground into masonry, see Fig. 7.3b, is pointed as major durability concern, due to water salt transport capability [178,179,216]. Winkler points to a variation of vertical capillary rising from 3 m to 10 m in porous diameters range of 20 μm to 6 μm, and to 10 m to 30 m in porous diameters of 6 μm to 2 μm. Therefore, as shown in Fig. 7.3c, lower diameters allow faster and higher water travelling on rocks.

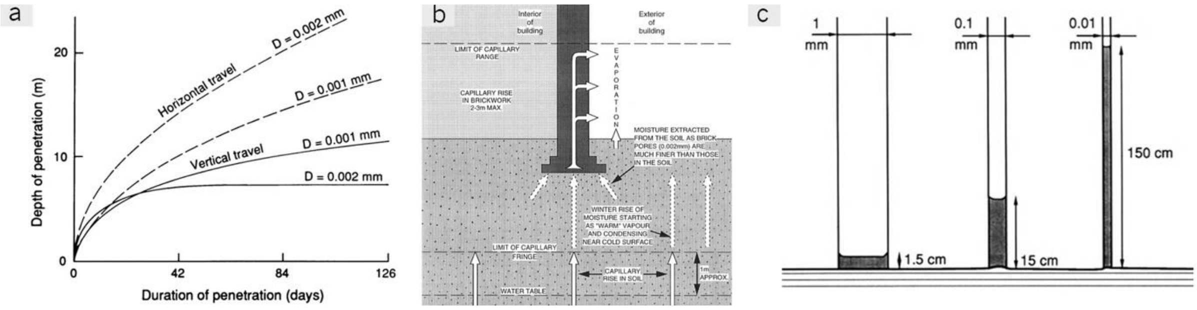


Fig. 7.3 – (a) example of water horizontal and vertical travel in masonry (after Winkler [179]); (b) schematic model of capillary rising in masonry walls of buildings (after Goudie [216]); (c) influence of capillary diameter on water rising (after Winkler [179]).

Besides porosity, either being foliation, natural voids or microcracks, internal discontinuities on rock masses also contribute decisively to rocks mechanical performance and durability [178,179]. Ultrasonic pulse velocity (UPV) is recognized as a potential and reliable NDT method of assessing the soundness rock masses [179]. By recording UPV transit time on a specific rock mass, with the use of mathematical correlations, it becomes possible to estimate several of its physical and mechanical parameters [212,222]. The method is based on the physical principle of wave pulse propagation in a specific environment that causes particles to oscillate, and results on an oscillatory movement around its equilibrium position [223]. Therefore, on rocks, P-waves are commonly used to estimate basic physical properties (e.g. anisotropy or porosity) and the state of decay (e.g. frost and salt damage or microcracks) [179,184,212,222,224–226]. According to Naik et al. [222], for relying on the elastic properties and mass of materials, by knowing these two parameters, it becomes possible the use UPV to estimate elastic properties and strength [222].

The identification of internal discontinuities is based in the principle, described by Vasanelli et al. [226], that energy propagation is faster in mass or water, but slower in air environments. When crossing different environments, depending on the used frequencies (kHz), a loss of energy and a decrease of wave amplitude and propagation velocity happens, making it possible to assess the existence of internal discontinuities inside masses such as rocks [179,222]. Therefore conditions for low or decreasing of UPV propagation can be related to intrinsic features of rocks such as porosity or the level interlocking between grains, but also due to the existence of microcracks or internal voids [179,212,226,227]. On the other hand, high or increasing UPV on rocks can be related to low porosity, high levels of homogeneous mineral arrangements with strong grain interlocking or high clay content [179,212,226,227]. Vasanelli et al. [226] points out a typical UPV limited increase tendency, caused by moisture saturation. As water fills porous and voids, it creates a more favourable pulse propagation environment. However, according to the author [226], cases were reported of rocks with high porosity or clay content that show a valid UPV decrease tendency. According to Karakul et al. [227] schistosity is also known to cause UPV measurements variations. Although the inherent potential of use of UPV based assessment methodologies, Winkler [179] highlights the difficulties regarding the interpretation of UPV results when dealing with natural materials, due to their frequent high physical and mechanical variability and a variety of unforeseen circumstances.

7.2.1 Porosity and density characterization

The tested schist and granite specimens were analysed for porosity and density according to the experimental procedures presented in EN 1936:2006 [228] standard. Therefore, specimens were tested and characterized for open porosity (ρ_o), apparent density (ρ_b), volume of open porous (V_o) and apparent volume (V_b). For each rock, reference and weathered rocks results are presented in Table 7.1, whereas specimens' individual results are presented in Fig. 7.4. In Fig. 7.5, valid correlation (R^2>0.7) between the different test parameters are presented. The tested rocks were rated for porosity content accordingly with the porosity classification for hard and soft rocks from the International Association for Engineering Geology (IAEG*) [229]. This classification distinguishes porosity into five categories as follows: very high (VH; > 30%); high (H; 30% – 15%); medium (M; 15% – 5%); low (L; 5% – 1%); very low (VL; < 1%).

Analysing results in Table 7.1 and Fig. 7.4, the tested schists show higher average ρ_o and V_o and, therefore, lower ρ_b in comparison with the granites. Regarding v_b results, although similar for all rocks, values obtained for granites and XA schists are slightly higher. Regarding the CoVs in Table 7.1 and individual specimens results for ρ_o and ρ_b, shown in Fig. 7.4, higher scattering is visible regarding porosity results, whereas inferior for density results.

Analysing correlations between the different physical parameters, as expected, an increase on open porosity is matched by a decrease on apparent density. As shown in Fig. 7.5, good linear correlations were found for ρ_o, ρ_b and V_o parameters, showing a direct relation between porosity increase and density decrease. However, no valid correlations were found for V_b. Therefore, V_b values may be influenced by other physical parameters of the studied rocks (e.g. foliation or internal voids).

Regarding schists, results are very similar, with just very slight variations. XR specimens (ρ_o – 20.7%; V_o – 26.3 ml; ρ_b – 2192 kg/m^3) show the higher ρ_o and V_o values, whereas the lower ρ_b values among the tested rocks. However, regarding ρ_b values, results are consistently higher for poorly-foliated schist (XA – 2375 kg/m^3; XM – 2353 kg/m^3) in comparison with well-defined foliation schists (XL – 2273 kg/m^3 and; XR – 2192 kg/m^3. Results among granites are consistent, and show the lower ρ_o and V_o values, slightly lower for GE (ρ_o – 3.3%; V_o – 4.7 ml) in comparison with GA (ρ_o – 4.7%; V_o – 6.3 ml), and the higher ρ_b (GE – 2552 kg/m^3; GA – 2503 kg/m^3) values among the tested rocks. Regarding results for dry m_d, saturated m_s and immerse m_i mass results, the denser granites show higher average values, whereas the less dense well-defined foliation schists show the lower average values.

The different types of grain and foliation regularity seem to play a key role on the results regarding porosity and density, with medium (XA and XM) and coarse-grain (GA and GE) rocks clearly showing higher ρ_b results in comparison with the fine-grain rocks (XL and XR). Applying the IAGE classification to rate and compare the tested and reference rocks, the analysed schists were rated as high porosity rocks H, and the granites as low porosity rocks L. Taken into consideration ρ_o and ρ_b values of the reference rocks shown in Table 7.1, it is clear the resemblance between results for the tested schists and granites, and results for the reference weathered rocks. Therefore, in the absence of direct fresh values, meaning non-weathered rocks or recently extracted at the quarry, regarding the rocks under analysis and by a comparison criterion, the tested rocks are considered as weathered.

Table 7.1 – Porosity and density tests results (EN 1936:2006 [228]).

Rocks	Dry Density m_d (g/cm^3)	Saturated Density m_s (g/cm^3)	Immersed Density m_i (g/cm^3)	Open Porosity ρ_o (%)	IAEG* [229]	Apparent Density ρ_b (kg/m^3)	Volume of Open Porous V_o (ml)	Apparent Volume V_b (ml)
XL	2.26 (4%) [2.15 – 2.51]	2.42 (3%) [2.26 – 2.63]	1.43 (4%) [1.34 – 1.55]	15.8 (19%) [11.7 – 23.1]	H	2273 (2%) [2177 – 2337]	19.7 (20%) [13.5 – 29.5]	124.6 (3%) [115.2 – 135.8]
XR	2.23 (2%) [2.13 – 2.32]	2.44 (2%) [2.34 – 2.52]	1.42 (2%) [1.36 – 1.48]	20.7 (7%) [18.6 – 23.7]	H	2192 (2%) [2111 – 2285]	26.3 (8%) [23.7 – 30.9]	126.9 (2%) [119.8 – 130.2]
XA	2.49 (4%) [2.30 – 2.59]	2.65 (3%) [2.47 – 2.74]	1.61 (4%) [1.49 – 1.67]	15.6 (9%) [13.5 – 18.0]	H	2375 (2%) [2306 – 2420]	20.5 (8%) [17.9 – 23.6]	131.0 (2%) [123.3 – 134.3]
XM	2.40 (5%) [2.07 – 2.48]	2.57 (3%) [2.31 – 2.66]	1.55 (5%) [1.34 – 1.62]	16.6 (18%) [12.7 – 24.9]	H	2353 (4%) [2138 – 2458]	21.1 (17%) [16.03 – 30.6]	127.7 (2%) [121.2 – 136.4]
Ref. fresh or non-weathered schists [230]				0.4 – 3.4	VL – L	2550 – 2990	n.a.	n.a.
Ref. weathered schists [231]				16.8 – 29.6	H	1968 – 2288	n.a.	n.a.
GA	2.67 (1%) [2.60 – 2.70]	2.72 (1%) [2.65 – 2.75]	1.65 (1%) [1.62 – 1.69]	4.7 (13%) [3.9 – 5.7]	L	2503 (1%) [2450 – 2554]	6.3 (13%) [5.3 – 7.6]	133.3 (1%) [129.9 – 137.3]
GE	2.68 (2%) [2.61 – 2.77]	2.72 (1%) [2.66 – 2.80]	1.67 (2%) [1.62 – 1.73]	3.3 (13%) [2.4 – 5.9]	L	2552 (1%) [2468 – 2600]	4.7 (18%) [3.2 – 7.7]	131.35 (1%) [128.2 – 135.0]
Ref. fresh or non-weathered granites [230]				0.1 - 3.4	VL – L	2550 – 2990	n.a.	n.a.
Ref. weathered granites [182]				1.6 – 7.2	L – M	2466 – 2646	n.a.	n.a.

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets. * IAGE Porosity Classification for Hard and Soft Rocks.

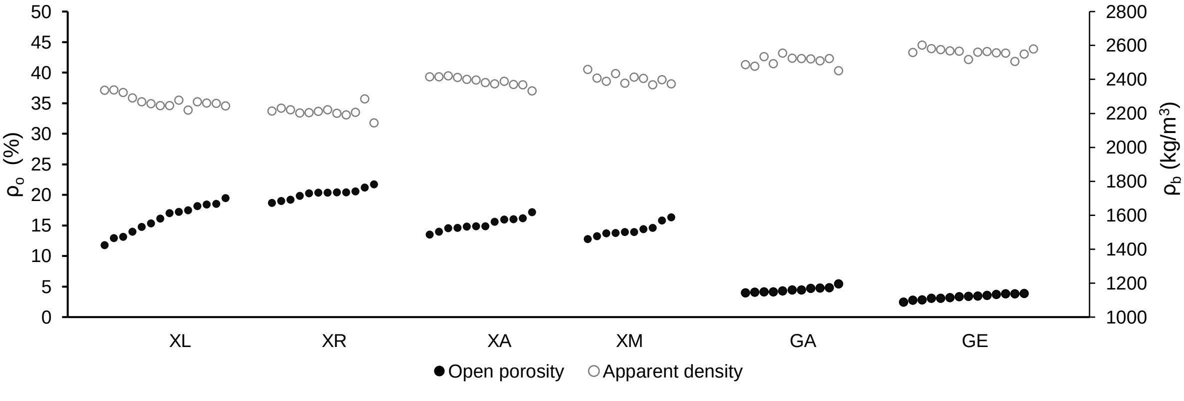


Fig. 7.4 – Open porosity and apparent density results by specimen.

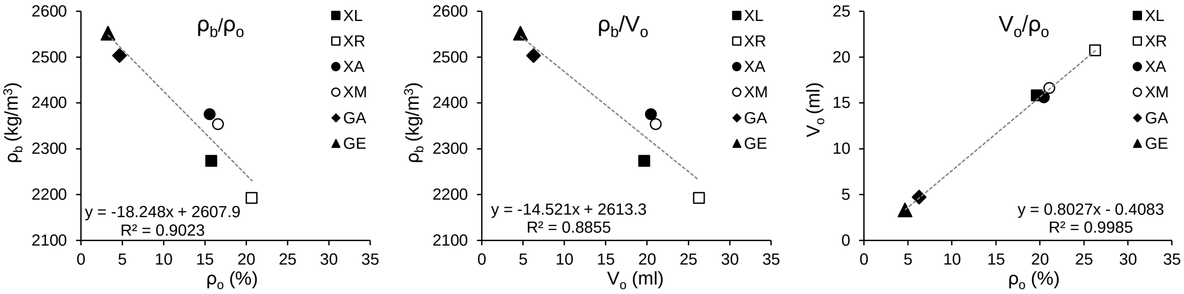


Fig. 7.5 – Linear correlations for porosity and density parameters.

7.2.2 Ultrasonic pulse velocity tests

The level of internal discontinuities on the tested schists and granites was analysed by UPV readings, performed accordingly to EN 14579:2007 [232] standard. The sonic classification for hard and soft rocks from the International Association for Engineering Geology (IAEG**) [229] was used to rate the tested rocks. This classification distinguishes sonic propagation on rocks into five categories as follows: very high (VH; > 5000 m/s); high (H; 4000 m/s – 5000 m/s); moderate (M; 3500 m/s – 4000 m/s); low (L; 2500 m/s – 3500 m/s); very low (VL; < 2500 m/s). The UPV readings were performed on sets of direct transit time measurements, made on specimens three perpendicular directions, see Fig. 7.2 (N, P1 and P2), by direct transmission method with transmitter and receiver placed between specimens' opposite parallel surfaces, as shown in Fig. 7.6.

Direct, semi-direct and indirect measurements techniques can be used to measure UPV propagation, however according to Naik et al. [222], the first method is the most reliable and accurate one taken into consideration the specific testing goals. Results (m/s) are an average of three valid readings on each direction, obtained by recording the ultrasonic pulse transit time and by knowing the distance travelled [181,222]. A Pundit Lab® equipment, with piezoelectric transmitter and receiver transducers of 150 kHz, was used, being calibrated before each measurement [212,222]. Due to small superficial irregularities, a coupling agent was applied to ensure perfect contact between transducers and surfaces. Preliminary readings revelled that schists had a high absorption rate of coupling gel type materials, typically used for such type of operations. Therefore, to avoid contaminating specimens destined for tests that required water absorption, modelling clay was used as a replacement for gel. Preliminary testing was performed to calibrate the equipment accordingly. UPV were performed on specimens under dry mass and water saturated conditions.

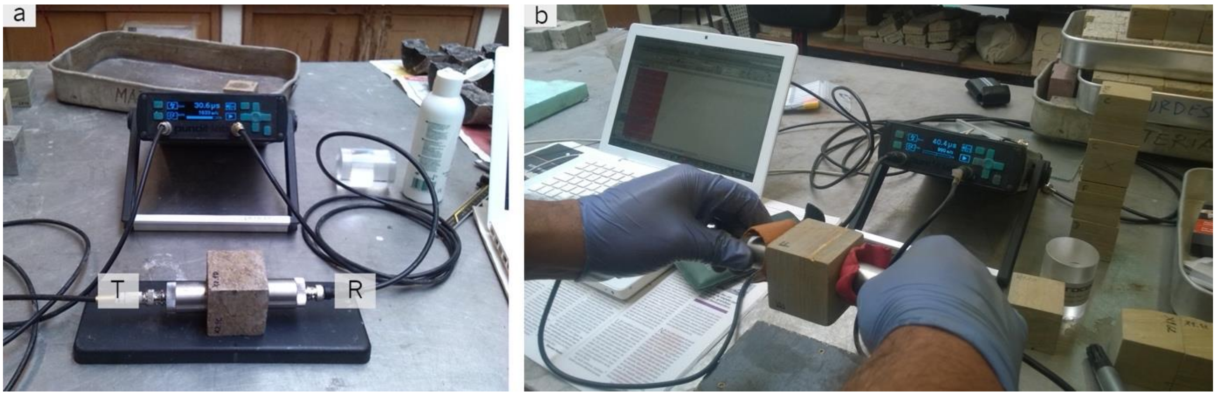


Fig. 7.6 – (a) UPV test setup (direct testing): T – transmitter; R – receiver [232]; (b) measuring UPV transit time. (b) testing procedure.

Analysing the results presented in Table 7.2, the tested rocks show different UPV values for each different direction. As shown in Table 7.2, for all tested rocks, UPV propagation is slower in N direction and faster in P directions. Direction P2 was assigned parallel to anisotropy direction, or preferred orientation, exhibiting the higher UPV value. Table 7.3 shows comparison ratios obtained from comparing on each rock, the propagation velocities for the three different sets of measurements.

For N direction, lower UPV propagation was recorded for well-defined foliation XL (1380 m/s) and XR (1340 m/s) specimens. For poorly-defined foliation schists, XM (1447 m/s) N direction UPV propagation is similar with XL and XR schist, whereas results for XA (2705 m/s) specimens show the highest N direction UPV propagation among the tested rocks. At the exception of the previous case, GA (2198 m/s) and GE (2117 m/s) specimens show consistent and higher N direction UPV propagation in comparison with the remaining schists. However, regarding P direction UPV propagation, well-defined foliation XL and XR schists show the higher values, an average of ≅ 1.2 times faster than on XA and XM poorly-define foliation schists, and an average of ≅ 1.8 times faster in comparison with the granites. GA (2831 m/s) and GE (2909 m/s) specimens show the slower P direction UPV propagation, 0.9 times slower in comparison with the slowest XM (3271 m/s).

Analysing P1/N and P2/N UPV propagation variation for the same type of rock, well-defined foliation XL (3; 3.8) and XR (2.8; 3.7) specimens show a large propagation velocity ratio, in comparison with the poorly-defined foliation XA (1.4; 2) and XM (2.3 and 2.8) specimens, and with GA and GE granite specimens (1.2 and 1.4 ratios). P2/P1 UPV propagation variations are similar for all rocks, with average variations of between 1.1 and 1.3. If one takes into consideration the relation between the three different sets of UPV readings, no valid correlations were found for schists, however good linear correlations were obtained for granites, see Fig. 7.8. As shown, propagation velocity seems to increase evenly for the three directions on granite specimens, although with clear prevalence of one direction over the other two. Based in these results and on specimens' individual results presented in Fig. 7.7, three clear sets of UPV values can be identified for schists, whereas two were identified for granites, pointing out the possible UPV propagation anisotropic or preferred orientation influenced behaviours.

Schists show slower UPV propagation on N direction, however faster on P directions. According to literature, causes of such effects may be related to schists typical planar structure (foliation) and schistosity [184,226,227,233,234]. On one hand, P-wave applied transversally to foliation and schistosity (N direction) must propagate through discontinuities and existing voids on the interface between the foliation layers. On the other hand, P-wave applied on parallel direction to foliation (P directions) propagate through a fine-grain and homogenous mineral arrangements environment, without clearly distinguishable voids or cracks, suitable for faster UPV propagation.

Therefore, results show that for XL and XR specimens, such type of blocking and acceleration effects are stronger, due to these rocks regular foliation and fine-grain and homogeneous mineral arrangement. Regarding XA and XM specimens, the above-described effects show lower effectiveness, due to these rocks' irregular foliation, medium-grain, and higher heterogeneous mineral arrangement. Therefore, UPV results in Fig. 7.9, show a tendency for a faster propagation on rocks directions with homogeneous mineral arrangements and slower on heterogeneous ones. These results also show that UPV propagation transversal to regular foliation is much slower that through irregular foliation. In the first case, voids seem concentrated on foliation joints, whereas in the latter seem more distributed inside rocks.

Regarding P1 and P2 variations, it may be attributed to platy-shaped grain geometry, typical of schistosity [183], but also to the foliation angle. Therefore, according to Ruedrich et al. [233], P-wave propagation velocity is affected by the angle formed between the ultrasonic pulse direction and the schistosity plan, becoming slower as the angle increases and faster in a parallel direction. To quantify the above-described anisotropic related behaviours, Apuani et al. [234] anisotropic scale (ANs) was used. Such scale is based on the variation between average maximum and minimum P-wave values for each type of rock, as followed (results in percentage):

$$ANs = \frac{\text{PARAMETER } max - \text{PARAMETER } min}{\text{PARAMETER max}} \times 100 \quad \text{(Eq. 7.1)}$$

being: PARAMETER the physical or mechanical property of the rock analysed for anisotropic behaviours; therefore, PARAMETER *max* is P2 UPV measurements and PARAMETER *min* the N UPV measurements.

The above-presented equation was also used to attribute a scale to granites preferred orientation (PFo) UPV behaviours. Results in Table 7.3 confirm an intense three direction anisotropy for XL (74%), XR (73%) and XM (64%) schists, whereas with lower intensity for XA schist (34%). Analysing any possible correlations between UPV propagation results and rocks physical parameters previously analysed, none was found. It is noteworthy that results for the tested schists do not show the expected direct relation between porosity increase and UPV propagation deceleration. As observed, UPV propagation on the tested schists is strongly influenced by other physical and intrinsic parameters that should be taken into consideration. Therefore, further research on the topic is required. According to Lindqvist et al. [235], porous shape (rounded or elongated) is known to also influence UPV propagation on magmatic (e.g. granites) and metamorphic (e.g. schist) rocks. Based in these results, natural discontinuities for the tested schists seem strongly concentrated over one anisotropic direction, generally following the existent planar structure (N), whereas being less intense on the remaining directions (P1 and P2).

Regarding the tested GA and GE granites, based on the work of Vasconcelos et al. [212], the two identified sets of UPV can be attributed to granites preferred orientation (PFo) [178], generally parallel to existing foliation on rock massifs (identified during the fieldwork) and the quarry plan. Nonetheless, existing microcracks along the preferred orientation are known to slow UPV propagation [182,235]. As expected, in comparison with GA specimens, GE specimens' lower open porosity and higher apparent density was matched by faster UPV propagation, see Table 7.2. Regarding GA and GE consistent UPV results, it may be explained by these rocks coarse-grain heterogeneous mineral arrangement without a clear and stronger planar structure (GA – 22% PFo; GE – 27% PFo). Therefore, one can conclude that existing discontinuities on the tested granites tend to a more homogeneous distribution along specimens fabric, showing a slight concentration regarding each specimen planar preferred orientation, denser microcracks concentration areas, or the presence of elongated grains [236]. Based in the above-presented observations regarding UPV propagation behaviour, one can conclude that the tested schists can be rated as anisotropic rocks, whereas granites are rated as isotropic rocks. [182,236].

Analysing the influence of water saturation over the tested rocks UPV propagation, results in Table 7.2 and Fig. 7.9 show an expected and consistent P-wave propagation velocity gain for GA and GE granites, and for XA schist. For these rocks, although with different levels of variation, a clear UPV propagation positive tendency was obtained for the three directions. Variation results in Fig. 7.10 show that GE specimens show the strongest UPV propagation gain under water saturated conditions, among the tested rocks. The same type of UPV propagation gain are consistent with the results for the reference granites shown in Table 7.2 [182]. However, regarding the XL, XR and XM schists, results show an unexpected P-wave negative propagation tendency, with velocity loss for two directions and a very slight gain on the remaining one. As shown in Fig. 7.10, for saturated conditions, the most consistent UPV velocity loss was obtained for XM specimens (P directions). As previously mentioned, although UPV propagation limited increase tendency is expected for rocks under saturated conditions [182], according to Karakul et al. [227] and Vasanelli et al. [226], UPV propagation speed decrease tendency are also valid in high porosity rocks or with high clay content.

Analysing ANs scale variations under saturated conditions for well-defined foliation XL (2.7%) and XR (-4.1%) schists, the presence of water seems to have no significant effect over the anisotropic behaviour of these rocks UPV. Instead, results for poorly-defined foliation XA (-17.6%) and XM (-23.5%) schists show a consistent effect. Regarding PFo scale variations, on one hand, GA (-4.5%) specimens show a very residual effect over its UPV propagation behaviour. On the other hand, GE (-22.2%) results show a consistent variation. Therefore, for the tested rocks, results show that water causes alterations on UPV propagation behaviours, being more consistent on both poorly-defined foliation schists and granites. Effects of weathering over UPV propagation for the tested rocks should be taken into consideration. In the absence of reference specimens (e.g. non-weathered), comparison was established with other Portuguese common rocks, presented in Table 7.2.

As previously-mentioned, higher porosities are frequently related to weathering effects [178]. Therefore, the tested schist UPV results and IAEG [229] rates are consistent with results obtained by Barros [181] for medium and low porosity schists, that show a decrease of UPV propagation with the increase of porosity. Regarding the UPV values and IAEG [229] rating for the tested granites, these are consistent with the results obtained by Vasconcelos [182] for weathered granites either under dry and saturated conditions. Thus, one can conclude that on weathered rocks, a decrease in UPV values is expected due to higher presence of internal discontinuities, caused by multiple phenomena such as grain disaggregation, microcracks, and in the case of schists, loss of lamellar cohesion [212,222].

Table 7.2 – UPV tests results for dry and water saturated conditions (EN 14579:2007 [232]).

Rocks	under dry mass conditions			IAEG* [229]	under water saturated conditions		
	N	P1	P2		N	P1	P2
XL	1380 (9%) [1240 – 1623]	4180 (4%) [3896 – 4475]	5220 (4%) [4810 – 5453]	VL H VH	1185 (8%) [1080 – 1300]	4185 (3%) [4024 – 4284]	5039 (2%) [4954 – 5162]
XR	1340 (4%) [1238 – 1458]	3775 (6%) [3389 – 4143]	5004 (8%) [4174 – 5475]	VL M VH	1367 (10%) [1228 – 1560]	3508 [5%] [3300 – 3748]	4569 (4) [4272 – 4758]
XA	2705 (13%) [1945 – 3115]	3881 (10%) [2845 – 4189]	4110 (9%) [2857 – 4409]	L M H	3260 (10%) [2878 – 3550]	3974 (3%) [3804 – 4082]	4513 (7%) [4068 – 4934]
XM	1447 (8%) [1317 – 1635]	3271 (9%) [2891 – 3885]	4057 (14%) [3162 – 4599]	VL M H	1524 (18%) [1344 – 1925]	2471 (4%) [2357 – 2605]	3010 (22%) [2026 – 3387]
Ref. medium porosity schists [181]	[626 – 2281]	[2968 – 5289]	[3783 – 5268]	VL – L L – VH M – VH	n.a.		
Ref. low porosity schists [181]	[1456 – 3692]	[2695 – 4822]	[4121 – 5712]	VL – M L – H H – VH	n.a.		
GA	2198 (9%) [1868 – 2439]	2318 (11%) [1949 – 2712]	2831 (7%) [2465 – 2831]	VL VL L	2918 (6%) [2678 – 3063]	2965 (8%) [2688 – 3286]	3697 (5%) [3519 – 3961]
GE	2117 (11%) [1793 – 2685]	2523 (10%) [2236 – 3135]	2909 (7%) [2723 – 3386]	VL L L	3192 (11%) [2638 – 3621]	3569 (6%) [3232 – 3746]	4025 (3%) [3921 – 4223]
Ref. fresh or non-weathered [182]	[2060 – 4040]**			VL H	[3271 – 4395]**		
Ref. weathered granites [182]	[1987 – 3586]**			VL M	[3289 – 5072]**		

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets. * IAGE Sonic velocity classes for hard and soft rocks. **average values for N, P1 and P2 directions.

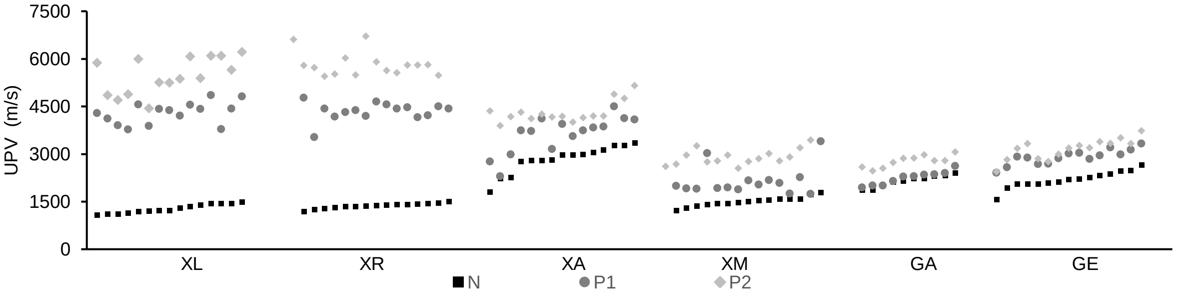


Fig. 7.7 – UPV results by specimen (dry conditions).

Table 7.3 – Comparison between the three UPV directions, anisotropy (ANs) and preferred orientation (PFo) scale.

Rocks	under dry mass conditions					under water saturated conditions				
	P1/N	P2/N	P1/P2	ANs [234]	PFo [234]	P1/N	P2/N	P1/P2	ANs [234]	PFo [234]
XL	3.0	3.8	1.2	74%	-	3.5	4.3	1.2	76%	-
XR	2.8	3.7	1.3	73%	-	2.6	3.3	1.3	70%	-
XA	1.4	2	1.1	34%	-	1.2	1.4	1.1	28%	-
XM	2.3	2.8	1.2	64%	-	1.6	2.0	1.2	49%	-
GA	1.1	1.3	1.2	-	22%	1.0	1.3	1.2	-	21%
GE	1.2	1.4	1.2	-	27%	1.1	1.3	1.1	-	21%

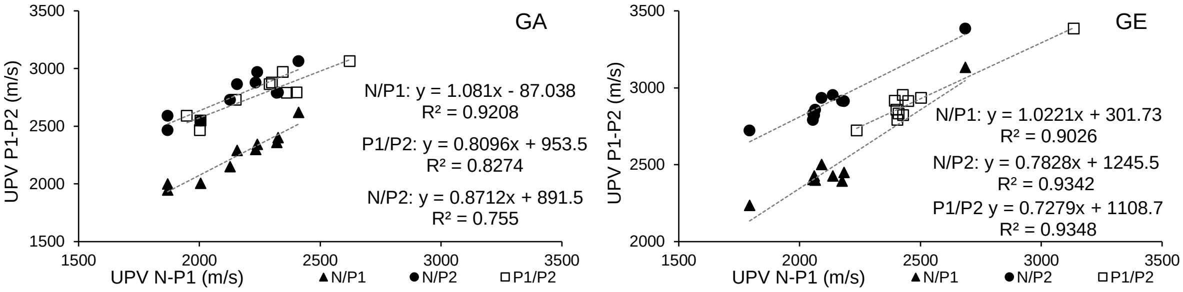


Fig. 7.8 – Valid linear correlations UPV readings on granites.

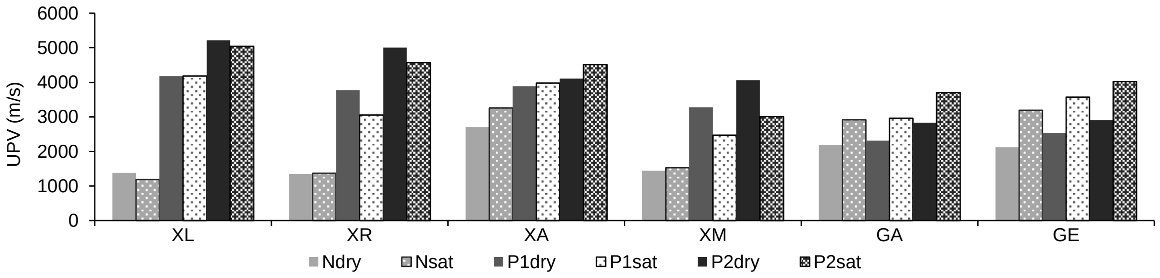


Fig. 7.9 – UPV results for dry and water saturated conditions.

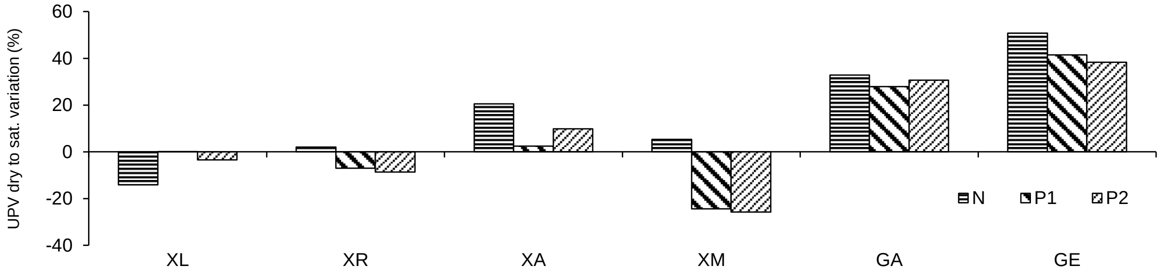


Fig. 7.10 – UPV variation from dry to water saturated conditions.

7.2.3 Water absorption tests

Regarding water absorption characterization, schists and granites were tested for both absorption at atmospheric pressure (A_b), according to NP EN 13755:2005 [237] standard, and for capillary absorption (C), according to NP EN 1925:2000 [238] standard. Both tests were performed on the same specimens. From each rock type, groups of 20 specimens were selected and tested for both types of absorption, first for A_b, and afterwards for C. Taking into consideration that the A_b testing procedure required the full immersion of specimens, possible anisotropic behaviours were only analysed for C. Therefore, specimens were divided into two groups of 10 specimens each, being one tested for N direction water rising, and the other for P direction water rising. Before each test, specimens were oven dried, weighted to determine dry mass (see NP EN 13755:2005 [237]) and cooled down naturally to room temperature.

According to the followed standards, A_b (immersion) testing results are expressed as a percentage of mass (%), whereas for C, results are expressed as a time progression coefficient of water absorption by specific contact area ($g/m^2s^{0.5}$). Each tested rock average, minimum and maximum results for both types of absorptions are presented in Table 7.4, whereas comparison ratios are shown in Table 7.5, and final saturation values in Table 7.6. Individual specimens' results are presented in Fig. 7.12. Images of specimens under A_b testing are presented in Fig. 7.11 and Fig. 7.16, whereas specimens under C testing are shown in Fig. 7.15.

Analysing A_b water absorption behaviours, results in Table 7.4 and Table 7.5, show higher A_b absorption for schists, on an average of 4 times (X / G) stronger in comparison with granites. XR specimens (7.5%) show the higher A_b values, ≅ 1.4 times higher in comparison with the other schists and ≅ 5 times higher in comparison with the granites. A_b results for the remaining schists are very similar for XL (5.1%) and XA (5.2%) specimens, although slightly higher for XM (6.2%) specimens. Regarding A_b for granites, GA (1.7%) and GE (1.3%) show similar results, with GE showing the lower A_b value of all tested rocks. Regarding capillary rising testing, following the NP EN 1925:2005 [238] standard, C coefficients for all rocks were obtained from typical two-branches absorption/time progression diagrams, presented on Fig. 7.13. C was calculated from the slope of the vertical stretch of the graphic, using least-squares linear regression. Results were considered valid if a linear correlation of $R^2 = 0.90$ (5 check points) or $R^2 = 0.95$ (4 check points) was achieved. According to Begonha [239], the vertical branch corresponds to the initial absorption phase, caused by a stronger open porosity related capillary absorption. According to the author [239], the horizontal stretch corresponds to a weaker capillary absorption, caused by the diffusion of air bubbles retained in the porous network into the absorbed mass of water. C results in Table 7.4 and Fig. 7.13 for schists, with the exception of XL N orientated specimens, show a faster and longer initial absorption in comparison with the tested granites. As for the secondary absorption, although showing a late start, saturation is reached faster in schist N orientated specimens in comparison with P orientated schist or granite specimens.

A closer look to schists C absorption behaviours shown in Fig. 7.13, P capillary absorption is faster during the initial absorption (except for XA specimens that show a very slight variation between N and P orientated absorption), but slower regarding the secondary absorption for the remaining schists. Schists C results and comparison ratios, respectively shown in Table 7.4 and Table 7.5, show a ratio of 2.48 obtained between the highest and lowest C for N direction, respectively XM (28.21 $g/m^2s^{0.5}$) and XL (11.37 $g/m^2s^{0.5}$). Regarding P direction, a comparison ratio of 2.36 was obtained between the highest and lowest C, respectively XR (53.21 $g/m^2s^{0.5}$) and XL (22.52 $g/m^2s^{0.5}$). Regarding individual specimen results for parameter C shown in Fig. 7.12, schist specimens show higher scatter in comparison with granite specimens, being higher in P direction for well-defined foliation XL and XR.

Therefore, based on the above-presented results, a clear anisotropic behaviour was identified regarding capillary absorption on schists, being visible at naked see Fig. 7.11a and Fig. 7.15. Water absorption anisotropy (ANs_w) was quantified by calculating N to P C variations by using Eq. 7.1. ANs_w results are presented in Table 7.4, and show a clear anisotropy for well-defined foliation XL (98.2%) and XR (172.1%), being stronger on XR schists, but a very low anisotropy regarding XA (0.1%) and XM (-0.7%) schists.

Regarding C results for granites, Fig. 7.13 diagrams show a slower and shorter initial absorption in comparison with schists, although similar regarding the secondary absorption. Analysing granites C values in Table 7.4, a comparison ratio of 1.94 was obtained between GA (13.66 $g/m^2s^{0.5}$) and GE (7.03 $g/m^2s^{0.5}$) specimens, with the latter showing the lowest C value from all tested rocks. In comparison with schists, granites C values are consistent with N direction absorption, however, considerably lower when compared with P direction absorptions.

Analysing and comparing both types of absorption, individual specimens' results presented in Fig. 7.12 show higher scatter levels for schists, particularly for well-defined foliation specimens and specifically for P direction capillary absorption. Individual specimens' results for granites, in comparison with schists, show a consistent lower level of scatter for both types of water absorption. Regarding the first, it is clear the influence of anisotropy over specimens' results, as for the latter, a heterogenous fabric may influence a more stable absorption process.

Taking into consideration saturation time and total amount of absorbed water, Table 7.6 results show that the amount of water absorbed for each type of rock is similar on both types of absorption, as proven by the average $Ab\ /\ C$ comparison ratio of ≅ 1 obtained. Analysing saturation time, and for A_b, at the exception of XR and XA schists (5760 min.), all other rocks were already saturated at the first successive weighing point (4320 min.). As for C, except for XL N direction absorption, wall rocks reached secondary absorption in the first 1440 min. Therefore, and as expected, saturation was reached faster for A_b than for C absorption. Analysing the above-presented results for schists, they are consistent with these rocks high ρ_o (H rated [229]) and lower ρ_b, but also with these rocks fine and medium-grain and anisotropy [216]. The presence of foliation and voids create additional water capillary penetration ways and retaining areas, but also additional water evaporation and air expulsion channels, as shown in Fig. 7.11 [181,219,220]. However, the absence of valid correlations between N direction C and both ρ_o and ρ_b, points to difficulties caused by these rocks' fabric to capillary water penetration following a transversal direction to foliation.

As for the granites, results are also consistent with their lower ρ_o (L rated [229]) and higher ρ_b, but also with their compact coarse-grain mineral arrangement, typically associated with tortuous paths for water penetration and travelling inside rocks [178]. Regarding granites C absorption, to higher ρ_o and lower ρ_b matches higher absorption capability. Except for N direction absorptions, Fig. 7.14 shows the expected valid linear correlations between A_b and C and ρ_o and ρ_b physical parameters. Analysing the diagrams, one can confirm that higher porosities match higher levels of absorption, while higher densities are associated to lower absorptions. It also become clear that porosity prevails over density in what concerns water absorptions. Comparing results of the tested schists (H) with the reference schist (M), as shown in Table 7.4, the obtained values of A_b are higher, therefore consistent with higher water absorption capability, due to weathering caused higher porosity levels. Regarding GA granite, results are consistent with the reference weathered granites results. However, regarding GE granite, results do not indicate a clear weathering effect over this rock A_b absorption.

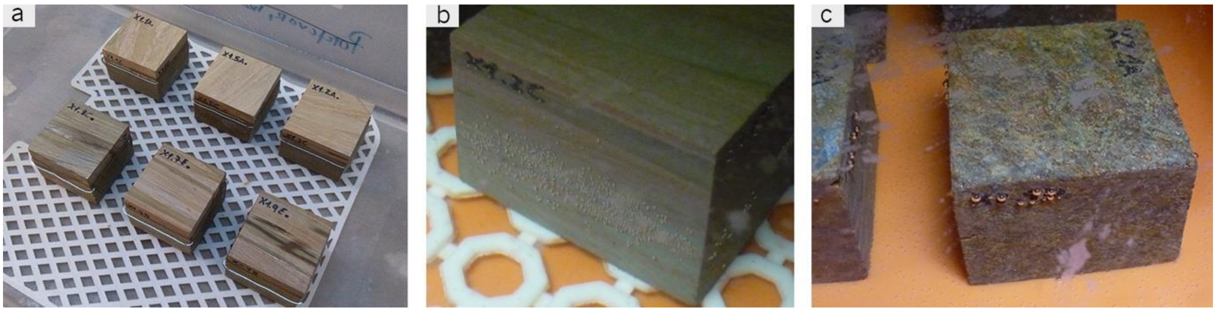


Fig. 7.11 – Water absorption at atmospheric pressure on XL specimens: (a) deeper and faster water rising using foliation joints on P orientated specimen; (b) and (c) expulsion of internal air through foliation joints and voids.

Table 7.4 – Water absorption at atmospheric pressure (NP EN 13755:2008 [237]) and capillary (NP EN 1925:2005 [238]).

Rocks	Atmospheric pressure A_b (%) NP EN 13755:2008 [237]	Capillarity C (g/m^{2}s$^{0.5}$) NP EN 1925:2005 [238]			IAEG* [229]
		N	P	ANS$_w$ (%)	
XL	5.1 (13%) [3.9 – 6.5]	11.37 (25%) [7.46 – 15.28]	22.52 (25%) [14.83 – 29.86]	98.2%	H
XR	7.5 (10%) [6.8 – 9.0]	19.56 (22%) [12.24 – 25.25]	53.21 (21%) [40.41 – 75.30]	172.1%	H
XA	5.2 (9%) [4.6 – 6.4]	17.47 (18%) [13.27 – 21.81]	17.49 (15%) [12.82 – 21.11]	0.1%	H
XM	6.1 (9%) [5.6 – 7.1]	28.21 (17%) [23.06 – 33.40]	28.02 (17%) [23.10 – 33.40]	-0.7%	H
Ref. medium porosity schists [181]	[2.99 – 3.55]	[10.3 – 17.8]	[18.6 – 23.6]	[33% – 81%]	M
Ref. low porosity schists [181]	[0.57 – 1.89]	[1.8 – 6.7]	[1.7 – 11.7]	[-6% – 75%]	L
GA	1.7 (12%) [1.5 – 2.0]	13.66 (7%) [12.24 – 15.04]		n.a	L
GE	1.3 (8%) [1.1 – 1.4]	7.66 (23%) [5.46 – 10.22]		n.a	L
Ref. fresh or non-weathered	[0.63 – 1.6] [182]	[0.74 – 3.38] [239]		n.a	VL – L
Ref. Weathered	[0.58 – 6.6] [182]	[3.15 – 22.0] [239]		n.a	L – M

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets. * IAGE Porosity Classification for Hard and Soft Rocks.

Table 7.5 – Comparison ratios ($y\ /\ x$) for water absorption at atmospheric pressure A_b and for capillary absorption C.

	Water absorption at atmospheric pressure A_b						Capillary absorption C									
(y/x)	XL	XR	XA	XM	GA	GE	XL		XR		XA		XM		GA	GE
							N	P	N	P	N	P	N	P		
XL	1,00	1,47	1,02	1,22	0,33	0,25	1,00	1,00	1,72	2,36	1,54	0,78	2,48	1,24	1,20	0,67
XR	0,68	1,00	0,69	0,83	0,23	0,17	0,58	0,42	1,00	1,00	0,89	0,33	1,44	0,53	0,70	0,39
XA	0,98	1,44	1,00	1,19	0,33	0,25	0,65	1,29	1,12	3,04	1,00	1,00	1,61	1,60	0,78	0,44
XM	0,82	1,21	0,84	1,00	0,27	0,21	0,40	0,80	0,69	1,90	0,62	0,62	1,00	1,00	0,48	0,27
GA	3,00	4,41	3,06	3,65	1,00	0,76	0,83	1,65	1,43	3,90	1,28	1,28	2,07	2,05	1,00	0,56
GE	3,92	5,77	4,00	4,77	1,31	1,00	1,48	2,94	2,55	6,95	2,28	2,28	3,68	3,66	1,78	1,00

Table 7.6 – Saturation (mass of water and time) for water absorption at atmospheric pressure and capillary.

Rocks		Atmospheric pressure		Capillary absorption		ratio (a/b)
		water mass (g/cm^2) (a)	time (min.)	water mass (g/cm^2) (b)	time (min.)	
XL	N	5730 (2%)	4320	6137 (16%)	11520	0,93
	P			5658 (14%)	8640	1,01
XR	N	8292 (2%)	5760	8332 (9%)	5760	1,00
	P			8090 (7%)	5760	1,02
XA	N	6657 (3%)	5760	6484 (8%)	5760	1,03
	P			6432 (5%)	5760	1,03
XM	N	7217 (3%)	4320	7705 (8%)	7200	0,94
	P			6906 (6%)	7200	1,05
GA		2275 (1%)	4320	1950 (8%)	4320	1,17
GE		1499 (1%)	4320	1369 (13%)	5760	1,09

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets.

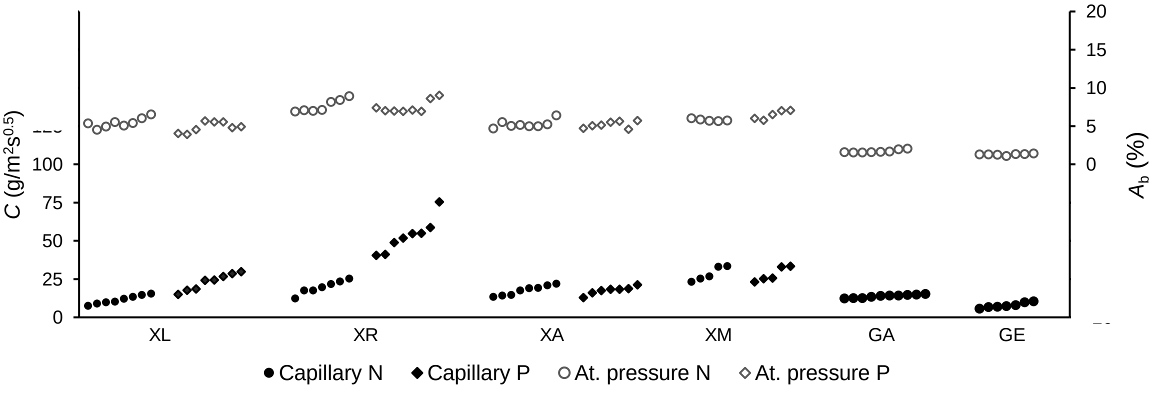


Fig. 7.12 – Water absorption results by specimen.

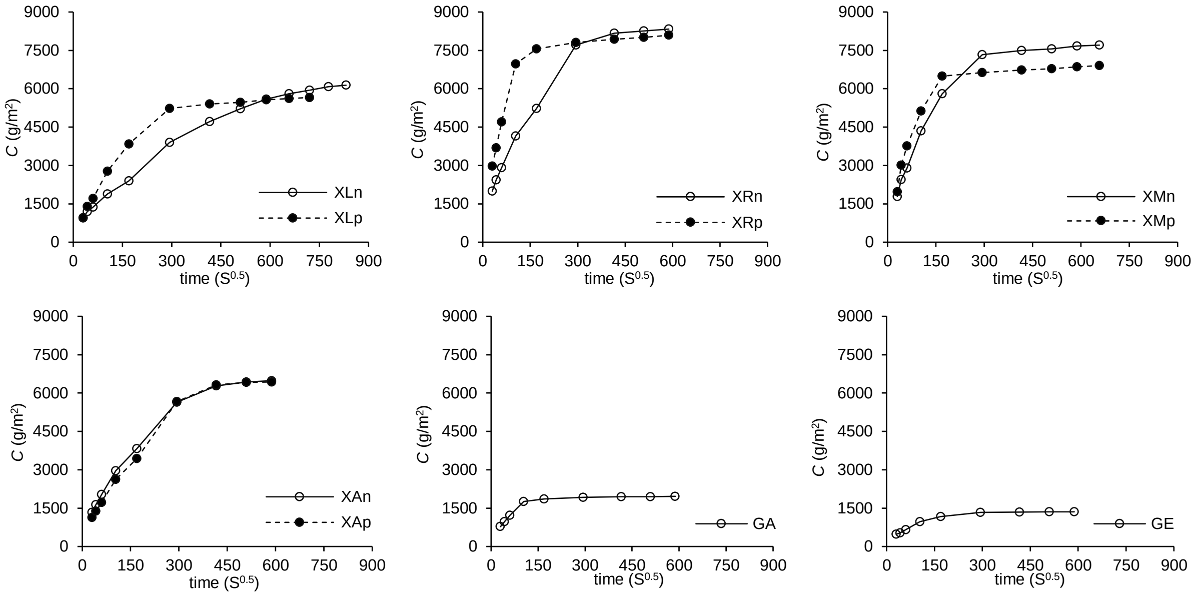


Fig. 7.13 – Average results for capillary absorption for each type of rock.

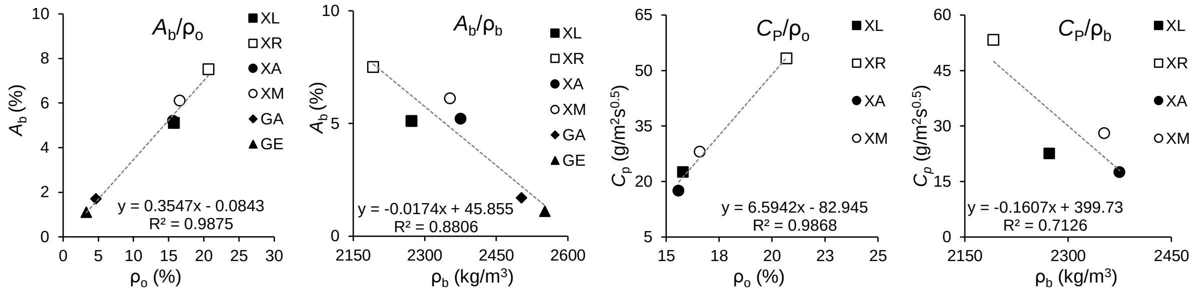


Fig. 7.14 – Linear correlations for water absorption (Ab and C) and physical parameters (ρo and ρb).

During the different tests, water penetration and rising on specimens was visually checked, being the same type of behaviour observed for immersion and capillary rising. Observing Fig. 7.15, on P orientated specimens, water rises faster through foliation joints. By confining water, joint's walls acted as channels, allowing a faster rising to the top [179]. On N orientated specimens, well-defined horizontal foliation joint's voids acted as barrier to the water rising, causing a slower rising to the top. It was observed that layers would become fully saturated before water could rise to the next one. This process may justify the shorter secondary absorption branches shown on Fig. 7.12 diagrams. On poorly-defined foliation XA and XM schists, the level of variability of the above-explained processes is higher, caused by the irregularity of these rocks planar structure.

As observed, N to P lower variation is related to capillary rising through tortuous paths, that can lead to slower absorption and to make water follow unpredictable paths to the top, or to migrate to other areas of the specimens. Nevertheless, on both XA and XM schists, existing surface voids and very small superficial microcracks also condition capillary rising. Regarding water capillary rising on granites, as shown in Fig. 7.16, it resembles the poorly-defined foliation schists, although significantly slower and with a more evenly water distribution through the specimens. Due to granites isotropic behaviour, mineral heterogeneous arrangement and compact surfaces, water rising on specimens was usually gradual, without showing any preferential paths, generally saturating specimens faces before moving inwards and to the top.

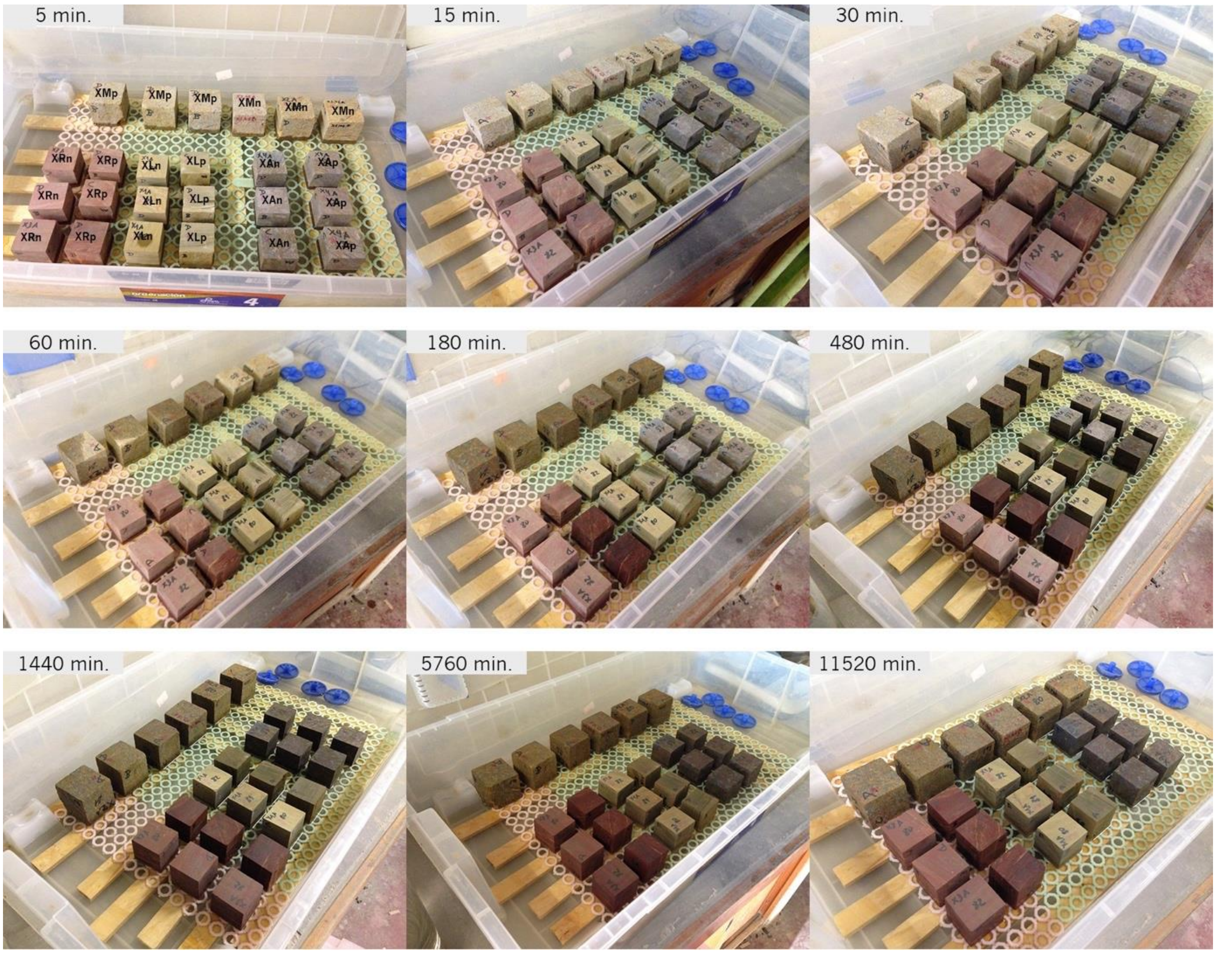


Fig. 7.15 – Water absorption by capillary testing on schists.

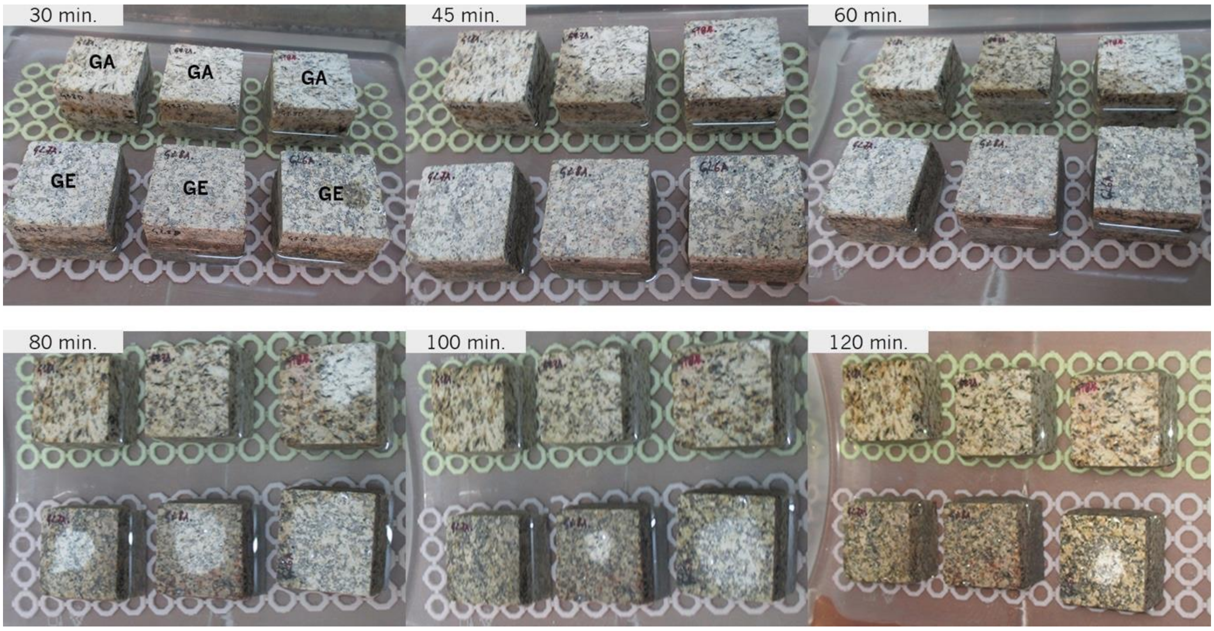


Fig. 7.16 - Water absorption at atmospheric pressure testing on granites.

7.3 Mechanical characterization

Rocks are described in literature as brittle or quasi-brittle natural materials, with a typical mechanical behaviour influenced by a broad diversity of variables of intrinsic or extrinsic origin [178,179,181,182,215,240,241]. Grain size and mineral arrangement are known to considerably influence rocks mechanical behaviour. Strength is known to increase as grain size decreases on homogenous rocks [179]. From compact rocks showing low porosity and higher density levels, failures with higher brittleness are expected, whereas from soft rocks showing high porosity levels and lower density, failures showing lower brittleness and higher ductility are often observed [240]. As for rocks with a defined planar structure, either being anisotropic or inhomogeneous, these are also known to show different mechanical behaviours with load applied in different directions. Such behaviours are reported in literature as typical from foliated rocks, such as schists (caused by schistosity) [181,242], or related to existing preferable orientation, such as granites (caused by the rift plan or quarry direction) [182]. According to Hudson et al. [215], the existence of tension caused microcracks, particularly if following rocks planar structure, also play an important role on rocks mechanical behaviour. Regarding extrinsic factors, over time effects such as the ones caused by environmental agents (weathering) are known to influence and alter the mechanical performance of rock masses [178,179,181,182,215,240,241]. Therefore, according to Hudson et al. [215], lower mechanical performance on rocks can be associated with over time microstructural damage due to creep, relaxation or fatigue phenomena.

Regarding the effects of water over rocks mechanical behaviour, high moister content is known for influencing strength and deformability. Hudson et al. [215] highlight that mechanical damage related to water is caused by swell, slack or, on rocks with high clay content, desiccation phenomena. Winkler [179] adds that the presence of moister in pores is known for diminishing bonding between grains, particularly in the presence of clay minerals. According to the author [179], moister is known to cause stress and damage when under pressure inside rocks capillary network, [182,219]. Regarding rock masses decay caused by weathering, either resulting from ageing or caused by physical, chemical, or biological damage, it diminishes rocks strength due to multiple factors such as growing disaggregation phenomena or internal discontinuities, changes to porosity and density or physical and chemical changes on minerals and grain interlocking. These are some of the typical rock masses reaction to environmental agents such as salts or pollution [178,179,181,182,215,240,241].

Intense research made by different fields of expertise in the last decades, from geology to engineering, resulted on a large diversity and different types of scientific literature focused on understanding the mechanical properties of rocks [178,179,181,182,215,240,241]. The detailed and full explanation regarding rocks mechanical behaviour overshoots the present research scope. Nonetheless, taking into consideration that stone masonry mechanical behaviour relies on several variables among which, stones mechanical resistance plays a very important role [173]. In the present research, the basic mechanical behaviour of the rocks studied was synthesized and analysed from construction point of view. Literature overview showed that rock masses mechanical behaviour is mainly governed by compression, tensile and shear forces, that cause rocks to deform (elastic and plastically [243]) within a certain limit, beyond which the material fails [215,240]. From a general point of view, rocks mechanical performance is acceptably described for a known good compression behaviour and a very fragile tensile behaviour [215]. According to Quelhas et al. [173], the latter is 10 times inferior to the respective compressive strength. Therefore, due to reduced tensile strength, rocks are prone to brittle failure [182].

According to Vasconcelos [182], stone masonry structures are mainly under compressive loading. Hudson et al. [215] highlights that compressive force corresponds to a very basic type of loading. The author [215] describes compressive strength as an arbitrary parameter regarding rocks microstructural decay process, meaning that rocks decay generally starts before maximum stress is reached.

Regarding stone blocks role on masonry structures, loads reach the ground through preferential compression lines that travel through stone blocks and joints. On one hand, a good compressive load transfer is dependent on properly bedded stone blocks with suitable interfaces, and on avoiding tension concentration areas [173]. On the other hand, poor compressive load transfers are generally an outcome of poorly bedded stone blocks and interfaces (e.g. different types of horizontal joints arrangements or using large amounts or stiffer wedges), that cause preferential compression lines to flow through stiffer areas, therefore, causing bending or flexural forces on stone blocks [173]. In this case, the upper section of stone blocks is under compression, whereas its lower section is under tensile forces. Under such conditions, tensile rupture hazard is high, particularly on stone beams or lintels [173].

Stone blocks and bedding joints failure can also outcome from in-plane or out-of-plane lateral or eccentric forces that cause shear stress. Regarding rocks stiffness or deformability, both parameters are described by the materials elastic and plastic properties [182,215,243]. Under elastic deformation, the material is able to recover to the initial state when unload (Young’s modulus or modulus of elasticity) [243]. Under plastic deformation, the material’s recovering ability is exceed and deformation becomes permanent [215,243]. According to Hudson et al. [215], reliable estimation regarding rocks elastic modulus can be determined from the stress-strain diagram pre-peak branch (linear behaviour), either as tangent or as secant modulus. When visible on stress-strain diagrams, rocks plastic behaviour is shown as a non-linear branch prior and subsequent to stress peak [215,240]. Regarding rocks common deformation by extension under axial load, Gercek [244] points out the Poisson’s effect as cause for rocks known phenomena of expanding perpendicularly to the axial loading direction, therefore, undergoing a transversal deformation [244]. The author [244] points out the narrow variation range regarding Poisson’s ratio values for rocks.

7.3.1 Uniaxial compressive testing

In order to determine strength and elastic properties for the tested schists and granites, rocks were tested under monotonical uniaxial compressive load, according to NP EN 1926:2000 [217] standard.

According to Hudson et al. [215], compressive strength is influenced by specimens geometry and loading conditions. Thus, when tested for uniaxial compression, rock strength and ductility increase as aspect ratio decreases (ratio between height and diameter) [182,215,240]. It is noteworthy that the selection of smaller specimens decreases the probability of containing internal flaws and microcracks, therefore reducing their influence over the post-peak behaviour [182,215]. According to Hudson et al. [215], size and shape effects are not significant on determining rocks elasticity modulus. However, taking into consideration loading conditions, a restraint effect is referred to in literature. It is reported as an outcome from the different elastic properties of rock specimens and boundary conditions that cause a triaxial compression stress state at the extremity of specimens [182,215].

Taking into consideration the above-mentioned observations, from each type of schist, specimens were divided into two groups of 10 specimens each, containing 5 N orientated specimens (common bedding orientation on vernacular masonry) and 5 P2 orientated specimens (stronger UPV propagation direction). From each type of granite, two groups of 5 specimens were selected and tested following the original stone blocks bedding orientation. The first group of each type of rock was tested under dry mass conditions (40 specimens of schist and 20 of granite), whereas the second was tested under water saturated conditions (40 specimens of schist and 20 of granite). All specimens were previously tested for physical characterization (see Section 7.2). Regarding specimens' size, 50 x 50 x 50 mm^3 cubic specimens were prepared from all tested rocks, with a proportion specimens size/grain size over 10:1, as required by the standard used. When need to ensure parallel and perfect contact surfaces, specimens' top and bottom faces were levelled using a sander to obtain perfect flatness (see Fig. 7.17a), or levelled using Nivedur®, a suitable fast hardening mortar [217] (see Fig. 7.17b).

The tests were performed under monotonic axial displacement control at a rate of 5 μm/s, using a servo-controlled testing machine (maximum load of 500 kN). The displacement was monitored by three LVDTs installed between plates (see Fig. 7.17d). According to Vasconcelos [182], lower loading velocities allow improved control over the damage location and a stable failure progress, therefore, making possible to obtain an accurate post-peak behaviour. Two Teflon sheets with lubricating oil were used to reduce friction between specimens top and bottom surfaces and the loadings plates (see Fig. 7.17c). Before initiating each test, specimens were properly aligned (to centre the load) and adjusted to the loading platen (to ensure full contact between surfaces). To do so, a pre-load was applied in force control (< 10 kN), and a spherical seat was used under the top loading platen. Tests were considered concluded when post-peak load was under 30% of the peak load, or in case of catastrophic rupture.

From stress-strain diagrams (without the pre-load branch), the peak load, the pre-peak and post-peak behaviours were obtained. The strength R was calculated based on the peak load added with the pre-load. The modulus of elasticity E was calculated from the pre-peak stress-strain branch (30% - 70% of peak load) using least-squares linear regression ($R^2 > 0.95$). R and E mean, minimum and maximum vales are presented in Table 7.7, for rocks tested under dry mass conditions, and in Table 7.8, for rocks tested under saturated conditions. Results for individual specimens are shown in Fig. 7.18. Dry to saturated variation is shown in Fig. 7.19. In order to compare the compressive strength of tested rocks with other Portuguese rocks, the IAEG classification was again used [229]. Here, strength classification for hard and soft rocks (in MPa) is grouped into five categories: weak ($1.5 < R \leq 15$, W); moderately strong ($15 < R \leq 50$, MS); strong ($50 < R \leq 120$, S); very strong ($120 < R \leq 230$, VS); extremely strong ($R > 230$, ES). Regarding stress-strain diagrams for both dry mass and saturated conditions, they are presented for XR and XA schists in Fig. 7.23, and for GE and GA granites in Fig. 7.24. Due to unforeseen technical difficulties, data regarding XL and XM deformations were lost. Examples regarding schists and granites failures under compression are presented in Fig. 7.26 and Fig. 7.27, respectively.

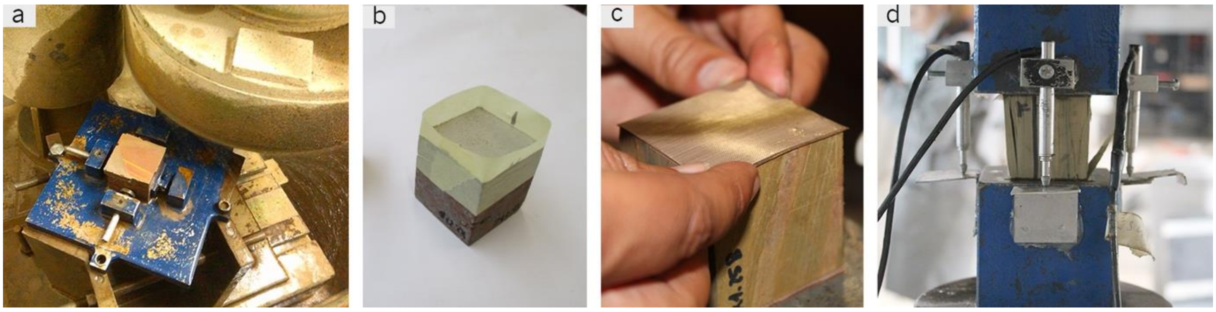


Fig. 7.17 – Uniaxial compression tests preparation: (a) levelling of specimens using Nivedur ®; (b) levelling of specimens using a sander; (c) applying Teflon sheets with lubrication oil; (d) test setup with three LVDTs and top and bottom loading platen.

a) Strength and deformability

Analysing *R* results presented in Table 7.7 for specimens tested under dry mass conditions, GE granite (81.75 MPa) is the strongest among the tested rocks, achieving the IAGE [229] rate of S, whereas the rate MS [229] was given to all the others. GE specimens are 49% stronger than GA (41.75 MPa) specimens and on an average of ≅ 54% and ≅ 58% stronger regarding schists loaded on N and P directions, respectively. Regarding *R* values for schists, XL (41.56 MPa) and XM (41.20 MPa) specimens show higher strength when load on N direction, whereas XR (35.75 MPa) and XA (35.43 MPa) show higher strength when loaded P2 direction. However, minimum, and maximum *R* values presented in Table 7.7, clearly show that schists loaded on N direction show a tendency to be stronger.

Regarding the scatter of *R* results, GE (11%) granite shows the lowest scatter level, whereas a tendency for higher scatter was observed for schists load on P2 direction, being higher for well-defined foliation XL (22%) and XR (25%) specimens. These results show that on one hand, higher predictability regarding *R* was observed on rocks showing higher levels of mineral heterogeneity, or with load applied transversally to foliation (N direction). On the other hand, a certain level of unpredictability can be expected regarding schists loaded parallel to foliation (P directions), increasing on schists with well-defined planar structures (XL and XR). Analysing *R* results for specimens tested under saturated conditions, see Table 7.8 and Fig. 7.18, it becomes clear a consistent loss of strength on all tested rocks, significantly more intense on schists than on granites.

Observing the dry to saturated *R* variation presented in Fig. 7.19, GE (-35.89%) and GA (-18.42%) show the lower strength loss among the tested rocks, whereas from results in Fig. 7.18 and Table 7.8, one can conclude that although with a slight increase for GE (17% CoV) specimens, granites *R* values scatter is similar under both test conditions.

As for schists, Fig. 7.19 shows that for well-defined foliation XL (N – -44.71% < P – -48.18%) and XR (N – -55.80%<P – -60.38%), strength loss is higher on specimens loaded on P2 directions, whereas for poorly-defined foliation XA (N – -54.71% > P – -45.55%) and XM schists (N – -78.47% > P – -72.93%), it is higher for specimens loaded on N direction.

Regarding the scatter of *R* values, Fig. 7.18 and Table 7.8 CoVs values show that, for well-defined foliation schists, the same tendency of higher scatter of *R* results for specimens with load applied on P2 direction is shown, with a scatter increase for the first (XL – 91%; XR – 48%) and decrease for the latter (XL – -33%; XR – 36%). As for poorly-defined foliation schists, for XM (N – -31%; P2 – -52%) specimens, the same CoV value was obtained for both directions, showing a consistent decrease of scatter, whereas a consistent increase on both directions was obtained for XA (N – 86%; P2 – 36%) specimens, higher on specimens loaded on N direction.

Based on the above-presented results for specimens tested under saturated conditions, one can conclude that water consistently, and negatively, affects the strength of the tested rocks, causing a loss of mechanical performance. As expected, from their higher porosity and lamellar structure, strength performance loss is higher for schists.

Analysing *E* results presented in Table 7.7 and Fig. 7.18, for specimens tested under dry mass conditions, GE (13.67 GPa) shows the higher elasticity modulus of the tested rocks, indicating the higher stiffness of this rock in comparison with the GA (5.27 GPa) granite, and with N direction loaded XA (4.77 GPa) and XR (1.43 GPa) schists. The latter shows the lowest stiffness of all tested rocks, being 9.6 times lower than for GE specimens. However, Table 7.7 results also show that when loaded on P2 direction, schists stiffness drastically increases with XR (11.9 GPa) and XA (10.35 GPa) specimens *E* results almost matching GE *E* values, and being ≅ 2 times stiffer than GA specimens, on average.

Analysing the scatter of *E* results, CoVs in Table 7.7 and individual results presented in Fig. 7.18, show that, with the exception of XA (3%) specimens loaded on N direction, all tested rocks *E* results present a significantly higher scatter in comparison with *R* results. *E* values scatter for granites is lower for GA (14%) specimens in comparison with GE (37%) specimens. N direction tested schists specimens show the lower *E* values scatter, much lower for XA (N – 3% < P – 46%) than for XR (N – 26% < P – 31%) specimens.

As for saturated conditions, presented in Table 7.8 and Fig. 7.19, *E* results show a consistent decrease tendency, meaning a generalized loss of stiffness (increase on deformability) for all tested rocks. Therefore, Fig. 7.19 *E* dry to saturation variation shows a stronger *E* decrease on the stiffer GE (-26.04%) granite in comparison with GA (-7.78%) specimens. Regarding schists, dry to saturation variation show that stiffness loss is much more intense for specimens with load applied on P direction. Therefore, when loaded on P direction, the deformability increase is much higher on well-defined foliation XR (-65.80%) specimens in comparison with poorly-defined foliation XM (-32.85) specimens. With load applied on N direction, XR (-27.27%) and XM (-22.01%) specimens show similar variations, Therefore, indicating a much lower influence of water over rocks deformability with load applied transversally to foliation.

Based on the above-presented results for specimens tested under water saturated conditions, it is clear the intense effect of water over the tested rocks elastic performance, causing a decrease on stiffness and increase on deformability, much more intense when load is applied in parallel to rocks foliation (P2 direction). It is noteworthy the strong correlation between both *R* and *E* mechanical parameters, either under dry mass and saturated conditions, as proven by the valid linear correlations shown in Fig. 7.20. In these, an increase on *R* is matched with an increase on *E*, whereas an increase on either parameter under dry mass conditions matches with an increase under saturated conditions for the same parameter.

To analyse the effect of anisotropy over schists mechanical performance, N to P2 variation was quantified for both dry mass and saturated conditions *R* (ANs_R) and *E* (ANs_E) results, by applying the anisotropic scale calculation presented on Eq. 7.1. Results are presented respectively in Table 7.7 for dry conditions and in Table 7.8 for saturated conditions.

Analysing the results, under dry mass conditions, ANs_R show a stronger *R* anisotropic behaviour for XL (-21%) and XM (-22%) specimens, due to higher *R* values obtained whit load applied on N direction. However, *R* anisotropy is less intense on XR (4%) and XM (7%) schists, being in these rocks higher *R* values obtained with load applied on P2 direction. ANs_R results for specimens tested under water saturated conditions, although with a very slight tendency inversion for XR specimens, show the same type of tendencies as for under dry mass conditions.

Analysing *E* anisotropy, ANs_E results for specimens tested under dry mass conditions show an extremely high anisotropic effect, much higher for well-defined foliation XR (732%) in comparison with the poorly-defined foliation XA (117%) specimens. As for ANs_E for specimens tested under water saturated conditions, although results still show an extremely high anisotropic effect, a consistent scale decrease is clear, stronger for well-defined foliation XR (ANs_E $732\%_{dry} > 291\%_{sat}$) specimens in comparison with XA (ANs_E $117\%_{dry} > 87\%_{sat}$) specimens.

Based on the presented results, it can be concluded that the effect of anisotropy over schists mechanical performance is high, being more intense for deformability in comparison to strength. In Fig. 7.21, valid correlations were found for XR and XA. On the diagrams, it is clear that for the same rock N and P direction, *R* and *E* values show a linear correlation. However, Fig. 7.21 diagrams also show that under saturated conditions, water disturbs such correlation. Linear correlations were only found for *R* on XA specimens, and for *E* on XM specimens. Therefore, it is concluded that water influences the anisotropic behaviour of the schists tested, regarding strength and deformability.

Comparing the results shown in Table 7.7 and Table 7.8, *R* and E values for GA (MS rated [229]) and GE (S rated [229]) are consistent with the results of weathered granites (MS – S rated [229]) tested for both dry mass and saturated conditions by Vasconcelos [182]. Regarding GE saturated specimens, *R* values are consistent with reference non-weathered granites. Therefore, both granites can be considered weathered rocks regarding their mechanical performance, however for GE granite, a lower level should be taken into consideration.

Regarding schists, and due to the absence of references values for *E* and for schists tested under saturated conditions, comparison was established based on *R* and porosity results. Therefore, *R* results for the tested schists, rated for porosity as H [229], are lower than the reference schists tested by Barros [181], and rated for porosity as M [229]. Such results, due to high porosity may point out to a possible influence of weathering over the tested schists mechanical performance. According to Vasconcelos[182], weathering causing high porosity is known to diminish rocks mechanical performance, and it can explain the very high dry to wet *R* and *E* variations observed.

Table 7.7 – Axial compression test results under dry mass conditions (NP EN 1926:2000 [217]).

Rocks	Compressive strength *R* (MPa)				Elastic modulus *E* (GPa)		
	N	P2	ANS$_R$ (%)	IAEG*	N	P2	ANS$_E$ (%)
XL	42.56 (15%) [37.51 – 51.43]	33.75 (22%) [20.60 – 52.44]	-21%	MS	–	–	–
XR	34.48 (25%) [26.03 – 48.08]	35.77 (25%) [24.17 – 45.09]	4%	MS	1.43 (26%) [0.99 – 1.79]	11.9 (31%) [9.66 – 17.40]	732%
XA	33.23 (14%) [28.81 – 40.40]	35.43 (16%) [27.18 – 40.05]	7%	MS	4.77 (3%) [4.57 – 4.88]	10.35 (46%) [5.65 – 15.83]	117%
XM	41.20 (13%) [36.32 – 49.45]	32.10 (19%) [23.79 – 38.77]	-22%	MS	–	–	–
Ref. medium porosity schists [181]	[46.00 – 53.60]	[29.7 – 45.40]	[-35% – -25%]	MS S	–	–	–
Ref. low porosity schists [181]	[79.10 – 144.90]	[88.60 – 151.90]	[26% – 5%]	S VS	–	–	–
GA	41.75 (15%) [36.34 – 51.22]		n.a.	MS	5.27 (19%) [4.58 – 6.75]		n.a.
GE	81.75 (11%) [71.78 – 93.61]		n.a.	S	13.67 (24%) [9.33 – 16.69]		n.a.
Ref. fresh or non–weathered [182]	[44.80 – 159.80]		n.a.	MS VS	[9.6 – 63.8]		n.a.
Ref. weathered [182]	[50.20 – 89.50]		n.a.	S	[7.8 – 35.1]		n.a.

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets. * IAGE Strength Classification for Hard and Soft Rocks.

Table 7.8 – Axial compression test results under saturated conditions (NP EN 1926:2000 [217]).

Rocks	Compressive strength *R* (MPa)				Elastic modulus *E* (GPa)		
	N	P2	ANS$_R$ (%)	IAEG*	N	P2	ANS$_E$ (%)
XL	23.53 (10%) [21.50 – 26.91]	17.49 (42%) [10.48 – 28.03]	- -26%	MS	–	–	-
XR	15.24 (16%) [13.01 – 18.24]	14.18 (37%) [7.84 – 20.72]	-7%	MS W	1.04 (14%) [0.83 – 1.16]	4.07 (31%) [2.72 – 5.78]	291%
XA	15.04 (26%) [11.10 – 20.45]	19.29 (11%) [27.18 – 40.05]	28%	MS	3.72 (33%) [2.57 – 5.30]	6.95 (35%) [3.98 – 6.71]	87%
XM	8.87 (9%) [8.14 – 9.96]	8.69 (9%) [7.68 – 9.79]	-2%	W	–	–	–
GA	34.06 (16%) [30.56 – 38.26]		n.a	MS	4.86 (14%) [3.91 – 5.52]		n.a.
GE	52.41 (17%) [43.42 – 65.19]		n.a.	S	10.11 (37%) [6.66 – 15.07]		n.a.
Ref. fresh or non–weathered [182]	[36.30 – 65.10]		n.a.	MS VS	[7.8 – 12.3]		n.a.
Ref. weathered [182]	[30.00 – 47.90]		n.a.	MS S	[10.7 – 25.2]		n.a.

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets. * IAGE Strength Classification for Hard and Soft Rocks.

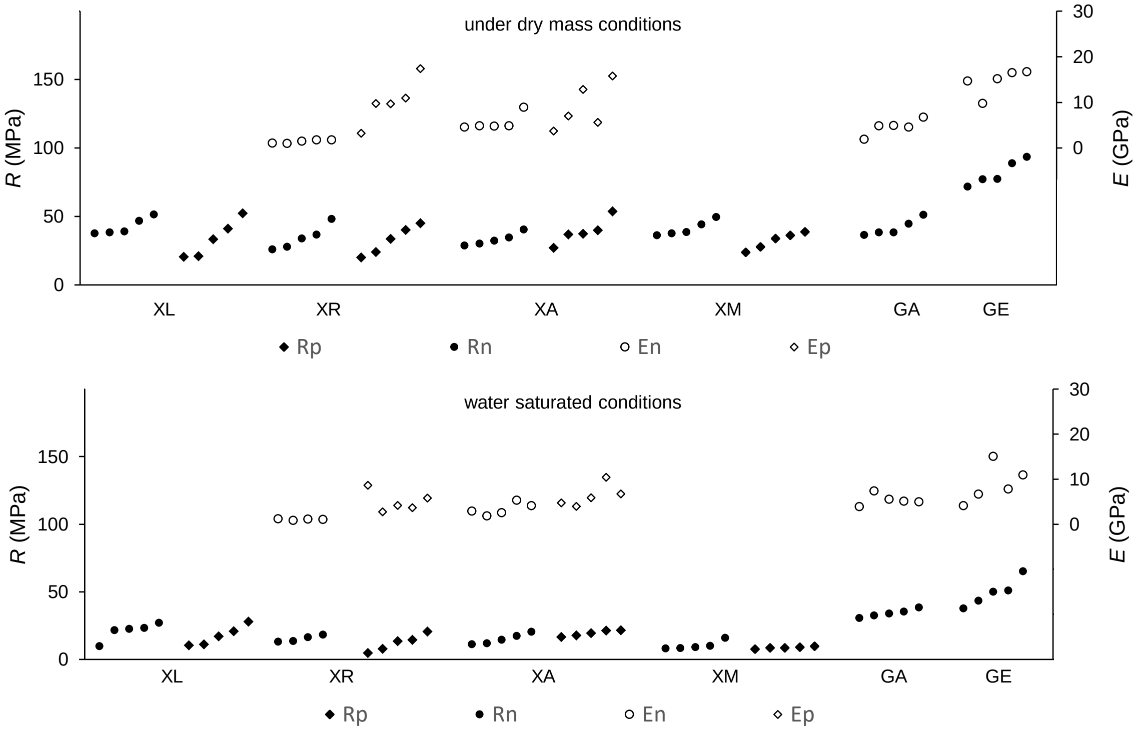


Fig. 7.18 – Individual strength R and elasticity modulus E results under dry mass (above) and saturated conditions (bellow).

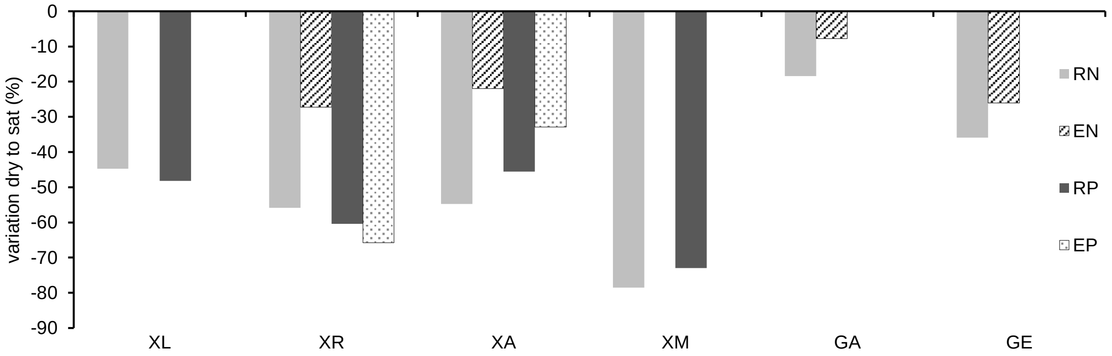


Fig. 7.19 – Variation of dry to saturated results (average values) of the tested schists and granites.

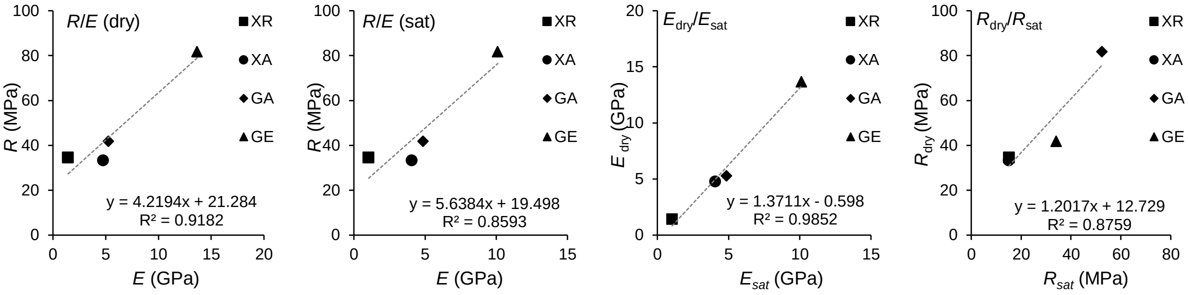


Fig. 7.20 – Valid correlation for R and E mechanical parameters for dry and saturated rock specimens.

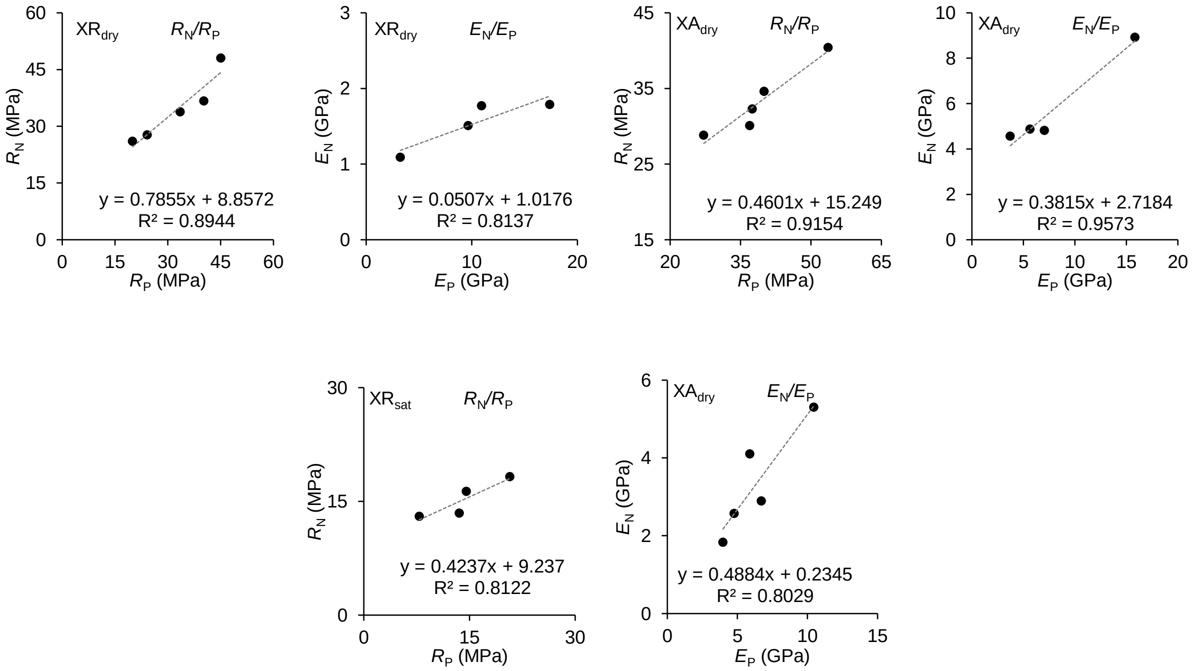


Fig. 7.21 – Valid correlation for R and E mechanical parameters for dry (above) and saturated (bellow) XR and XA specimens.

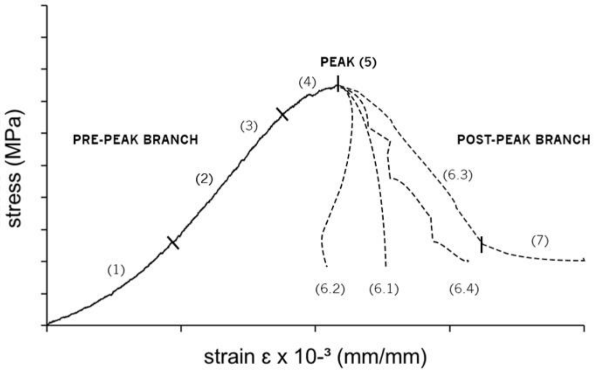
b) Pre and post-peak compressive behaviour

In Fig. 7.23 and Fig. 7.24, the stress-strain diagrams obtained for schists and granites tested, respectively, under dry mass and saturated conditions are shown. According to several authors (e.g. Vasconcelos [182], Hudson et al. [215]), for brittle materials such as rocks, stress-strain diagrams can be divided into a pre-peak and a post-peak behaviour. According to Vasconcelos [182], the post-peak branch can also be divided into four different stages, as shown in Fig. 7.22 (see figure for reference numbers inside round brackets).

The first stage (1), corresponds to a non-linear branch resulting from the compression and closing of existent pores, microcracks and voids, that precedes a second linear elastic stage (2) caused by formation of reversible strains, and a third still essentially linear stage (3), caused by the formation and stable propagation of compressive-stress parallel microcracks. According to Vasconcelos [182], such type of microcracks does not affect the stiffness of the material and, therefore, does not change the stress-strain linear development, since the deformation sustained by specimens on this stage is mostly completely reversible if load is removed.

Prior to reaching the peak, a fourth non-linear stage (4) is characterized by the formation of unstable microcracks, that due to propagation become coalescent, leading to the formation of cracks and to the intensification of lateral strains. According to Vasconcelos [182], in this stage the material reaches its maximum compaction and, with the formation of cracks, starts a dilation process. Such a process is described by the author [182] as resulting from a volume increase, that in this stage exceeds the volume decrease caused by compression. After reaching the peak (5), strain deformation becomes localized in the damage area, and the softening branch or post-peak starts.

This stress-strain descent branch is described by Vasconcelos [182] as resulting from the propagation of the macrocracks originated by coalescent microcracks. Therefore, after peak, the material is prone to tensile and shear fractures caused by strains localization. As shown in Fig. 7.22, post-peak can present several distinct types of behaviours. Abrupt drops of softening behaviour (6.1) are typical of brittle rocks, whereas snap back behaviours (6.2) are generally observed on stronger rocks [182,215,245]. Regarding post-peak of weaker rocks or showing higher ductility levels, a typical smooth descent (6.3) with high energy dissipation softening post-peak behaviour is common, frequently showing a long tail (7) caused by residual strength [182,215,245].



(1) crack closure (non-linear)
(2) elastic deformation (linear)
(3) stable microcracks formation and almost fully recoverable damage (essentially linear)
(4) unstable microcracking and cracks caused damage that lead to lateral strain intensification
(5) maximum stress
(6.1) abrupt vertical drop-off post-peak
(6.2) snap back post-peak
(6.3) smooth descent post-peak
(6.4) step like post-peak (e.g. smooth descent) post-peak
(7) residual strength

Fig. 7.22 – Schematic stress-strain diagram for rocks under monotonical uniaxial compression testing [179,182,215].

Step like softening branches (6.4) are described by Vasconcelos [182], resulting from the process of macrocracks formation and strain re-localization, are characterized by unloading (drop-off) and recovering (smooth descent) of the material.

Analysing the stress-strain diagrams presented in Fig. 7.23, for schists, and Fig. 7.24, for granites, a typical brittle behaviour was observed for all tested rocks. Comparing each rock under dry mass and under saturated conditions in terms of stress-strain diagrams, the same type of behaviour can be observed for both types of conditions. As expected by observing *R* and *E* results, under saturated conditions stress-strain diagrams are consistent with mechanical performance losses. In Fig. 7.23 stress-strain diagrams for XR specimens, anisotropy influence is clearly recognizable on the different compressive behaviours seen for N and P2 direction loaded specimens. XR N direction loaded specimens show the most ductile pre-peak behaviour from all tested specimens, followed by a brittle and abrupt drop-off post-peak, whereas P2 loaded specimens show a very brittle behaviour. On the first case, with axial load applied transversally to the well-defined foliation (N direction), it caused the initial closure of voids existing between the foliation layers, therefore increasing the level of sustained pre-peak deformation. Such behaviour can be clearly observed on specimens showing a step like post-peaks, indicating cases of strain re-location due to individual foliation layers failure.

On the second case, with axial load applied in parallel to foliation (P direction), pre-peak behaviours show higher stiffness and very low levels of ductility in comparison with the latter. Peak load was generally reached immediately after the elastic deformation, with a very short and residual unstable microcracks formation stage. As expected, post-peak for P2 specimens showed typical abrupt drop-off behaviour. Regarding the observed anisotropy of XR specimens, it seems to be strongly related to its well-defined foliation, and water influence over it. Analysing Fig. 7.23 and Fig. 7.24 stress-strain diagrams, similar compressive brittle behaviours can be observed for XA and GA specimens, however, showing a slightly increase on pre and post-peak ductility in comparison with P loaded XR and with GE specimens, although inferior in comparison with N loaded XR specimens. Therefore, analysing XA and GA stress-strain diagrams, pre and post-peak exhibit similar behaviour under both testing conditions and, for XA specimens respectively for both loading direction. The influence of water is clearly visible on both rocks by the lower peak values obtained. Regarding XA specimens, the effect of anisotropy over their compressive behaviour seems considerably weaker in comparison with XR specimens' anisotropy, probably due to XA higher foliation irregularity and medium-coarse grain. Regarding GE specimens under dry mass and water saturation stress-strain diagrams, shown in Fig. 7.24, both exhibit a strong brittle behaviour. Due to this granite higher strength and stiffness, stress-strain diagrams are sensitive to the initial compression adjustment.

As expected, GE specimens post-peak is characterized by a typical abrupt drop-off with no residual strength tail behaviour. Stress-strain diagrams for specimens tested under water saturated conditions exhibit slightly more ductile behaviour, with some specimens showing post-peak strain re-locations. Granites coarse-grain and heterogeneous mineral arrangement without a clear planar structure may be pointed out as cause, for these rocks observed stable and predictable compressive behaviour.

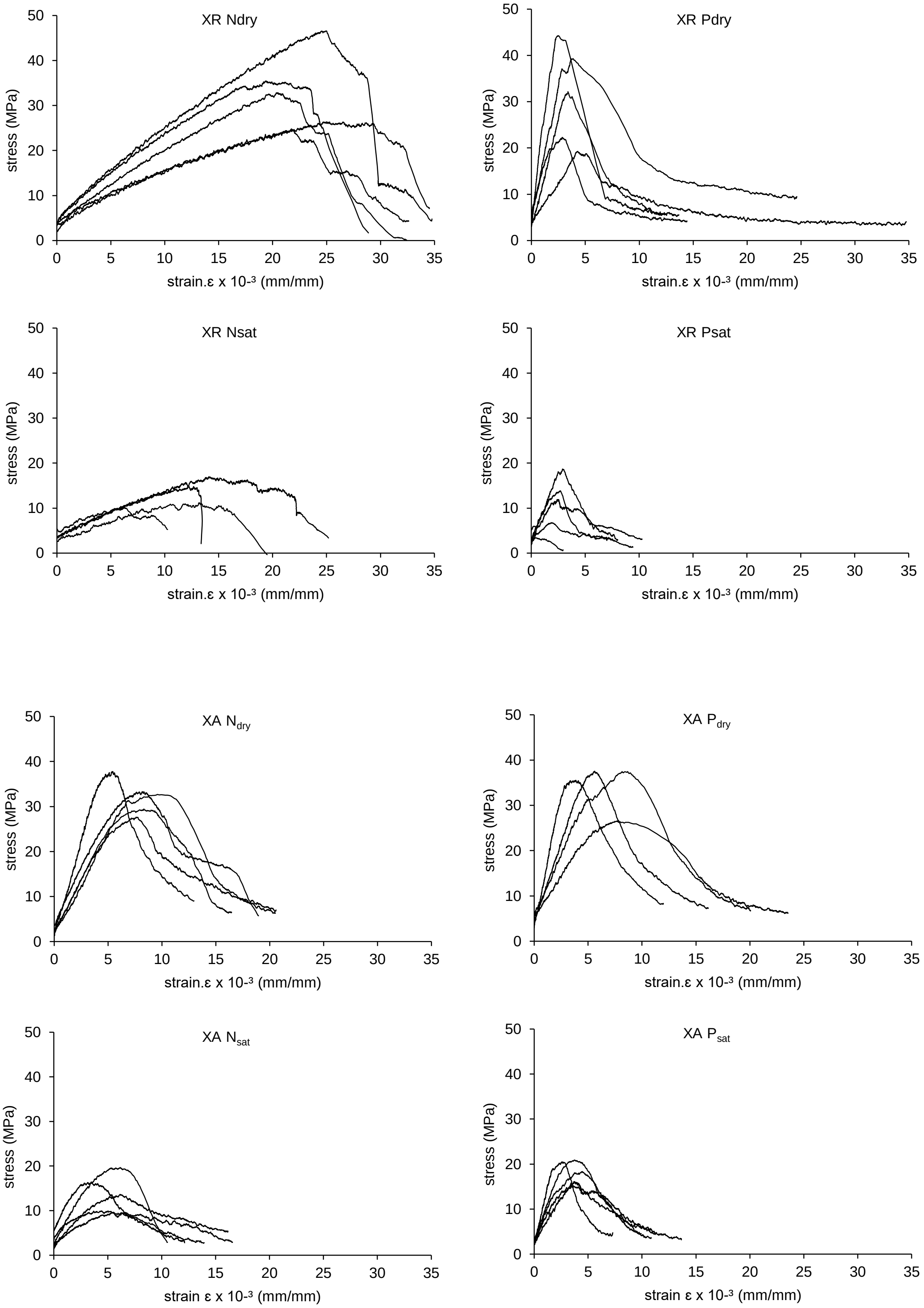


Fig. 7.23 – Stress-strain diagrams for XR and XA schists tested under dry conditions (above) and saturation conditions (bellow).

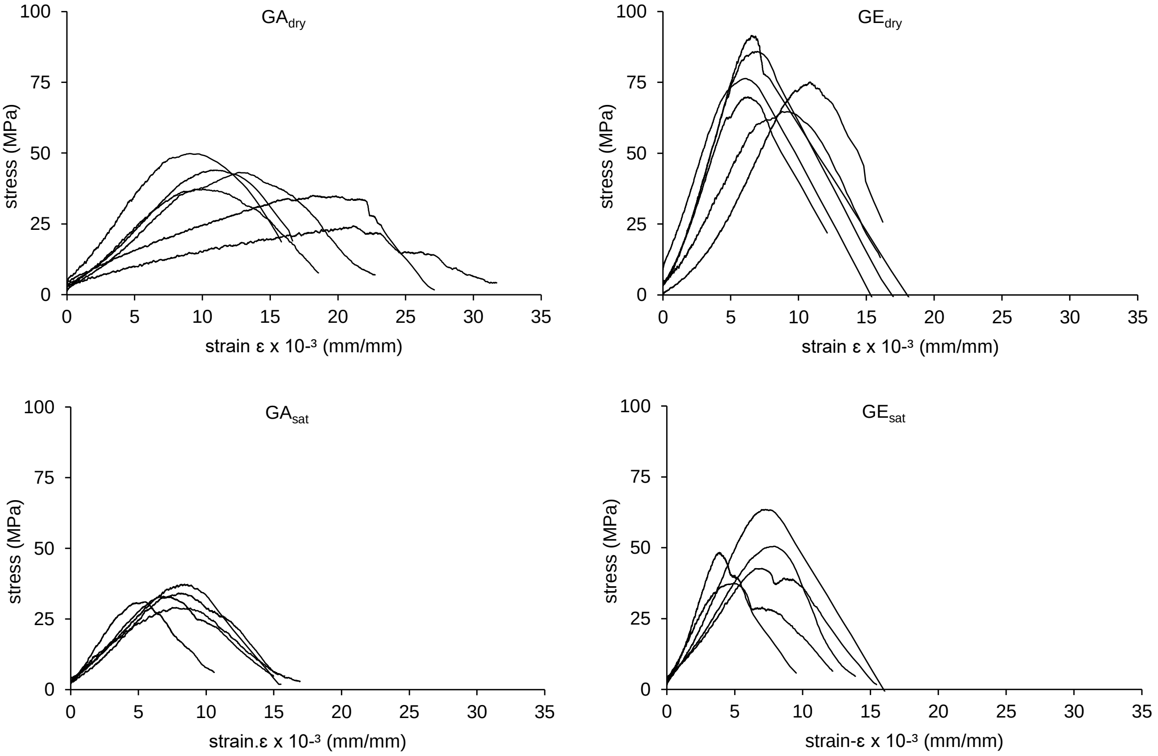


Fig. 7.24 – Stress-strain diagrams for GA and GE granites tested under dry conditions (above) and saturation conditions (bellow).

c) Failure modes

Regarding failures of rock masses, Basu et al. [246] points out difficulties regarding the prediction and the feasibility of using mathematical numerical models for the task, mostly due to the natural origin of the material. Therefore, the author [246] highlights the importance of data collection through experimental works. As shown in Fig. 7.25a, Winkler [179] points out to extension or axial splitting along parallel planes to the axial stress, (tensile cracking), and to shear failure (shear cracking) as the two main types of failures observed on rocks.

Regarding axial splitting failure, Nemat-Nasser et al. [241] describes this type of rupture mechanism as the outcome of frictional sliding of existent microcracks under axial compression, that originate tension cracks at their tips, also known as wing cracks [246]. As shown in Fig. 7.25b, these wing cracks propagate in parallel to the axial load direction and become unstable due to boundary caused lateral tension, leading to axial splitting failure [241,246]. Nemat-Nasser et al. [241] describes the shear failure as the outcome of unstable coalescent growth of microcracks. According to the author [241], the process is started due to the lateral confining effect, that blocks the growth of larger microcracks and leads to the activation of smaller and closed microcracks, causing them to interact. As shown in Fig. 7.25b, dense microcrack areas are formed, resulting into a macroscopic shear failure plane [215,241,246]. Analysing the tested schists and granites specimens for their failure under uniaxial compression, shown respectively in Fig. 7.26 and Fig. 7.27, it becomes clear that brittle ruptures were obtained for all tested specimens, and for both dry mass and saturated test conditions. As expected, single or multiple planes axial splitting, causing lamellar or multiple fracturing, and single or multiple planes shear failure, causing V and Y shaped rupture, were the main types of ruptures observed [246].

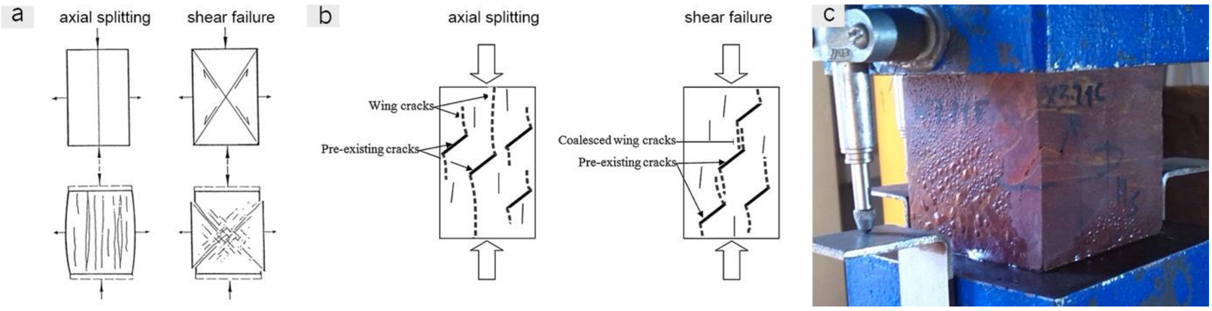


Fig. 7.25 – (a) typical failure modes of rocks under axial compression (after Winkler [179]); (b) process of the propagation of wing cracks (after Basu et al. [246]); (c) XR water saturated specimen tested for axial compression.

Analysing failures for GE and GA specimens, shown in the examples presented in Fig. 7.26, for both types of granites, ruptures were significantly more fragile in comparison with the ones observed for schists, being stronger for GE specimens in comparison to GA specimens. For both rocks, ruptures were typically due to multiple parallel plane axial splitting and shear (V shape) failures, observed either for dry mass and water saturated specimens. Loss of material on edges, was a common type of observed damage that had higher intensity on water saturated specimens.

Regarding well-defined XL and XR schists, shown in Fig. 7.27, a clear anisotropic behaviour over specimen’s failure was detected, whereas for poorly-defined foliation XA and XM schists, the anisotropic influence over failure modes was weaker. According to Hudson et al. [215], axial load applied transversally to discontinuities (N direction loading), such as joints from rocks existing planar structures or foliation, compresses them together causing the increase of the stiffness of compressed rock mass to the limit of an intact state.

Therefore, and as shown in Fig. 7.23, although higher levels of deformation are expected on schists specimens during the initial loading stage, once the stiffness limit is reached, brittle failure is common. As shown in Fig. 7.25c, compression of the foliation layers and the loss of internal space was confirmed by the expulsion of retained water on specimens tested under saturated conditions. For specimens loaded in parallel to discontinuities or to foliation layers (P2 direction loading), according to the author [215], axial load causes tensile failure localized along the discontinuities. According to Vasconcelos [182], with load applied in parallel to a foliation plane, each one acts as a weakness plan. Therefore, lateral strain and the formation of microcracks along foliation joints can intensify the loss of cohesion of the material, leading to lamellar disaggregation [179,182]. Analysing examples of tested schist specimen shown Fig. 7.27, for N loaded XL and XR specimens, both types of failure were observed, although being more brittle in the case of XL specimens. XL specimens with load applied on N direction, showed both axial splitting and shear failure, whereas only shear failure was observed for XR specimens. For a reduced number of XL N loaded specimens, axial splitting caused multiple fracturing, resulted from the formation of uncharacteristic horizontal cracks. As observed, such type of cracks was the outcome of the sliding under compression of foliation layers due to the loss of planar cohesion. Causes for such phenomenon can be attributed to the angle formed between the planar structure of the tested specimens, and the axial load angle. As for P2 loaded XL and XR specimens, typical failures resulted from axial splitting caused lamellar disaggregation, and shear failure. As shown in Fig. 7.27, the first type was more often observed for XL specimens (higher foliation regularity), whereas the second was common for XR specimens (with lower foliation regularity). In the first case, causes may be related to this type of schist apparent higher foliation regularity that seems to reduce the bond between its layers when under parallel loading, whereas for the second, a slightly higher foliation irregularity seems to improve bond between its layers when under parallel loading.

Analysing the failure of poorly-defined schists, XA specimens exhibit a tendency for axial splitting and shear failure when loaded on N direction, whereas only of shear failure (multiple directions) when loaded on P direction. However, for XM specimens, shear failure was observed on specimens with loading applied on N direction, whereas lamellar disaggregation caused by axial splitting, and shear failure were both observed for specimens with load applied on P2 direction. Lower planar regularity, medium-grain and higher mineral heterogeneous arrangement can explain these poorly-defined foliation, less predictable failures in comparison with well-defined foliation schists.

Based on the above-present results, the tested rocks present similar failures modes, although clearly more unpredictable due to the influence of anisotropy on the tested schist specimens. Foliation seems to play an important role on schists rupture mechanisms. Regarding the tested granites, failure modes show a higher level of predictability, and do not show any type of planar influence over them.

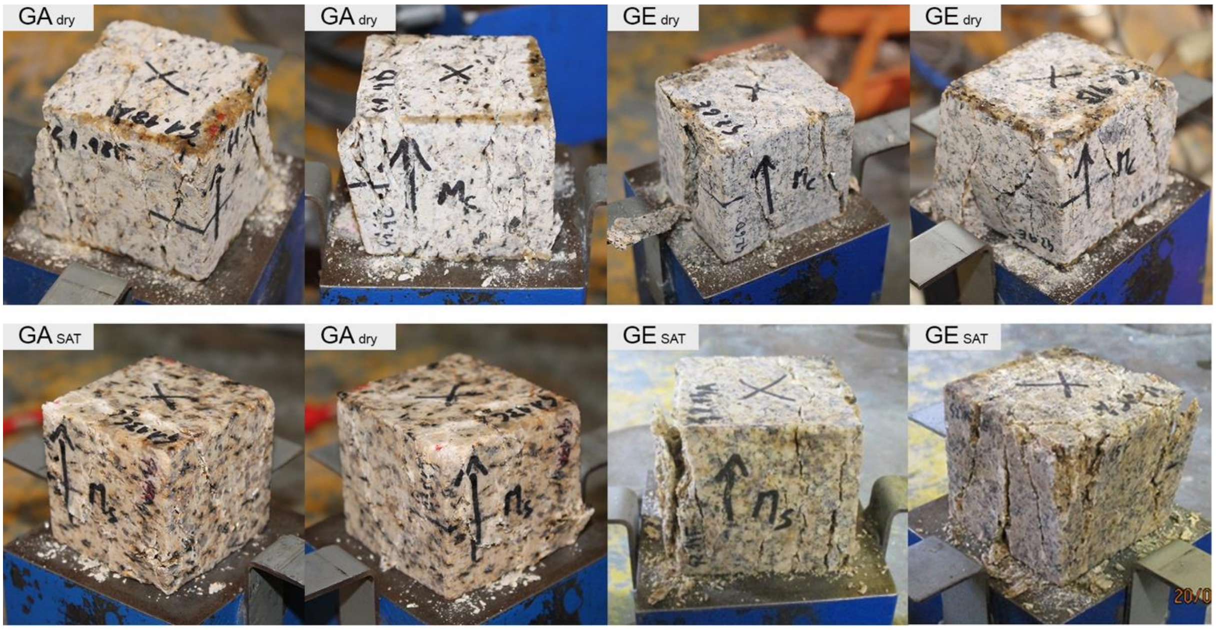


Fig. 7.26 – Examples of granite specimens tested under dry mass and saturated conditions, exhibiting the most commonly observed types of failures.

Fig. 7.27 – Examples of schist specimens tested under dry mass and saturated conditions, exhibiting the most commonly observed types of failures.

7.3.2 Flexural resistance

a) Flexural strength

To determine granites and schist flexural strength under uniform bending moment (R_{tc}), specimens were prepared and tested using the 4-point bedding test described on the NP EN 13161:2006 [247] standard. According to Mardalizad et al. [248], when under flexion, rocks specimens middle span (*i*) is under compression stress at the top, while under tensile stress at the bottom. Therefore, and according to the beam theory, the flexural strength corresponds to the maximum stress or ultimate loading (R_{tc}). From the collected stone blocks, prismatic cubic specimens of 40 x 40 x 240 mm^3 (h x b x L), with a ratio (L/h) of 6:1 [247], were sawn and tested under dry mass and water saturated conditions. As mentioned for other tests, due to the limited size of the stone blocks from which all specimens used throughout the experimental campaign were cut, the number of tested rocks and analysed directions were reduced respectively to one type of well-defined foliation schist (XR), one type of poorly-defined foliation schist (XA) and one type of granite (GE). The criteria for the selection of the tested directions was to test rocks to determine performance on bedding direction, based on the observation performed during the exploratory visits (see Section 6.1).

Due to the strong mechanical anisotropy identified on the previous section, XR schist was tested for N and P2 directions (two groups of 6 N and 6 P2 orientated specimens each). XA was used by masons to shape larger stone blocks, lintels, and pillars. Without a clearly visible foliation at naked eye, it was during shaping that masons established the bedding orientations. Therefore, XA specimens were only tested according to the bedding orientation of the source stone block, meaning on N direction (two groups of 6 specimens each).

Regarding granites, it was observed that GE granite platy stone blocks were used to make larger corbelled dome structures, see Section 9.2. Therefore, GE granite was tested for flexural strength according to its source stone block bedding orientation, identified by UPV as N direction (two groups of 6 specimens each). To obtain failure onto an pre-established observation area, a 0.5 mm notch was sawn at specimens middle span's bottom, giving specimens a wider than thicker proportion ($h < b$ [247]) [249,250]. The 4-point bending tests were performed by applying monotonical axial load under displacement control at a rate of 2 μm/s, using a servo-controlled (2) testing machine (100 kN). Pictures from the testing setup are shown in Fig. 7.28 (see figure for reference numbers).

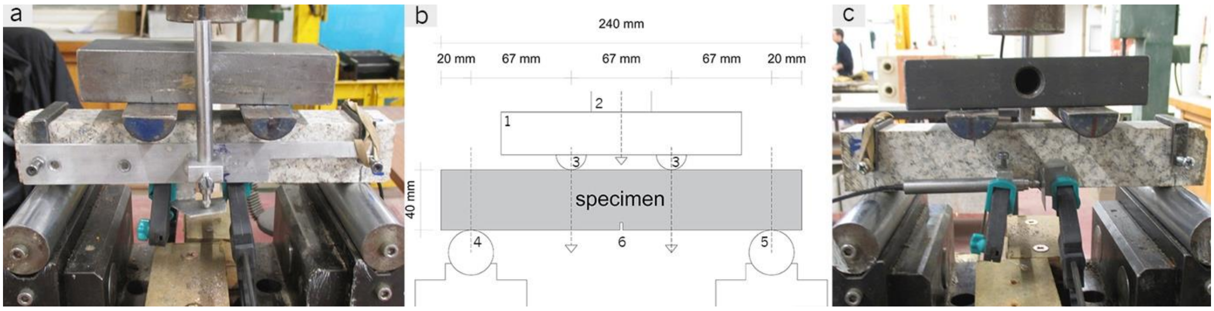


Fig. 7.28 – 4-points bending test setup: (a) displacement LVDT; (b) testing setup schematic; (c) crack opening LVDT. Reference numbers of image b: 1 – load distribution metal bar; 2 – loading mechanism; 3 – top cylindrical steel rods; 4 – base cylindrical steel rod; 5 – movable base cylindrical steel rod; 6 – notch. Load axis are indicated by dashed lines with direction arrows.

The specimens were placed over a pair of cylindrical steel rods (4), being one movable (5) to help adjust the beams. The axial load was applied to a larger steel bar (1) that distributed it evenly to two smaller cylindrical steel rods (3), placed centred over the top of the specimens. The displacement was monitored by a vertical LVDT, whereas the crack opening was monitored by a horizontal LVDT. Due to the reduced size of the specimens, the above-mentioned LVDTs were placed in opposite lateral faces. As shown in Fig. 7.28a, the vertical LVDT was attached to a moving bar connected to the specimens by clamps aligned with the support rods. The measuring target was laterally glued to the specimen. The horizontal LVDT, see Fig. 7.28b, and the respective measuring target were attached aligned with the bottom edge of the specimens, each at 2 cm to each side of the notch. Due to moister, plastic clamps were used as a replacement for glue on saturated specimens.

Analysing dry mass results presented in Table 7.9, one can see that both schists show higher R_{tc} in comparison with the granite. XR specimens (12.37 MPa) with load applied in parallel to foliation (P direction) show the higher average R_{tc} value among the tested rocks, 1.2 times stronger in comparison to N loaded XR (10.56 MPa) specimens, and 1.1 and 1.4 times stronger than respectively XA (10.97 MPa) and GE (8.67 MPa) specimens. Results also show that both N orientated schists specimens show consistent R_{tc} values. To be noticed, for being weathered schists, XR and XA specimens R_{tc} results are consistent with the weaker part of the range of results presented as reference schists in Table 7.9. Among the tested rocks, GE is the rock with the lowest R_{tc} value among the rocks tested under dry mass conditions, however, results show that it presents the higher R_{tc} when tested under saturated conditions.

In such conditions, GE (7.56 MPa) specimens are on an average of ≅ 1.2 times stronger than XR (N – 6.29 MPa; P – 6.11 MPa) specimens, and of 1.4 times stronger than XA (5.59 MPa) specimens. Being a weathered granite, GE specimens R_{tc} results are consistent with the weaker ones among the range of results presented as reference granites in Table 7.9. Analysing the influence of water over the tested rocks R_{tc} values, results for dry to saturation R_{tc} variation presented in Fig. 7.29b show a consistent strength loss for all rocks, with GE specimens showing the lower R_{tc} loss (12.8%) in comparison with the XR (N – 40.4%; P – 50.6%) and XA (49.0%) specimens.

Taking into consideration results for individual specimens presented in Fig. 7.29b, and the CoVs, presented in Table 7.9, one can conclude that under dry mass conditions, the level of scatter is similar for all rocks, being slightly higher for both directions for well-defined foliation XR specimens (N and P – 17% CoV) when compared with GE (14% CoV) and XA (10% CoV) specimens. However, under saturated conditions, individual specimens' R_{tc} results scatter show a decrease tendency for N loaded XR (10% CoV) and XA (7% CoV), whereas an increasing tendency for P loaded XR (18% CoV) and GE (18% CV).

Regarding displacement (d_{peak}) at peak load, results shown in Table 7.9, show high CoVs for specimens tested under dry mass conditions, increasing drastically for specimens tested under saturated conditions. Such type of CoV values and dry to saturation variation can also be observed regarding crack opening (c_{peak}) at peak load. Based in these results, one can conclude that for these two parameters, results should not be considered reliable. To be noticed, it was concluded that d_{peak} and c_{peak} results were negatively affected by the setup option regarding the attachment of both LVDTs. Causes were related to unforeseen testing conditions such as the sliding of clamps due to moister under higher levels of stress, or by glue detachment caused by failure conditions such as lamellar disaggregation on schists specimens.

Regarding XR specimens' R_{tc} anisotropic behaviour (ANs_{F}, see Eq. 7.1) results show a low effect (17.14%), even lower under saturated conditions as shown by N to P variation ($0.17_{dry} > -0.03_{sat}$). However, such results are misleading as it was observed during the tests. In fact, deformation and failure of specimens were affected by XR well-defined foliation under both testing conditions. Such behaviours are explained ahead. Therefore, and as expected from the previous results, anisotropy influences schist flexural behaviour. Based in the above-presented results, one can conclude that water has a strong negative influence over the tested rocks flexural strength performance, less significant in the case of GE granite.

Table 7.9 – points bending test results for dry mass and water saturated conditions (NP EN 13161:2006 [247]).

Rocks	under dry conditions			under water saturated conditions		
	Flexural strength R_{tc} (MPa)	Displacement at peak load d_{peak} (mm)	Crack opening at peak load c_{peak}(mm)	Flexural strength R_{tc} (MPa)	Displacement at peak load d_{peak} (mm)	Crack opening at peak load c_{peak}(mm)
XR_N	10.56 (17%) [8.78 – 13.54]	0.067 (31%) [0.046 – 0.093]	0.009 (42%) [0.005 – 0.014]	6.29 (10%) [5.24 – 6.78]	0.211 (171%) [0.017 – 0.750]	0.115 (202%) [0.005 – 0.533]
XR_P	12.37 (17%) [8.74 – 13.64]	0.036 (32%) [0.019 – 0.048]	0.004 (122%) [0.000 – 0.011]	6.11 (18%) [5.00 – 7.75]	0.021 (121%) [-0.007 – 0.043]	0,010 (40%) [0.005 – 0.016]
XA_N	10.97 (10%) [9.76 – 12.06]	0.103 (42%) [0.055 – 0.173]	0.006 (104%) [-0.001 - 0.013]	5.59 (7%) [5.12 – 6.26]	0.021 (109%) [-0.007 – 0.051]	0.017 (35%) [0.023 – 0.010]
Ref. fresh schist [230,251]	[9.8 – 77.6]	–	–	–	–	–
GE	8.67 (14%) [6.87 – 10.37]	0.133 (19%) [0.111 – 0.179]	0.024 (104%) [0.006 – 0.040]	7.56 (18%) [6.10 – 8.92]	0.144 (19%) [0.108 – 0.209]	0.039 (26%) [0.029 – 0.052]
Ref. fresh granite [230]	[6.96 – 18.83]	-	-	-	-	-

Note: coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets.

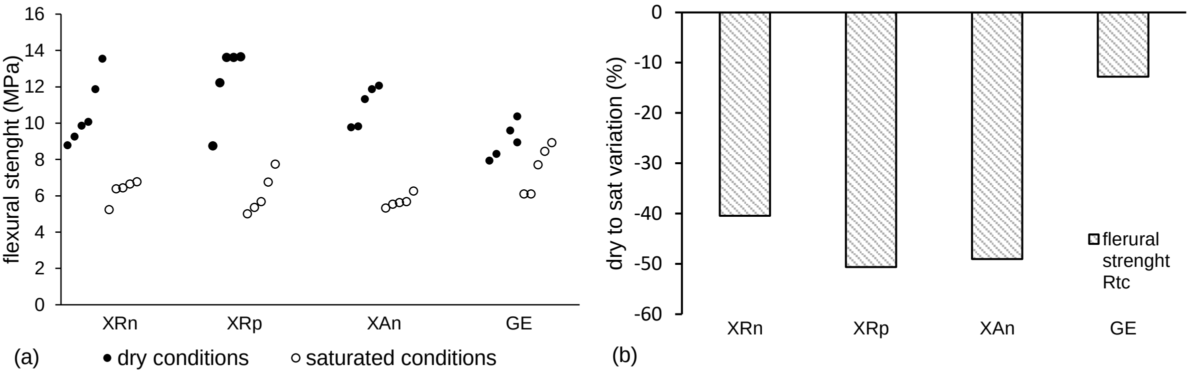


Fig. 7.29 – (a) - individual specimens Rtc results; (b) – R_{tc} dry to sat variation.

b) *Pre and post-peak flexural behaviour*

In order to understand the behaviour of the tested rocks under the 4-point bending testing, load-displacement diagrams are presented in Fig. 7.30, for GE specimens, and in Fig. 7.31 and Fig. 7.32, respectively for XR and XA specimens.

Analysing the load-displacement diagrams, one can observe a similar behaviour and brittle failure for all specimens tested under dry mass and saturated conditions. Nonetheless, except for N loaded XR specimens, load-displacement diagrams confirm that all tested rocks exhibit slightly lower fragile behaviours when tested under saturated conditions. A closer look to the diagrams reveals a common feature to all tested rocks, namely, two or three-branches pre-peak behaviour, with an initial linear and stiffer vertical branch (adjustment phase), followed by a linear elastic branch, either up to the peak or to a non-linear and shorter plastic branch, which precedes peak. For all and for both testing conditions, obtained post-peaks confirm fragile behaviours and brittle failures on the tested rocks.

Analysing Fig. 7.30 load-displacement diagrams for GE specimens, one can see a less fragile behaviour in comparison with the schists, for both pre and post-peak branches, even less intense under saturated conditions. Typical pre-peak behaviour show an initial short adjustment branch, followed by a linear elastic and a non-linear plastic stage prior to peak. Diagrams soft branches show typical brittle failure drop-off post-peak. In comparison with the schists, GE granites show lower R_{tc} and a more predictable flexural behaviour. GE load-displacement diagrams for specimens tested under saturated conditions confirms this rock lower susceptibility, when compared with the schists, to be negatively affected by moister over its flexural behaviour.

Analysing N loaded XR and XA load-displacement diagrams, respectively shown in Fig. 7.31 and Fig. 7.32, one can observe a pre-peak branch that tend to a linear behaviour up to the peak, followed by brittle rupture with characteristic drop-off post-peak. As for P loaded XR specimens, Fig. 7.31 load-displacement diagram show that specimens fail due to catastrophic brittle rupture, therefore, only the linear pre-peak behaviour could be obtain, like the above-described pre-peak behaviour.

Load-displacement diagrams for saturated conditions for XA specimens exhibit a less fragile behaviour when compared with results for dry mass tested specimens, visible by the non-linear or short plastic deformation branch that precedes peak.

Regarding saturated N loaded XR specimens, one can observe an increase of step like pre-peak behaviours and on failure due to catastrophic rupture, that makes it impossible to obtain post-peak behaviours. For saturated P loaded XR specimens, these become less fragile than under dry mass conditions, with some specimens exhibiting some plastic deformation prior to peak.

Therefore, XR specimens tested under dry mass conditions show a brittle behaviour, stronger on P loaded specimens, being less fragile on N loaded specimens. On the other hand, under saturated conditions, one can observe that P loaded XR specimens becomes less fragile, however, being stronger brittle failure observed for N loaded XR specimens. Based on prior observations, such behaviours can be explained by XR schist well-defined foliation and strong anisotropy. Under dry mass conditions, N loaded specimens become less fragile, due to a phenomenon observed in several cases, of individual and successive rupture of individual foliation layers, either during pre- or post-peak (step-like branches). P loaded specimens did not exhibit such type of phenomena. However, the presence of water and its effect over the rock (e.g. strength reduction or clay activation), seems to make it more fragile for N loaded specimens, by eliminating lamellar disaggregation (see Fig. 7.35 further ahead), whereas less fragile by reducing lamellar cohesion on P loaded specimens [178,184,252].

As observed during the bending tests performed on XR specimens with load applied transversally to foliation (N direction), typical failure occurred by crack propagation upwards and inwards from one foliation layer on to the next one, until full rupture. Therefore, the sequential release of energy and strain localization caused by the individual rupture of the foliation layers makes it less fragile, being translated in the load-displacement diagram by a typical stepwise like behaviour. Different levels of bond and friction between foliation layers may explain the different fragile behaviours observed in XR N orientated specimens [215]. Regarding the behaviour of XR specimens with load applied in parallel to foliation (P direction), failure may be explained by loss of cohesion caused by the rocks planar structure. The loss of flexural performance observed on schists tested under saturated conditions, as previously explained regarding other mechanical behaviours, can be reported to internal stress caused by water pressure under compression, and known effects of moisture over clays and granular bond [179,182,215,219].

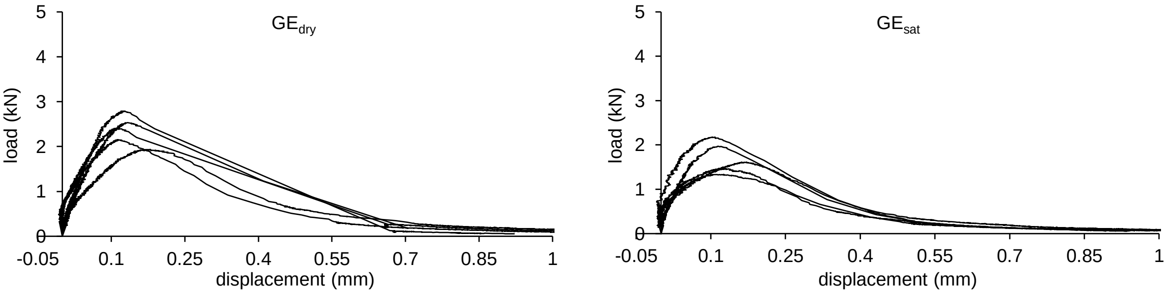


Fig. 7.30 – Flexural load-displacement diagrams of tested GE specimens: dry mass (right) and saturated (left) conditions.

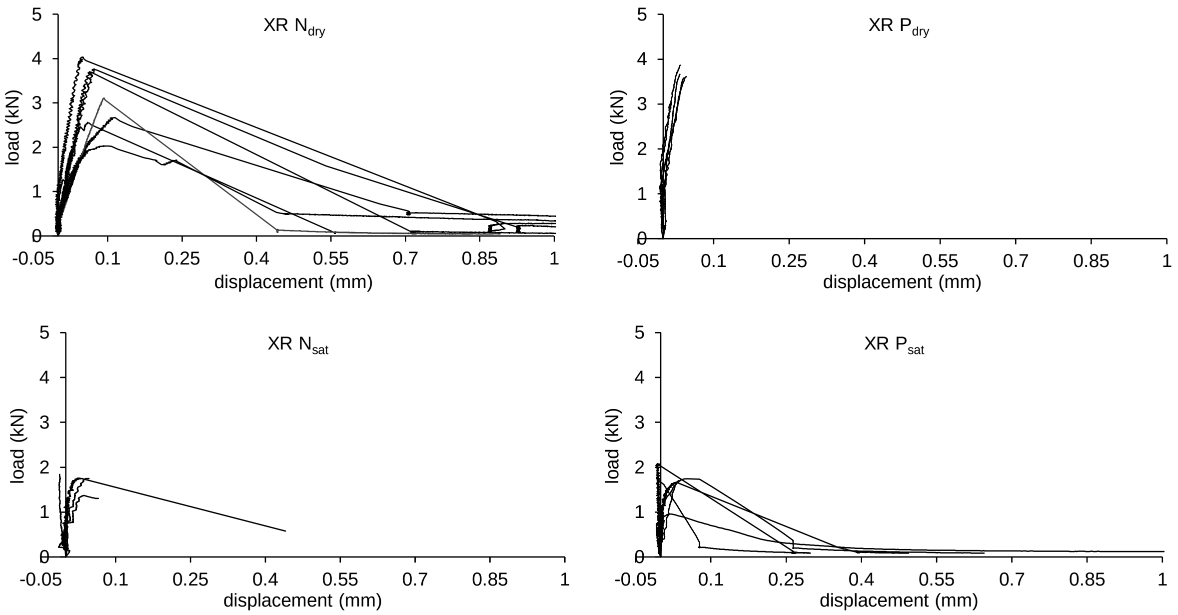


Fig. 7.31 – Flexural load-displacement diagrams of tested XR specimens: dry mass (above) and saturated (bellow) conditions.

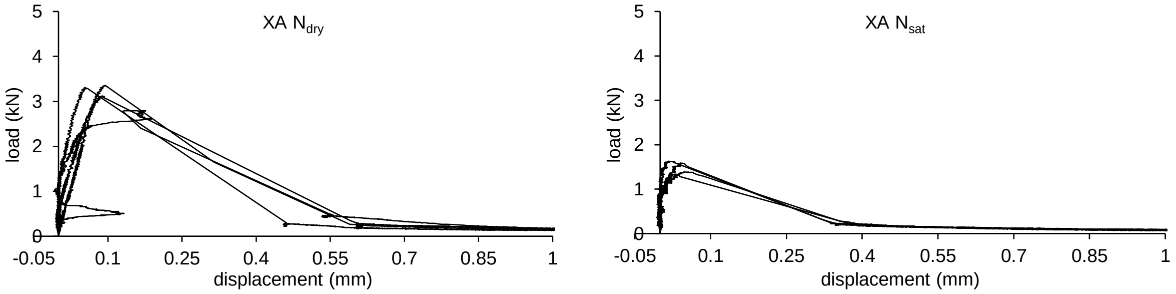


Fig. 7.32 – Flexural load-displacement diagrams of tested XA specimens: dry mass (right) and saturated (left) conditions.

c) Failure modes under flexural loading

To analyse failure on specimens under four-points bending testing, in Fig. 7.33, Fig. 7.34 and Fig. 7.35, are shown images from the groups of specimens tested under dry mass and saturated conditions. Analysing the images, one can conclude that the most typical failure was due to tensile crack formation from the notch upwards and inwards, causing specimens to split into two independent halves. Cases of eccentric cracking were residual. In the previously reported cases of catastrophic brittle failure, the rupture plane and the tensile crack would seem to split the entire specimen at once, without any visible propagation.

Analysing the above-mentioned images, GE specimens' failures are shown in Fig. 7.33, and can be described as the most regular failure observed on the tested rocks, with rupture being caused by a single vertical or slightly diagonal crack. As observed, either under dry mass or saturated conditions, excessive stress lead to the formation of regular rupture planes, with a low roughness interface surface.

Causes for such type of failure may be related to GE granite course-grain and heterogeneous mineral arrangement.

Regarding XA specimens tested under dry mass conditions, as shown in Fig. 7.34, tensile cracks propagated from the notch to the top following irregular vertical and slightly diagonal or curved paths. Nonetheless, under saturated conditions, tensile cracks showed a higher level of regularity, mostly following vertical paths. Under both testing conditions, rupture planes exhibit high irregularity and a strong roughness interface surface. Causes for such type failure may be attributed to this type of poorly-defined foliation and medium-grain mineral arrangement schist, that in comparison with the granite, caused frequents weaker plans and stress to relocate and change path. Analysing XR specimens' failures shown in Fig. 7.35, the previously described anisotropic behaviour becomes clear, with water significantly changing the rocks behaviour under transversal to foliation loading (N direction).

Therefore, analysing failure under dry mass conditions, on N loaded XR specimens, cracking and ruptures occur simultaneously by tensile stress, including lamellar disaggregation. As observed in several cases, crack propagation followed irregular and diagonal paths from the notch upwards, sometimes changing direction due to foliation. Under excessive stress, weaker foliation joints would rupture, causing stress to re-localize, causing upwards lamellar disaggregation. On P loaded XR specimens, catastrophic ruptures occurred by tensile failure caused by a diagonal crack, being cases of rupture by lamellar disaggregation only reported in one specimen.

Therefore, such failure mode was not considered significant for this loading direction. Under saturated conditions, both N and P loaded XR specimens showed similar tensile failures, caused by diagonal crack formation. At the exception of specimens exhibiting lamellar disaggregation, XR rupture planes showed a tendency for regularity and for smother superficial roughness, due to the fain-grain fabric of this type of schist. As expected, XR above-described failures are strongly conditioned by this schist well-defined and regular foliation, that on N loaded schists caused irregular rupture plans, being much more regular on P loaded specimens.

Analysing the above-presented results, one can conclude that under dry mass conditions, the tested schists, in comparison with the tested granite, show higher flexural strength and improved flexural behaviour. However, under saturated conditions it considerably loses flexural performance. Therefore, a more reliable and predictable flexural behaviour can be observed for granites, in this case GE granite, therefore justifying masons' preference on using granite to make beams and lintels.

Well-defined foliation schists, in this case XR schist, although showing higher flexural strength than poorly-defined foliation schists or granites, due to experimentally confirmed lamellar disaggregation when bent on N direction, and to stronger brittle failure when bent on P direction, confirms masons' reservations on using such type of schists to make lintels or beams.

Regarding poorly-defined foliation schists observed flexural behaviour, in this case XA schist, it is much closer to granites than to well-defined foliation schists, it confirms masons' choice for this type of rock as an alternative for granites to make beams and lintels.

Fig. 7.33 – Images from GE specimens tested for flexural strength (4-points bending test). Rupture plans (right); front and back views (centre); detail from a rupture surface interface (left).

Fig. 7.34 – Images from XA specimens tested for flexural strength (4-points bending test). Rupture plans (right); front and back views (centre); detail from a rupture surface interface (left).

Fig. 7.35 – Images from XR specimens tested for flexural strength (4-points bending test). Rupture plans (right); front and back views (centre); detail from a rupture surface interface (left).

7.4 Final remarks

Although being from the same family of natural materials and sharing the same regional area, the experimental characterization showed that schist and granites have intrinsic features that decisively influence their use as masonry material. These are related to mineralogical parameters such as the type of grain, minerals crystals and their arrangement, type of fabric and, regarding the tested schists, the presence of clays. Rocks microstructural features such as porous geometry, interconnectivity, and capillary network, and macrostructural parameters such as foliation or existing preferred orientation, decisively dictate rocks physical and mechanical behaviours. Therefore, the experimental knowledge collected about such physical parameters and their influence over rocks behaviour as a masonry material, came as a scientific confirmation to masons' experience acquired vernacular constructive knowledge.

Results from the experimental campaign showed that being rocks, common parameters such as porosity and density play a key role regarding schists and granites mechanical performance. Results show that high porosity is matched by low density, and therefore, by lower strength and some ductility. Such relation becomes clear comparing schists and granites performances. Experimental results also show that porosity and rocks' micro and microstructural parameters decisively dictate schists and granites water absorption behaviour, and expectably, their durability. Therefore, higher porosity seems related to higher water absorption and retaining capability, while the type of grain affects capillary absorption. As observed, the tested fine-grain rocks show higher capillary absorption capability. However, the presence of water proved to be a strength reducing and ductility increase factor.

Macrostructural features proven to decisively influence rocks overall performance, particularly with the presence of schistosity. Results proved the influence of anisotropy over schists performance, with a strong effect on well-defined foliation schists, influencing both physical and mechanical performance. However, anisotropy influence seemed to diminish in face of foliation irregularity and medium-grain mineral arrangement, as observed by the results for poorly-defined foliation schists. As for granites, the influence of a preferred orientation was clearly seen for some of the physical parameters. By using UPV, both anisotropy and preferred orientation influence over rocks internal discontinuities became clear, with schist showing a strong three direction anisotropy, whereas granites showed a two-direction planar organization.

Although without references from undamaged rocks, by comparison and taking into consideration that the tested rocks were under service conditions for prolonged periods of time, the analysed stone blocks were considered weathered. It was concluded that the tested rocks lower strength and higher ductility are also an outcome from such conditions, meaning, that both types of fresh rocks should present higher performances. Therefore, additional effort should be placed on assuring compatibility when applying new materials or fresh stones to vernacular structures, but also the pre-existing materials protection against weathering during preservation, rehabilitation, or maintenance operations should be considered a priority.

Chapter 8

DURABILITY ASSESSMENT OF STONES FROM VERNACULAR BUILDINGS

As observed during the fieldwork, salt and freeze-thaw damage are two of the most devastating types of material damages identified in vernacular masonry. As shown in Fig. 8.1, salt weathering in the study area represent very different levels of risk to vernacular buildings. Fieldwork observations revealed that in masonry built with strong rocks such as granites, salts damage was of non-structural type and generally located at superficial levels (see Fig. 8.2b). However, on masonry built with soft stones such as schists, cases of severe salt damage, that posed threats to structural safety of masonry walls, were identified (see Fig. 8.2a). Several origins for salts in the observed masonry walls can be pointed out, from human origin such as the contact between masonry and livestock (manures) or the proximity to agricultural fertilizers, or from environmental origin such as soils with high water table or exposure to sea spray [216].

However, as reported on examples from literature on the topic, it is expected that in the last decades, industrial farming and exposure to air pollutants such as the ones resulting from vehicles, may contribute significantly to the increase of salt weathering in more sensitive vernacular masonry, and to the diversification of the types of salts present [179,221].

Regarding frost damage, as described in Chapter 4, yearlong high humidity levels combined with very low temperatures, create the perfect conditions for peaks of superficial freezing in stones, at the lowland sub-region, and for intense frost weathering at the highland sub-region due to snow, see Fig. 8.2c. Frost damage was observed on buildings and granite masses at the temporary settlements built on the mountain range plateaus. Superficial damage was observed on granite structures at these remote locations, particularly on the platy shape stone slabs of corbelled domes, that due to superficial irregularities, allowed water to easily accumulate on its horizontal surfaces. As shown in Fig. 8.3, this specific type of stone blocks detached naturally from the larger granite masses, due to the water freezing on natural foliation or voids of rock outcrops.

Fig. 8.1 – Examples of damage observed during the fieldwork: (a) severe salt damage on well-defined foliation schist masonry wall (livestock compartment); (b) severe salt damage on well-defined foliation schist masonry wall (wine cellar), with large amonts of disaggregated material (powdering) accumulated at the base of the wall; (c) *“branda”* of Aveleira (Peneda mountain range) covered with snow during the winter.

Fig. 8.2 – (a) intense powdering and lamellar disaggregation caused by salts on XL and XR schists [36]; (b) example of salt efflorescence and sanding on GE granites [36]; (c) superficial disaggregation (splintering) caused by frost damage on GE granite corbelled dome platy shape stone blocks [36].

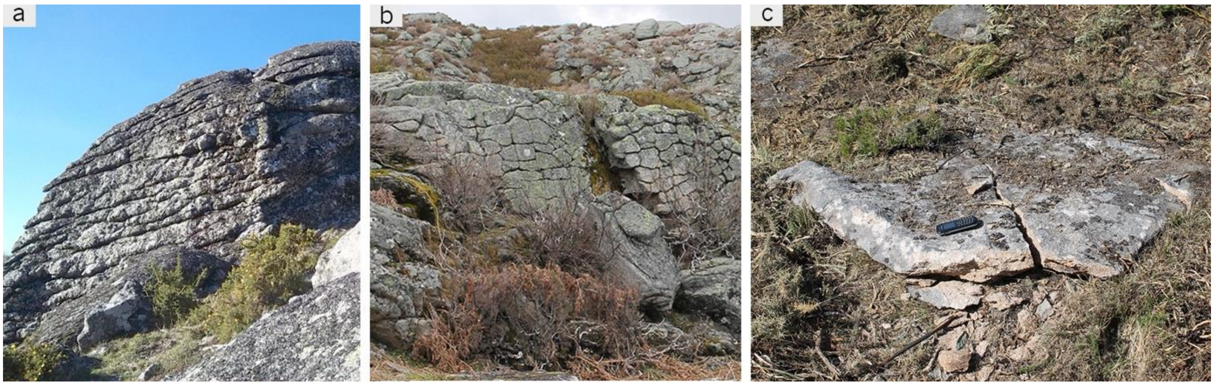


Fig. 8.3 – Examples of frost damage on granite outcrops: (a) failure along a preferred orientation; (b) fracturing of a face of granite outcrop; (c) detachment of a small platy shaped granite stone block.

According to literature, salt and frost damage are intimately related, since both weathering mechanisms rely on rock's porosity and capillary network, both cause crystallization and are highly dependent on water [174,178,179,216,221].

A general overview of salt weathering dynamics show the influence of a wide range of variables, ranging from type of salt to environmental conditions (e.g. sodium chlorite (NaCl) is not very reactive to temperature whereas sodium sulphate depends on thermodynamics to change phase, causing thernadite (Na_2SO_4) to precipitate to mirabilite ($Na_2SO_4.10H_2O$) [216]). It depends also on the presence of multiple salts acting simultaneously in the same rock (e.g. thernadite hydration and precipitation to mirabilite transition causes a temperature drop [216], whereas sodium chlorite deliquescence increases moisture content [221]). The interaction of salts with rock's mineralogic features, or with other acting weathering effects, can also enhance deterioration of rocks (e.g. sodium chlorite (NaCl) hydrates near the freezing temperature of water, thus contributing to enhance frost damage [179,216]).

As said previously, literature points out to the high dependence of salts on water, not only to impregnate and to move throughout the capillary rock network, but also through very dynamic interaction processes. Therefore, deliquescent salts such as sodium chlorite (NaCl) can absorb humidity from the environment when relative humidity (RH) is below the salt equilibrium, thus increasing rock's moisture content [216,221], whereas others such as sodium sulphate (Na_2SO_4), requires moisture to hydrate and change phase [216]. Charola [221] points to salts as a possible cause for the increase of capillary absorption and to higher amounts of retained water.

Regarding basic mechanisms of salt damage, it can be described as the outcome of internal stress induced over rock's structure, due to salts phase change (from dissolution to precipitation) [216]. Inside pores, dissolved salts precipitate (crystallize) in supersaturated solutions, causing a volume expansion process (crystals plus the residual saturated solution). Therefore, inside the confined space of smaller porous, pressure is induced leading to stress over the fabric of the rock [178,216,221,253]. In this process, Doehne [253] points out to the vital role of supersaturated solutions, easier to maintain on smaller porous. According to the author [253], salt nucleation (crystallization) starts on smaller porous, prior to its start on larger porous. Besides pure crystallization pressure, stress caused by salt weathering can also be the outcome of hydration pressure, osmotic swelling of clays or differential thermal expansion, all depending of each salt specific features [179,216,253].

As Goudie [216] points out, environmental conditions such as frequent wet-dry cycles, that potentiate salts phase change (dissolution and recrystallization), high evaporation rates that increase saturation of salt solutions, or the continuous contact with salt sources, contribute to increase vertiginously the effects of salt weathering.

Being frequently combined with salt weathering, frost weathering is described by Ruedrich et al. [233] as one of the main causes for visible damage in historic masonries. As salt damage, frost damage is also highly dependent on water saturation and evaporation rates, but also on RH and on environmental temperature, to cause the damaging freeze-thaw cycles [178,179]. Besides the previously mentioned interaction with salts, Ruedrich et al. [233] highlights rocks minerology and fabric properties for its considerable influence in the developing of the frost weathering process.

As for the frost damage mechanism, it is described in literature as complex and presenting high uncertainty regarding clear identification of its causes [178,179,233]. Nonetheless, according to Winkler [179], the interaction between ice-water temperature, pressure and volume expansion are the key elements to explain the dynamics of damage caused by frost. Water retained inside rocks in porous or voids, due to super cooling phenomena, changes from the liquid to the ice phase [178,179,233].

With the formation of ice crystals, and consequent volume expansion (around ≅ 9% [178]), an ice-front moves inwards, causing pressure on the walls of porous and over the confined unfreeze water, therefore, placing the fabric of the rock under stress [178,179,233]. Attending to observations performed by Ruedrich et al. [233] on sandstones tested for frost damage, ice crystals formation at different temperatures induce different levels of stress over rocks, caused by the dilation and contraction of the material throughout the freeze-thaw cycles. According to Winkler [179], such stress can reach a maximum of 200 MPa at a temperature of -22 ℃.

Bell [178] points out the role of pores over the behaviour of rocks under the effect frost weathering. According to the author [178], such behaviour is conditioned by features such as pores geometry, distribution and interconnectivity. On one hand, rocks showing high porosity and large amount of micro-pores are able to retain larger amounts of water, due to slower drainage and evaporation, thus making these rocks more susceptible to both frost and salt damage [178,216,233]. On the other hand, rocks with lower porosity and larger pores, show faster water drainage and evaporation, making them less susceptible to both types of weathering [178,216,233]. According to Bell [178], rocks with pores size over 5 μm seem less prone to frost damage. However, the author [178] points out that in face of critical moisture contents (between 75 to 96%), all rocks fail under freeze-thaw cycles.

The complete and detailed characterization of both weathering phenomena regarding the tested rocks lies outside the scope of the present research. Therefore, the experimental research developed within this thesis is focused first on analysing the level of resistance of the material to salt and frost damage, and secondly, on a very synthetic characterization of the damage observed on the tested specimens. Taking into consideration the destructive nature of such experimental procedures, two groups of specimens were prepared and tested under cyclic salt loading and freeze-thaw.

All specimens used for the durability tests were previously tested for physical characterization, following the experimental procedure presented on Section 7.2. Subsequently, for specimens showing an acceptable cohesion state, physical tests were repeated followed by axial compression tests, as presented in Section 7.3. Based on literature, the damage assessment table presented in Table 8.1 was elaborated and applied to support the visual assessments performed on specimens throughout the experimental campaign.

Table 8.1 – Reference damage assessment and rating for specimens tested for salt crystallization (NP EN 12370:2001 [254]) and frost damage (NP EN 12371:2006 [255]).

Damage rating (1 to 6) (adapted from NP EN:12371:2006 [255])	Observable damage (based on [36,178,181,216])	
	structural	superficial
LD1 Extremely resistant	discoloration and formation of light deposits	
LD2 Strongly resistant	showing one or several small cracks (≤ 1 mm width); or the loss of small fragments (≤ 1 mm^2 each fragment),	low levels of erosion of surfaces and edges (e.g. rounding of edges, low level of pitting or scaling); deposits formation
LD3 Moderately resistant	one or several cracks, low level of lamellar disaggregation (joints clearly identifiable), holes or fragments losses (≥ 5 mm^2 each fragment); or showing changes in the material contained in the material's veins	moderate erosion due to disintegration of edges or surfaces (e.g. sanding or powdering), alveolation, and formation of film and patina; deposits formation
LD4 Poorly resistant	specimen splits into two individual halves; the loss of large fragments (≥ 5 mm^2 each fragment); or showing large and deep cracks > 1mm; opening of foliation joints*	intense erosion with strong superficial disaggregation; formation of deposits; intense sanding with lamellar reattaching if the material is compressed*
LD5 Very poorly or non-resistant	full rupture; strong fragmentation with visible deep cracks into several different orientations; lamellar disintegration*	very intense erosion that compromises the cohesion of the material
LD6 Non-resistant (schist only)	very strong or full disintegration of the planer structure of the rock	

Note: *parameter only observable on schist specimens

8.1 Salt damage

Salt resistance tests were performed on groups of 6 specimens of each type of rock (40 x 40 x 40 mm^3), on 24h wet and dry cycles, following the experimental procedure presented in NP EN 12370:2001 standard [254]. As shown in Fig. 8.4a, larger XM specimens were used (50 x 50 x 50 mm^3) due to the unavailability of smaller specimens.

An 14% $Na_2SO_4 \cdot 10H_2O$ (mirabilite) solution was prepared, as shown in Fig. 8.4b and used to load the specimens with salt. Specimens were immersed in the solution for a period of 2h, followed by an 15h oven drying period (105℃). A pump was used to avoid solution crystallization during the immersion cycle, see Fig. 8.4c. During the remaining time, specimens were cooled at room temperature, weighted to determine mass variation (see Fig. 8.6 and Fig. 8.7). Afterwards they were visually inspected and photographed to identify visible damage (Fig. 8.5 and Fig. 8.9). The salt solution was replaced at each cycle to avoid contamination with suspension particles, see Fig. 8.4d.

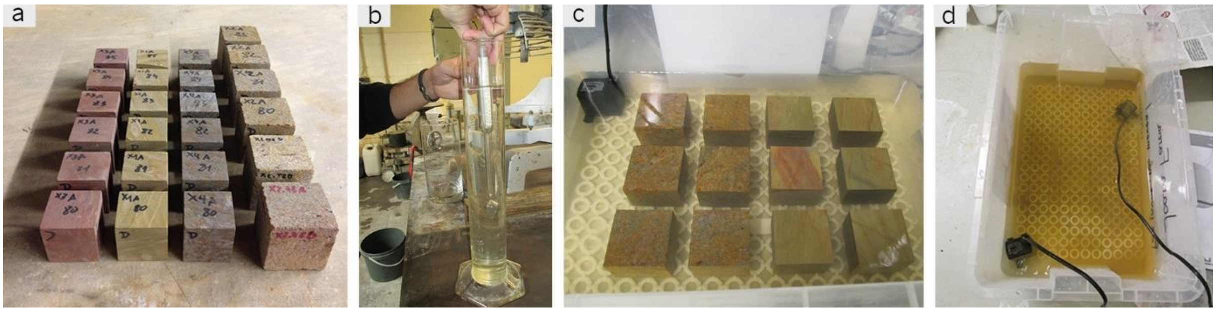


Fig. 8.4 – Images from the salt resistance tests on schists: (a) group of schists specimens used; (b) $Na_2SO_4 \cdot 10H_2O$ solution preparation and density check using a densimeter; (c) immersion cycle; (d) salt solution after the removal of the specimens, showing visible deposits of lost schist particles.

Regarding the visual damage assessment, rocks were assessed as damaged if LD3 was reached in at least three of the tested specimens. The rupture (Ru) of the tested rocks was determined when full rupture was observed in at least three specimens.

Comparison between the level of damage observed during the fieldwork shown in Fig. 8.2, with the damage observed on the tested specimens, see Fig. 8.9, showed that to achieve the same level of damage, more than 15 cycles (indicated in the standard) were required. Therefore, the testing was extended for an additional period of 15 cycles, being the first 15 cycles (15c) of salt loading named as short-term exposure period, and the additional 15 cycles (30c) named long-term salt loading period.

At the end of the testing and before the final oven drying and weighting, specimens were carefully washed on distilled water to remove the retained salt as much as possible. Specimens reaching cycle 30 and showing acceptable cohesion levels, were re-tested for physical parameters characterization and for strength, see Table 8.3 and Fig. 8.8. The testing results and each rock salt resistance rating are presented in Table 8.2.

Analysing the mass variation of schists and granites, respectively presented in Fig. 8.6 in Fig. 8.7, an initial gain of mass was observed for all tested specimens. These results are consistent with the observations of Ruedrich et al. [233], that points to initial salt accumulation inside specimens to explain such behaviour, meaning that the gain of mass due to salt accumulation is superior to the mass loss by the specimen at this phase of the salt loading. Regarding the global results shown in Table 8.2 and Fig. 8.5, it becomes clear that the tested schists present a very poor global resistance to salt damage, whereas the tested granites show a much better global response.

Regarding the salt resistance for the tested well-defined foliation schist, specimens show the poorest performance among the tested rocks, with XL (2c) and XR (1c) specimens achieving LD3 damage in the first two cycles, being full ruptures observed at cycles 5 and 3 respectively. Due to the specimens' premature loss of cohesion, damage monitoring on XL and XR schist specimens was only possible through visual inspection. As observed, the highest level of sustained damage for XL (6c) and XR (4c) specimens was LD6, achieved before the first quarter of the testing. However, to properly understand, from a qualitative point of view, the progression of the severe growing superficial damage, specimens from both types of schists were kept under testing until their complete disintegration.

As for poorly-defined foliation schists, results presented in Table 8.2 and Fig. 8.5 show XA and XM specimens improved resistance to salt loading in comparison with the well-defined foliation specimens. Although LD3 damage was also observed at early stages for XA (3c) and later for and XM (9c) specimens, results show a considerably slower damage progression on poorly-defined foliation schists specimens in comparison with well-defined foliation schists specimens. As observed, although XA (LD5) specimens presented a faster initial damage progression, their final level of sustained damage was inferior to the one achieved by XM (LD6) specimens.

Analysing mass variation results, at cycle 15, XM (-12.17% – LD4) specimens show an intense loss, 1.66 times superior in comparison with XA (-7.32% – LD4) specimens. However, both types of schist show a similar and very strong loss of mass at cycle 30, 1.05 times stronger on XA (-45.97% – LD5) specimens in comparison with XM (-42.51% – LD6) specimens. Results in Fig. 8.6 regarding mass variation in time show that after the stable initial gain of mass, mass losses increase consistently for XA (10c to 26c) and XM (8c to 21c), becoming significantly stronger in last branch of each diagram. These results are consistent with the visual damage assessment shown in Fig. 8.5.

Regarding granites, Table 8.2 and Fig. 8.5 results show that GE granite presents the strongest resistance to salt damage among the tested rocks, with its specimens reaching a maximum of LD1 level of damage at the end of the test (30c). GA specimens show higher susceptibility to salt damage, becoming damaged by the end of the short-term exposure period (LD3 – 14c), and became stable until the end of the testing. Analysing mass variation for the short-term exposure period, both GE (0.32% – LD1) and GA (0.15% – LD3) specimens only show mass gain by cycle 15. Fig. 8.7 mass variation diagrams show a consistent positive gain tendency for GE (0.27%– 30c) specimens, whereas for GA (-0.58% - LD3) specimens, the positive gain tendency is replaced at the final quarter of the testing, by negative tendency. GA final variation average results may be affected by the more intense damage shown by one of its specimens (loss a larger fragment). Nonetheless, mass variation results for granites are also consistent with the visual damage assessment shown in Fig. 8.5.

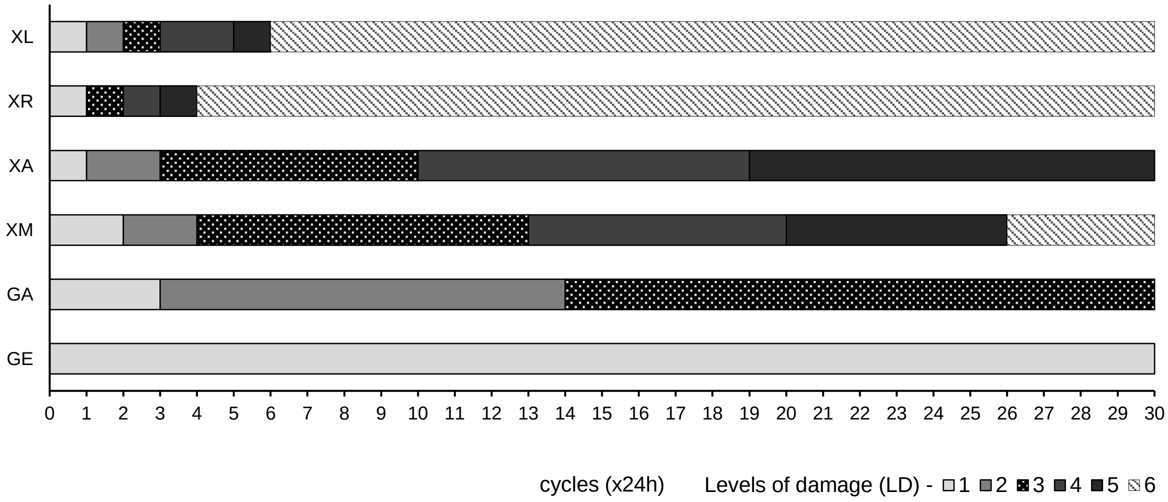


Fig. 8.5 – Damage rating of specimens tested for salt crystallization (see Table 8.1 for LD). Rocks are considered damaged when LD3 is reached on three specimens [255].

Table 8.2 – Salt weathering damage assessment and rating (NP EN 12370:2001 [254]).

Rock	Damage assessment through visual inspection (≥ 3 specimens showing LD3*)	mass variation coefficient (ΔM)		salt resistance rating (after Barros [181])* (15c/30c)
		ΔM 15c (%)	ΔM 30c (%)	
XL	LD3 – 2c Final: LD6 – 6c	Ru – 5c	n.a.	Non-resistant
XR	LD3 – 1c Final: LD6 – 4c	Ru – 3c	n.a.	Non-resistant
XA	LD3 – 9c Final: LD5 – 19c	-7.32 (25%) [-9.69 – -5.22]	-45.97 (51%) [-83.49 – -22.82]	Poorly resistant Non-resistant
XM	LD3 – 3c Final: LD6 – 26c	-12.17 (21%) [-16.63 – -9.74]	-42.51 (19%) [-50.88 – -31.06]	Poorly resistant Non-resistant
GA	LD3 – 14c Final: LD3 – 14c	0.15 (101%) [-0.07 – 0.28]	-0.58 (145%) [-1.78 – 0.10]	Moderately resistant
GE	LD1 – 1c Final: LD3 – 1c	0.32 (23%) [0.21 – 0.39]	0.27 (25%) [0.18 – 0.35]	Extremely resistant

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets; c - number of cycles to reach the indicated damage; *see Table 8.1.

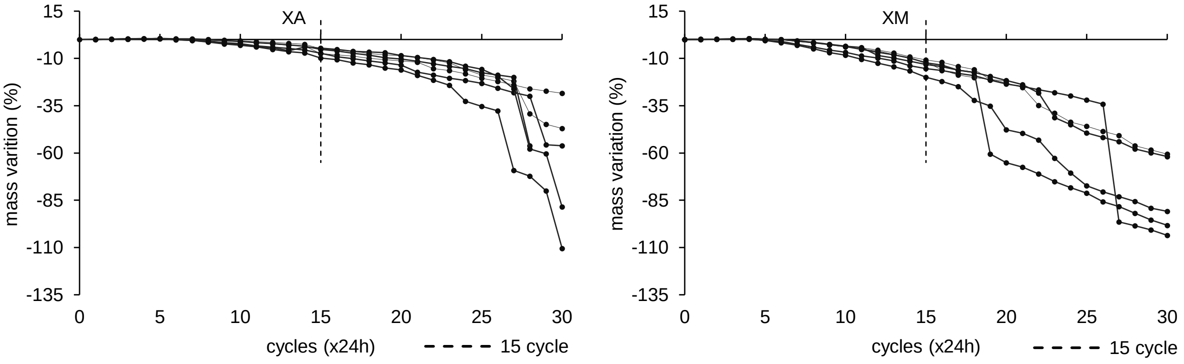


Fig. 8.6 – Mass variation on poorly-defined foliation XA and XM schists, along the salt crystallization tests.

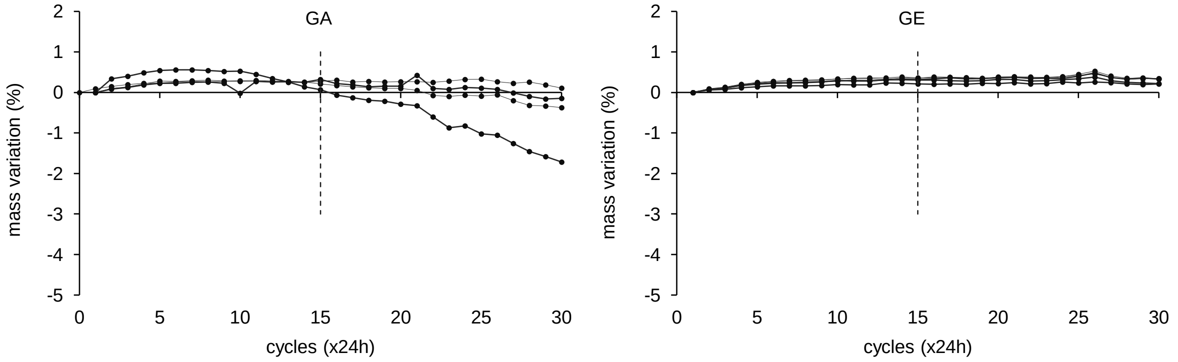


Fig. 8.7 – Mass variation on GA and GE granites, along the salt crystallization tests.

Due to the acceptable cohesion shown at the end of the testing by granite specimens, they were physically and mechanically characterized. As shown in Table 8.3 and Fig. 8.8, a global loss of physical and mechanical performance was detected on both granites, being more intense on GA specimens. To be noticed, Fig. 8.8 parameters positive variation represents higher values after cycle 30c, whereas negative represents lower value after cycle 30c. Analysing the results, it is clear the increase on porosity (ρ_o) and a decrease on apparent volume (V_b), although no significative changes to apparent density (ρ_b) can be observed. The observed consistent loss of UPV propagation, indicates an increase on the amount of internal discontinuities. Although any retained salt would lead to an increase on propagation velocity, salts successive recrystallizations are known to induce stress to the material and to cause microcracks and porous enlargement, therefore to create new voids and barriers to UPV propagation [216,233]. Consistent with these results are the water absorption values. Higher absorption at atmospheric pressure (A_b) is consistent with rocks with higher porosity and voids to retain water, whereas slower capillarity absorption (C) is consistent with the presence of larger porous [179]. Due to higher internal discontinuities and possible granular breakdown caused by the cyclic recrystallizations associated to higher porosity levels, as expected, a loss of strength (R) and an increase on deformability (E) was confirmed by the obtained results [178,179]. The stronger average relative variations observed for GA in comparison with GE specimens, may be due to GA granite stronger initial weathering level.

Table 8.3 – Physical and mechanical parameters of GA and GE granites tested for salt crystallization resistance: before (0c) and after (30c).

Rocks	Cycle	Open Porosity ρ_o (%)	IAEG*	Apparent Density ρ_b (kg/m^3)	Apparent Volume V_b (ml)	Water absorption		UPV (m/s)			Compressive strength *R* (MPa)	Elastic Modulus E (GPa)
						A_b (%)	C (g/m^{2}s$^{0.5}$)	N	P1	P2		
GA	0c	4.6 (12%)	L	2473 (1%)	134.43 (1%)	1.7 (10%)	13.25 (8%)	2198 (9%)	2318 (11%)	2831 (7%)	42.61 (16%)	5.39 (22%)
	30c	5.5 (18%)	M	2496 (1%)	130.06 (3%)	1.9 (18%)	10.47 (20%)	1922 (17%)	2121 (21%)	2662 (14%)	39.43 (31%)	4.87 (33%)
GE	0c	3.3 (11%)	L	2539 (1%)	131.29 (1%)	1.1 (10%)	7.37 (10%)	2117 (11%)	2523 (10%)	2909 (7%)	79.53 (14%)	13.37 (27%)
	30c	3.8 (14%)	L	2552 (1%)	130.71 (1%)	1.3 (16%)	3.79 (18%)	1888 (18%)	2530 (12%)	2779 (9%)	66.48 (23%)	12.41 (26%)

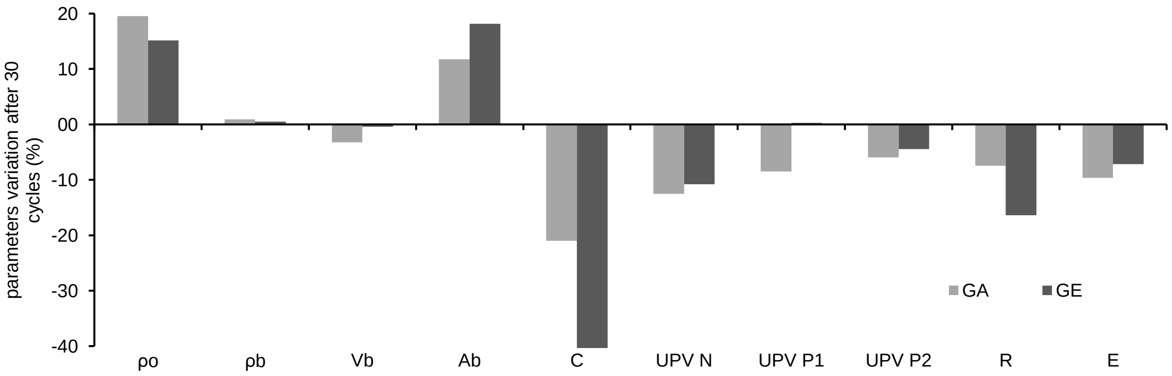


Fig. 8.8 – Physical and mechanical parameters variation on GA and GE granites tested for salt crystallization resistance.

Analysing the images from specimens tested for salt weathering presented in Fig. 8.9, GE granites show very light superficial damage, whereas GA granite show strong edges erosion by crumbling, and low deep cracks and light sanding on faces.

Visible salt damage on schists is considerably more intense. On well-defined foliation XL and XR schist, it is clear the strong influence of anisotropy by the concentration of damage over the foliation joints and, therefore, causing lamellar disaggregation. As was also observed, the same type of phenomena was observed on specimens with pre-existing cracks or voids. According to Goudie [216], regarding salt damage, structures such as foliation or preferred orientation of minerals act as weakness planes and increase the surface area exposed to salt damage. Therefore, crystallization in the foliation joints, due to the consequent volume expansion, induces stress over the interface, and often causes the rupture of the schist specimens. As for the observed superficial damage identified on the schist specimens, causes may be related to the presence of clays.

According to Charola [221], the presence of clays on rocks is known to promote salt damage. According to the author [221], clays accumulated along bedding planes are known to cause delamination and scaling damage, whereas if present in discrete pockets, rocks show a tendency for alveolation. According to Jiménez-González et al. [252], stress is caused during wet-dry cycles by clays swelling and shrinkage due to moisture. This phenomenon is stronger with salt loading (salt activated clays swelling or osmotic swelling [221,256]).

Analysing XL and XR specimens damage, one can clearly observe the above-described process of rupture following foliation organization of the rocks. Failure started by large transversal cracks, resulting from the opening of weaker foliation joints that split specimens into large sections. Damage progression caused a strong delamination by the continuous splitting of specimens into smaller sections, following the rocks preferred orientation. Intense peeling was observed on the rupture interfaces and surfaces parallel to foliation such as the top and bottom faces and interface between layers. As for the strong powdering and rounding of edges seen in these schists, can also be explained by their high porosity and fine grain structure. According to Goudie [216], such type of rocks often present high amounts of smaller porous with higher water retaining capability, caused by a slower evaporation process. Therefore, according to the author [216], salt solutions show a higher tendency to supersaturate near the surface under such conditions, promoting the effect of salt weathering. Analysing the damage shown by poorly-defined foliation XA and XM specimens, although similar damage patterns were observed, their intensity was considerably different. In comparison with XA specimens, XM specimens exhibit earlier superficial damage of roughening of faces and rounding of edges. XA specimens exhibited initially sanding processes (loss of larger grains), followed by intense powdering and superficial crumbling. Delamination became intense during the last quarter of the long-term exposure period, followed by splitting and rupture of specimens. XA specimens showed a slower damage progression, evolving to a much less intense delamination damage, followed by formation of large and deep cracks that fragmented and failed. Explanations to the damage observed on the poorly-defined foliation schists, may be related to these rocks' medium-grain and irregular foliation.

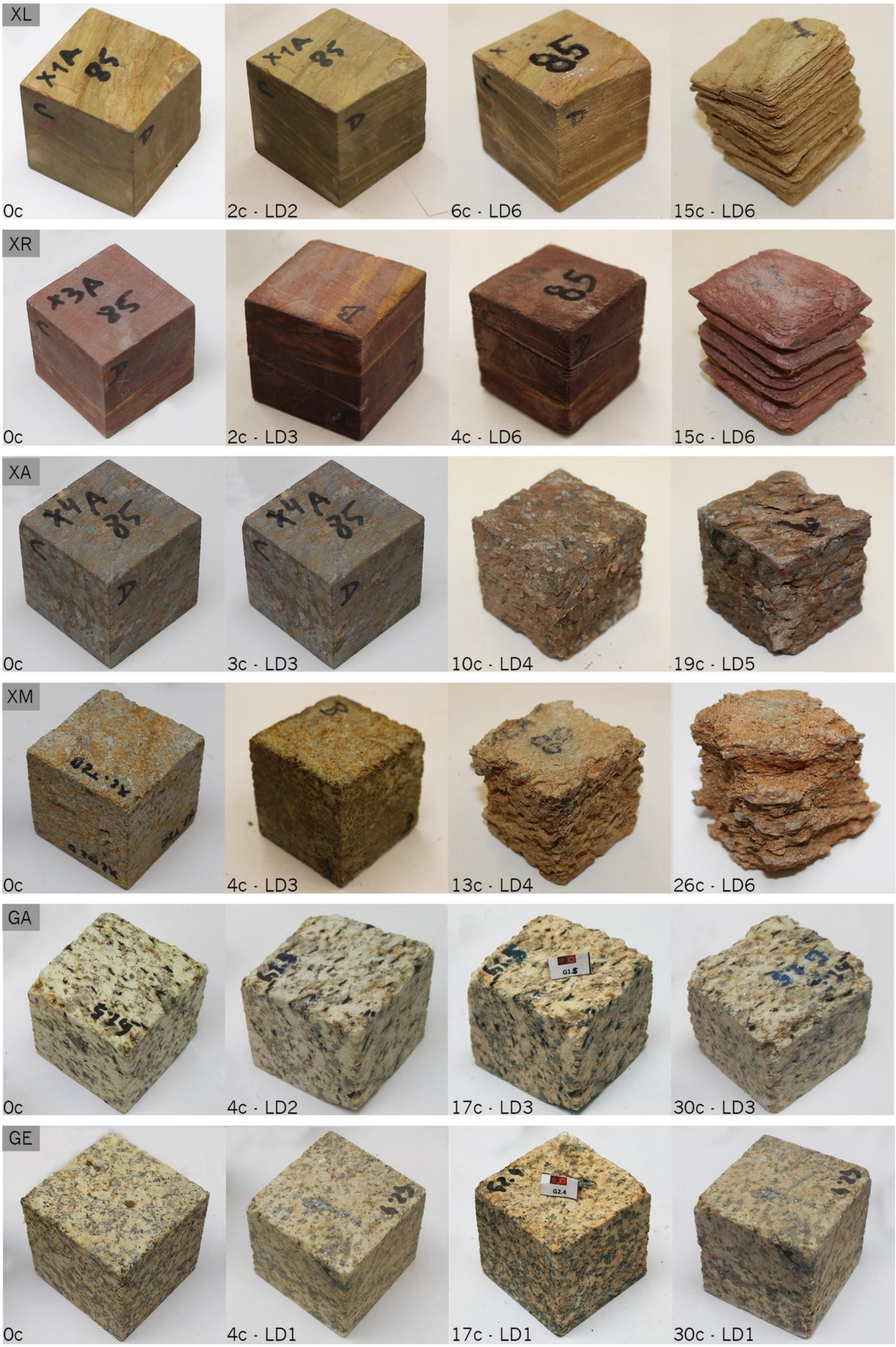


Fig. 8.9 – Specimens tested for salt resistance. The type of rock is shown above and the cycle (c) and damage rate (LD) is also indicated in each picture.

Analysing the damage observed on granites, GE specimens showed a very low level of superficial damage mainly by exhibiting colour changes (brownish shade). GA specimens showed progressive erosion of surfaces due to sanding, and losses of material on edges due to intense rounding. The exceptionally low level of damage showed by GE granite may result from this rock lower initial weathering level in comparison with GA specimens. Both granites show higher salt weathering resistance in comparison with the tested schists, which may be explained by their coarse-grain fabric and lower porosity. According to Goudie [216], such type of grain is generally associated to larger pores that provide improved entry and evaporation points to moisture, reducing the exposure of the material to supersaturated solutions, therefore, to salt weathering.

Taking into consideration the above-presented results for the salt weathering tests, as shown in Table 8.2, GE granite was globally rated as Extremely Resistant to salt weathering, whereas GA granite was rate as Moderately resistant to salt weathering. Such results were expected, taking into consideration the lower porosity, meaning lower susceptibility to water penetration, and higher strength of these rocks, able to sustain higher levels of internal stress caused by crystallization [216]. However, according to Barros [181], by gaining mass during the salt loading, may indicate future salt damage hazard due to its high concentrations inside the rocks. Regarding XA and XM poorly-defined foliation schists, results show a poor performance during the short-term exposure period, becoming severely deteriorated under longer exposure periods. Therefore, for short-periods exposure, the tested poorly-defined foliation schists were rated as poorly resistant, becoming non-resistant for long-term exposure periods. As for the well-defined foliation XL and XR specimens, these rocks are rated as Non-resistant to salts weathering. The results obtained for the schists are consistent with the results obtained by Barros [181] for several types of schists tested for salt resistance. According to Barros [181], schists with high levels of open porosity and water absorption are prone to higher levels of salt damage.

8.2 Frost damage

To better understand the effect of frost weathering over the study of schist and granite, they were tested according to the experimental procedure for frost resistance determination, presented in NP EN 12371:2006 [255] standard. The testing campaign was carried out in 24h freeze-thaw cycles (c), repeated to a maximum of 350 cycles. Specimens were monitored according to pre-established checks, to determine any damage progression.

Taking into consideration the salt weathering test results, the frost resistance experimental campaign design was based into a short-term exposure period of 90 cycles, followed by a long-term exposure of additional 260 cycles. In this way, it became possible to be aware of early damage sustained by rocks with higher sensitivity to frost damage, while allowing a longer period of testing for rocks with higher resistant to frost damage. During the first freezing-thawing exposure period, regular checks were performed each 15 cycles, whereas during the second, these were performed every 30 cycles. Ruedrich et al. [233], point to the close relation between high susceptibility to salt and frost damage, and to the important role of moisture on both types of weathering. Therefore, for showing stronger water absorption, it was expected higher susceptibility of schists to frost damage. Taking into consideration the strong and fast delamination of well-defined foliation schists caused by salt crystal expansion, the same phenomena was expected caused by ice crystals expansion. Such concern lead to perform shorter initial visual checks at every 5 cycles, until cycle 30 was reached. Based on specimens' availability, limited by the option of always resorting to specimens of the same stone blocks throughout the experimental campaign, lead to the selection of only GE granite for testing, and, as shown in Fig. 8.10b, limited specimens size to 50 x 50 x 50 mm^3. Due to the shortage of larger XR specimens, 40 x 40 x 40 mm^3 were used instead.

Specimens were divided into 5 groups (G30 to G350), each with 5 specimens for each type of rock, in a total of 25 specimens per group, and tested according to a pre-established testing periods of 30c, 60c, 90c, 175c and 350c respectively. All groups were visually inspected throughout the experimental campaign at each programmed check (each 15c or 30c), to visually identify damage and conditions that could severely compromise specimens' integrity. G350 underwent detailed visual inspection and physically characterized at each programmed check, whereas for the remaining groups, these were only visually inspected.

As for the test setup and equipment, see Fig. 8.10a, a fully automated Fitoclima® 6400 EC25 climatic chamber was used to perform the 24h freeze-thaw cycles, alternating and maintain temperatures from 20℃ (max.) to -25℃ (min.) [255], as shown in Fig. 8.11. Inside the chamber, specimens were placed over a plastic mesh 15 cm above the ground to maximize absorption from the bottom face, and to protected specimens from frozen residual water. Tap water was used for the immersion cycle, and it was introduced into the climatic chamber at room temperature. The immersion cycle was slightly inferior to 2h. A long thaw cycle made sure that the water feeding mechanisms (hoses and internal pump) were fully unfreeze. Water was fully removed from the mechanisms before temperature dropped below 0℃. An external reservoir was used to store the tap water. A submersible pump permanently placed inside the reservoir was used to feed the climatic chamber with water at the beginning of the immersion cycle, whereas a pump placed inside the chamber sent the water back to the reservoir at the end of the cycle.

Fig. 8.10 – Frost resistance test: (a) Fitoclima® 6400 EC25 climatic chamber used to automatically perform the freeze-thaw cycles; (b) groups of specimens tested for frost resistance.

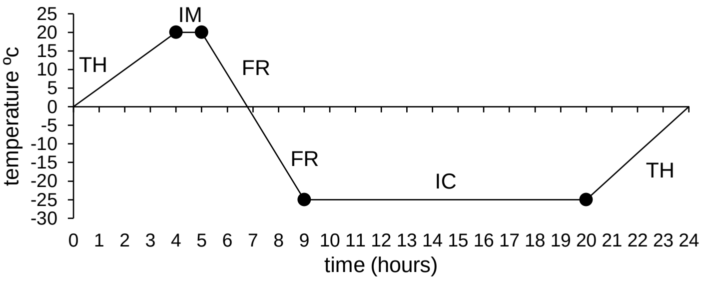


Fig. 8.11 – Freeze-thaw cycle program: IC – Ice cycle; FR – freezing cycle; TH – thawing cycle; IM – immersion cycle.

As for the procedure used to monitor the effects of frost weathering over G350, specimens were removed from the climatic chamber before the end of the immersion cycle, warmed naturally at room temperature for 2h, followed by oven drying (105℃). Specimens were weighted to determine their dry mass (m_d), visually inspected and photographed for visual damage identification and analysed for UPV. Afterwards, specimens were saturated using a vacuum chamber (800 psi) and weighted for saturated (m_s) and immersed (m_i) mass determination. Specimens were returned to the climatic chamber at the start of the immersion cycle to resume the testing. The same monitoring procedure was performed once each group concluded their freezing-thawing exposure period, complemented by water absorption tests, before performing the axial compression tests.

According to NP EN 12371:2006 [255] standard, frost damage assessment can be performed either by identification criteria or by technological criteria. By the first type of assessment, damage evaluation is based on visual inspection (LD), and on apparent volume (V_b [228]) and dynamic modulus variations (E_d). For the visual inspection damage assessment, all tested specimens were taken into consideration. For the apparent volume and dynamic modulus variation criteria, it was performed by using G350 specimens continuous time variation monitoring. Regarding the second type of assessment, specimens that outlasted each programmed number of freeze-thaw cycles, were destructively tested for strength (R) and elastic modulus determination (E) [217]. Complementary analysis was also carried out to determine changes to specimens' porosity (ρ_o), apparent density (ρ_b), internal discontinuities formation by UPV and water absorption behaviours. To be noticed, that all mentioned physical and mechanical parameters characterized during the frost resistance testing, followed the procedures presented in detail respectively on Section 7.2 and Section 7.3. To rate a rock as damaged by frost weathering, one of the above-mentioned damage criteria should be clearly identified. Therefore, and for the sake of clearness, a group of specimens was rated as damaged when two or more specimens were rated as showing any of the pre-established damage criteria. A type of rock was considered damaged when at least three out of five groups were rated as such. The final assessment was based on a qualitative assessment, that took into consideration all the results obtained throughout the frost resistance experimental campaign. Due to the severity of the damage sustained by XL and XR specimens, that fully compromised specimens' cohesion to the point of making all physical and mechanical analysis unfeasible, their frost weathering assessment is exclusively performed by visual damage assessment criterion.

8.2.1 Damage identification by visual inspection

The visual assessment of damage (LD), was carried out according with the rating previously presented in Table 8.1. Damage time progression by rock type is presented in Fig. 8.12, and images of tested specimens are presented in Fig. 8.13 for the granite, and in Fig. 8.14 for schists.

As expected by the salt weathering results, schist present a more intense and fast evolving damage in comparison with the granite. Well-defined foliation schists presented already very severe level of damage (LD4) by the first visual check (5c), characterized by having acquired a lighter shade, already with specimens showing deeper cracks, others split and already fragmentated. As observed on XL and XR specimens, freeze-thaw cycles caused a very early opening of foliation joints and cracking in any existent weakness plans such as pre-existing cracks and voids. Full lamellar disintegration and specimens' complete loss of cohesion (LD6) was reached by the cycle 25 for XL schist and cycle 50 for XR schist. Although very similar, damage progression was faster on XL specimens. As observed in Fig. 8.14, XL specimens' foliation higher regularity caused a more intense and stronger process of lamellar disaggregation in comparison with XR specimens, evolving to intense flacking and disintegration during the final freeze-thaw cycles.

A fine-grain and regular foliation, that facilitated water retaining and penetration into the specimens [216], and the combined effect of stress (tensile and or shear) caused by the ice crystals expansion inside the weaker foliation joints (Taber-Everette effect [224]) and possible phenomena of clay swelling and shrinking caused by hydration, are variables that, isolated or combined, may explain the severity of the observed damage [224,233,252]. Regarding clay swelling, according to Jiménez-González et al. [252], superficial damage such as flacking and cracking can result from shear stresses associated to the wetting and drying of the material. According to the author [252], with the stress located between the wet/dry interface of layers, superficial and interface damage results from buckling of the wet surface.

Contrary to the type of superficial damage observed during the salt weathering tests, no traces of powdering or sanding were directly observed on the faces of specimens. However, the rounding of edges and vertices, and the presence of a thin layer of sediments inside the external water reservoir, show that such damage was in fact acting over specimens.

Analysing the visible damage on poorly-defined foliation XA and XM schists, it was considerably less severe in comparison with well-defined foliation schists. Nonetheless, XA and XM schists were rated as damaged during the long-term exposure period for reaching LD3. Comparing both schists, XA shows a slower damage progression that stabilized at LD3, whereas XM shows a faster damage progression, that only stabilized at LD4.

Analysing Fig. 8.14, visible damage on XA specimens show that specimens acquired a more brownish shade, with damage concentrations in voids and pre-existent cracks, causing a few losses of fragments, cracks deepening due to the dissolution of filling materials. A very light superficial erosion with traces of pitting was observed. As for the identified damage on XM schist, specimens acquired a more yellowish shade. Faces and edges showed a stronger superficial disaggregation caused by sanding, with loss of material. During the long-term exposure period, intense superficial disaggregation of faces, by scaling and cracking, become a frequent damage. As in the case of XA specimens, damage concentrated on pre-existent cracks and voids, generally evolving to very deep and wider cracks and the enlargement of voids. Cases of specimens with the losses of large fragments were very residual. For both types of schists, no evidences of lamellar disaggregation were identified during the freeze-thaw cycles. Explanation may be related to these rocks irregular foliation and medium-coarse grain [216,233]. Regarding examples of tested GE specimens shown in Fig. 8.13, they show a consistent brownish shade that may be explained by their proximity to schist specimens inside the chamber, indicating that the stones may absorbed materials during the immersion cycles. Nonetheless, observed damage was residual with no changes to surfaces or considerable damage concentration on pre-existent defects. Visible damage was restricted to very light traces of edges and vertices erosion, resulting in the loss of residual quantities of grain. Therefore, damage identified in tested GE specimens was not higher than LD1. Higher strength and lower level of weathering in comparison with the schists, a very heterogeneous and coarse-grain fabric may explain GE granite results [216].

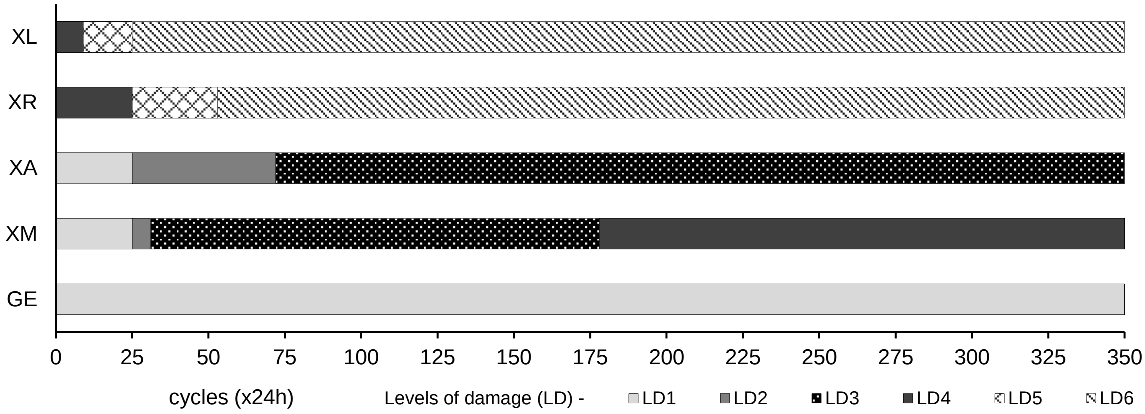


Fig. 8.12 – Damage analysis of specimens tested for frost resistance through visual inspection (see Table 8.1 for LD) [48].

Fig. 8.13 – Granite specimens tested for frost resistance.

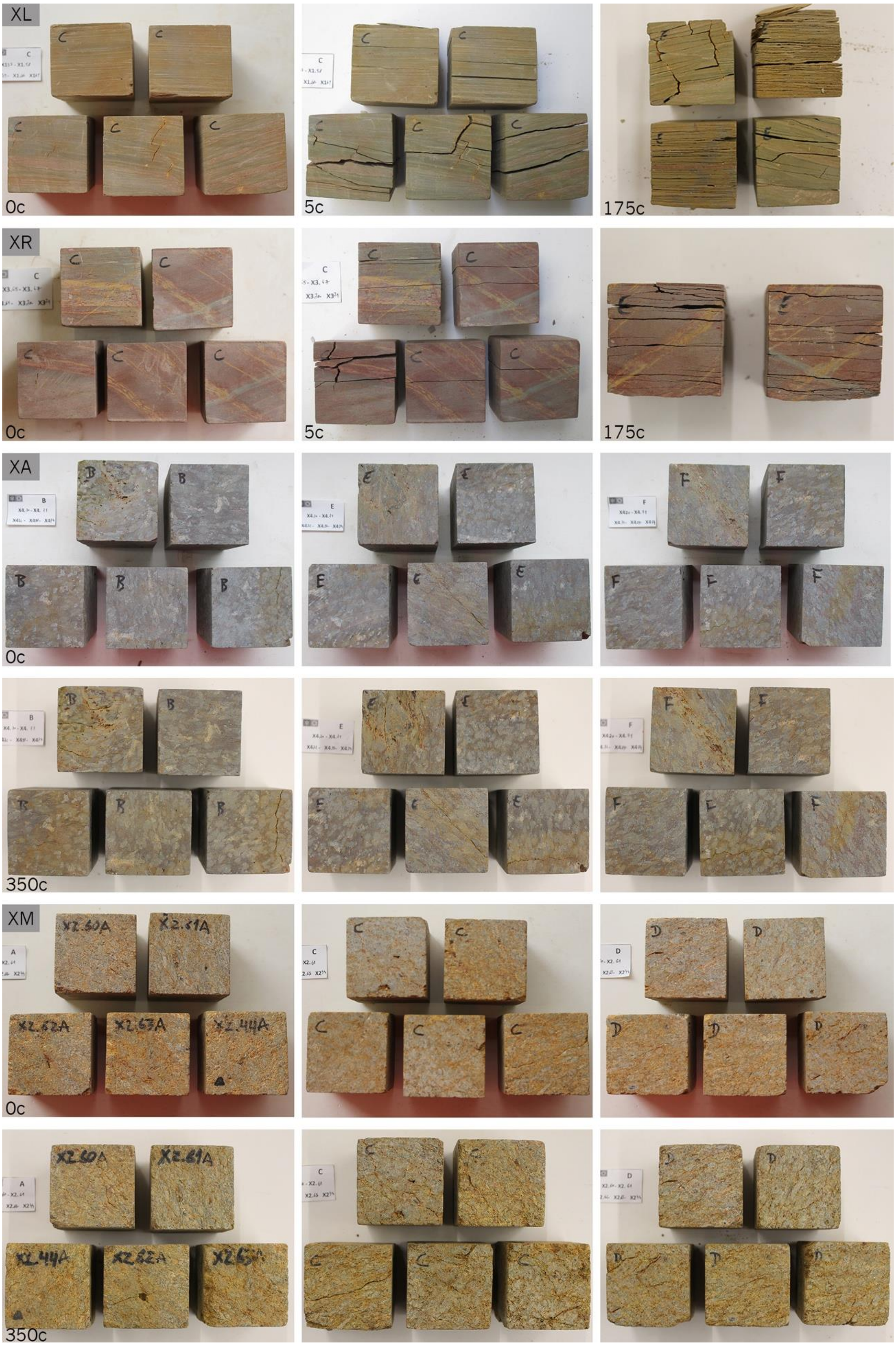


Fig. 8.14 – Well-defined foliation (above) and poorly-defined foliation (bellow) specimens tested for frost resistance.

8.2.2 Damage identification by apparent volume variation

NP EN 12371:2006 standard establishes that apparent volume (V_b) variations higher than 1% are proof of frost damage. Therefore, G350 specimens V_b variations were determined according to the experimental procedure presented in EN 1936:2006 [228] standard (see Section 7.2a). Simultaneously, specimens were also analysed for dry mass (m_d), open porosity (ρ_o) and apparent density (ρ_b) variations. Due to the known relation between rocks physical features and water [179,215], all groups of specimens were also analysed for their water absorption behaviour changes. In Fig. 8.15, Fig. 8.16 and Fig. 8.17, physical parameters time variation for G350 specimens are shown, whereas in Table 8.4, group results are presented.

In Fig. 8.15, G350 dry mass (m_d) time variation diagrams show a negative trend (loss of mass) for all tested specimens. Although not visually detected, results show a very residual loss of m_d for GE (< 0.2%) and XA (< 0.2%) specimens, and a more consistent loss for XM (< 1.5%), being in the latter ≅ 7.5 higher in comparison with both XA and GE specimens. Therefore, m_d results are consistent with the type of damage described by visual inspection. Analysing G350 open porosity (ρ_o) time variation diagrams presented in Fig. 8.16, one can observe an unexpected negative trend (decrease) for GE specimens, and positive (increase) and consistent trends for XA and XM specimens. A closer analysis to Fig. 8.16 diagrams reveals a clear two-branches variation progression, also observed although less clear for m_d. Such behaviour is clear for GE (75c) and XA (90c), but less evident for XM (175c) specimens. It reveals a faster and stronger initial effect of frost weathering over ρ_o during the initial short-term exposure period, becoming progressively slower and losing intensity during the long-term exposure period. Such behaviour is consistent with the results obtained by Martins et al. [224] for granites tested for frost damage. Although showing a more linear ρ_o variation, the presence of such non-linear behaviour on XM specimens should be taken into consideration. Its noteworthy that EN 1936:2006 [228] dry-immerse-saturated weighing method, used for physical parameters determination, may be negatively influenced by XM visible superficial damage (loss of mass). According to Martínez-Martínez [257] consideration, typical frost caused damage progression shows a tendency for non-linearity progression.

Results for ρ_o variation regarding both tested schists, show consistent ρ_o increase, higher for XA specimens (14.0%$_{ini}$/ 15.7%$_{fin}$; 12.1% var.) in comparison with XM specimens (15.8%$_{ini}$/ 16.4%$_{fin}$; 3.8% var.). Such results are consistent with the tested rocks higher initial ρ_o, and, therefore, higher susceptibility to water penetration and to porous damaged cause by frost weathering [216,233,257,258]. Regarding ρ_o GE granites results, its decrease is clear (3.8%$_{ini}$/ 3.5%$_{fin}$; -7.9% var.). This behaviour may be related to this rock lower initial ρ_o in comparison with the schists, therefore, lower susceptibility to water penetration [216,233,257,258]. However, the understanding of the frost weathering dynamics causing such unusual behaviour requires further research.

Analysing Fig. 8.16 G350 time variation diagrams for apparent density (ρ_b), results show a very slight variation (< 1%) that may justify the scatter of values observed. As expected, a negative trend was obtained for XM specimens, indicating a slight ρ_b decrease (2394 kg/m$^3_{ini}$/$\rho_{b\,fin}$ 2382 kg/m$^3_{fin}$; -0.5% var.).

Regarding ρ_b result for XA specimens, results show a higher level of scatter, with the diagram showing an unclear trend. However, XA G350 ρ_b results shown in Table 8.6, indicate an unexpected increase that requires additional research (2388 kg/m^3_{ini}/ 2409 kg/m^3_{fin}; 0.9% var.). A clear positive (increase) trend can be observed for GE specimens, also indicating a slight increase on ρ_b values (2542 kg/m^3_{ini}/ 2563 kg/m^3_{fin}; 0.8% var.), thus consistent with GE G350 ρ_o results. As for each group, average results and initial/final variation are respectively presented in Table 8.6. and Fig. 8.18. An overview over each rock ρ_o and ρ_b progression throughout the frost resistant testing camping (from G30 to G350), show an apparent ρ_o decrease followed by slight ρ_b increase. Fig. 8.18 results are consistent for XA specimens, while showing some scatter for XM and GE, that can be considered as in the range with each rock natural variability (see results on Section 7.2.1).

Regarding the analysis of frost weathering effect over rocks water absorption behaviours, the groups were tested for water absorption at atmospheric pressure (A_b) and by capillarity (C). Due to the previously mentioned time limitations regarding the frost resistance testing campaign, specimens were only tested as each group concluded their freeze-thaw exposure periods, and only according to their bedding orientation (N direction). Average results presented in Table 8.4 and Fig. 8.19, show two clear tendencies regarding the tested rocks water absorption capability. Therefore, a negative tendency for both A_b (XA – -10.3%; XM – -7.7%; GE – -18.4%) and C (XA – -5.43%; XM – 18.96; GE – -39.13) was observed for the first half of the frost resistance testing (G30 – G175). For this period, results show a clear loss of water absorption capability, consistent with the groups ρo and ρb results. As for the second half of the testing (G175 – G350) Ab results (XA – 4.5%; XM – 1.5; GE – 12.3) show a positive tendency, followed by XM and GE C results (XA – -22.49%; XM – 33.56; GE – 33.65), indicating a clear increase on rocks water absorption capability. Based in the above-presented water absorption results, it can be concluded that longer exposure to freeze-thaw cycles causes an increase on rocks water absorption capability. According to literature, internal microstructural changes in rocks (e.g. porous, discontinuities or grain bounding) over time leads to higher water absorption rates, thus, to higher levels of frost damage [233,257]. Results also show a less intense effect of freeze-thaw cycles over the tested rocks A_b, visibly stronger over C.

Regarding the apparent volume (V_b) variation criterion, results are presented in Fig. 8.17 G350 time variation diagrams. One can observe a negative trend (decrease) for all rocks, very clear for GE and XM specimens. Due to the very low V_b variation level (average of 2%), the scatter of results is high and with clear increase from cycle 235 onwards, confirming the stronger frost weathering susceptibility of the tested rocks for long exposure to freeze-thaw cycles. Groups V_b average values and respective variation are presented in Table 8.4 and Fig. 8.18. Analysing these results, average results show a very low variation level, being a consistent tendency obtain for XM and GE specimens, whereas being negative tendency regarding XA specimens. Therefore, applying the followed standard criterion to Fig. 8.17 diagrams, it can be concluded that all tested rocks are rated as damage due to long-term exposure to freeze-thaw cycles, with XA schist showing higher susceptibility to this type of damage (275c) in comparison with XM schist (305c) and GE granite (305c).

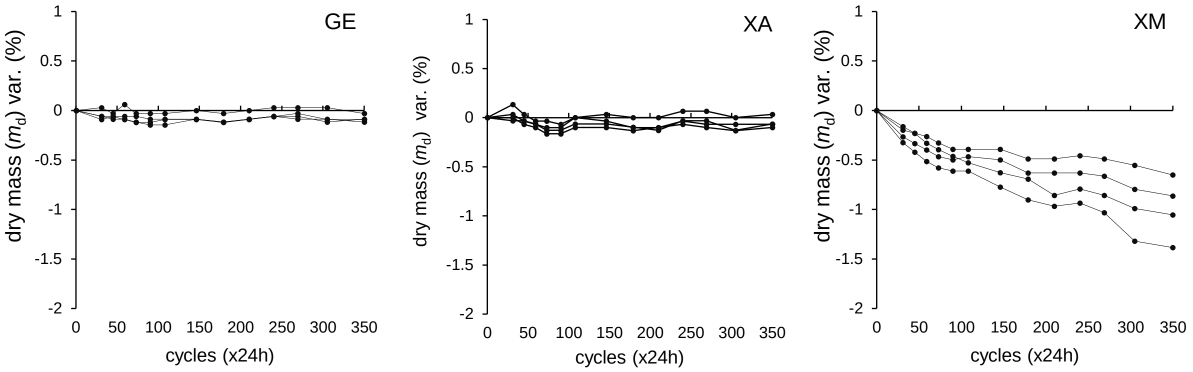


Fig. 8.15 – G350 specimens mass variation in time.

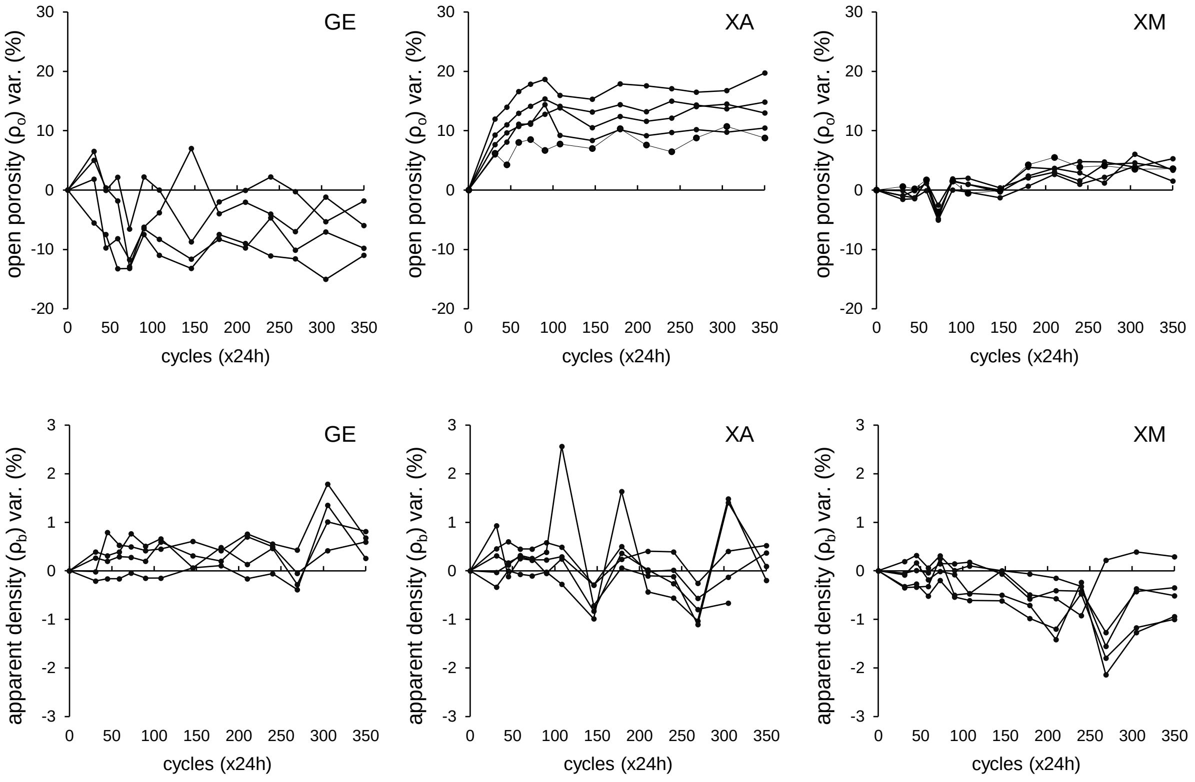


Fig. 8.16 – G350 specimens open porosity (above) and apparent density (bellow) variation in time.

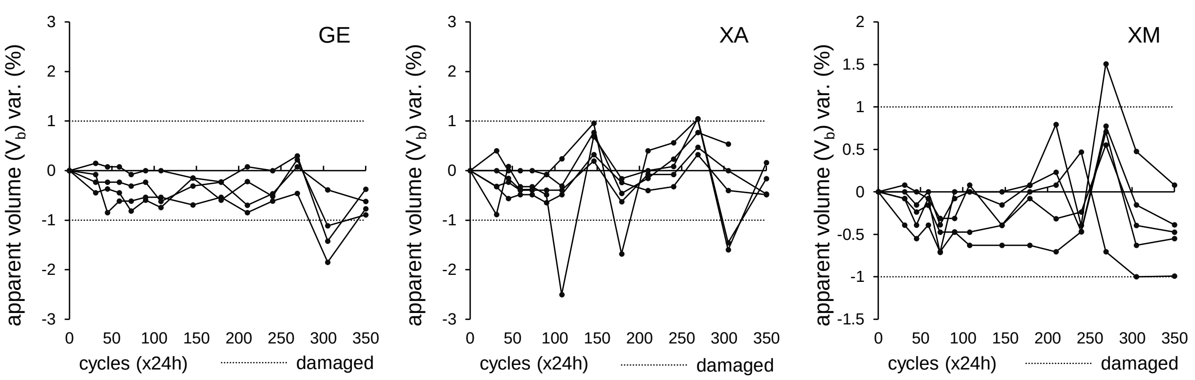


Fig. 8.17 – G350 specimens apparent volume variation in time.

Table 8.4 – Summary of the physical parameters of groups of specimens tested for frost resistance: open porosity (ρ_o); apparent density (ρ_b); apparent volume (V_b); ultrasonic pulse velocity (UPV); anisotropic scale (ANs); water absorption at atmospheric pressure (A_b); water at atmospheric pressure; water absorption by capillary (C).

XA	30c	60c	90c	175c	350c
ρ_o (%)	16.6 (10%)	15.6 (8%)	15.5 (5%)	15.3 (5%)	15,7 (10%)
ρ_b (kg/m^3)	2370 (2%)	2381 (1%)	2398 (1%)	2401 (1%)	2409 (2%)
V_b (ml)	128.38 (3%)	130.90 (2%)	130.48 (1%)	128.40 (2%)	125,13 (1%)
UPV N (m/s)	3017 (7%)	3234 (9%)	3186 (5%)	2907 (8%)	1958 (25%)
UPV P1 (m/s)	3557 (24%)	3557 (20%)	3841 (14%)	3886 (5%)	3113 (11%)
UPV P2 (m/s)	4408 (6%)	4409 (2%)	4578 (4%)	4500 (7%)	3954 (7%)
ANs (%)	32%	27%	30%	35%	50%
A_b (%)	5.72 (12%) [5.30 – 6.75]	5.54 (10%) [4.97 – 6.25]	5.39 (7%) [5.14 – 5.79]	5.13 (10%) [4.68 – 5.95]	5.36 (10%) [4.97 – 6.24]
C (g/m^{2}s$^{0.5}$)	26.89 (20%) [20.83 – 31.46]	34.07 (22%) [19.93 – 33.37]	28,67 (22%) [18.26 – 28.67]	25.43 (24%) [20.87 – 33.56]	19.71 (40%) [14.44 – 36.92]
XM	30c	60c	90c	175c	350c
ρ_o (%)	21.1 (34%)	17.3 (24%)	16.9 (16%)	17.1 (19%)	16,4 (3%)
ρ_b (kg/m^3)	2339 (4%)	2343 (5%)	2367 (3%)	2366 (4%)	2382 (1%)
V_b (ml)	126.43 (2%)	126.41 (2%)	126.73 (1%)	125.97 (1%)	127.03 (1%)
UPV N (m/s)	1454 (17%)	1479 (10%)	1506 (9%)	1437 (6%)	Ru (145c)
UPV P1 (m/s)	2259 (20%)	2295 (22%)	2333 (30%)	2295 (27%)	Ru (275c)
UPV P2 (m/s)	2944 (10%)	2983 (7%)	2981 (13%)	2960 (13%)	Ru (305c)
ANs (%)	51%	50%	49%	51%	n.a.
A_b (%)	6.5 (17%) [5.85 – 8.42]	6.47 (27%) [5.31 – 9.45]	6.12 (15%) [5.60 – 7.75]	6.00 (17%) [5.40 – 7.87]	6.09 (5%) [5.66 – 6.45]
C (g/m^{2}s$^{0.5}$)	59.06 (22%) [38.57 – 63.16]	58.01 (18%) [45.79 – 68.15]	48.21 (14%) [41.18 – 58.17]	47.86 (15%) [37.07 – 54.60]	63.92 (9%) [54.58 – 70.48]
GE	30c	60c	90c	175c	350c
ρ_o (%)	3.9 (13%)	3.8 (11%)	3.5 (13%)	3.6 (18%)	3.6 (8%)
ρ_b (kg/m^3)	2552 (1%)	2551 (1%)	2568 (1%)	2556 (1%)	2557 (1%)
V_b (ml)	130.34 (1%)	130,90 (1%)	129.30 (1%)	129.42 (2%)	130.04 (2%)
UPV N (m/s)	2164 (10%)	2286 (18%)	2235 (6%)	2253 (13%)	1993 (13%)
UPV P1 (m/s)	2871 (10%)	2948 (9%)	2985 (8%)	2953 (5%)	2626 (11%)
UPV P2 (m/s)	3142 (12%)	3150 (14%)	3200 (7%)	3357 (8%)	2762 (9%)
A_b (%)	1.30 (14%) [1.09 – 1.53]	1.23 (14%) [1.10 – 1.50]	1.14 (13%) [0.93 – 1.34]	1.06 (13%) [0.91 – 1.24]	1.19 (12%) [1.00 – 1.34]
C (g/m^{2}s$^{0.5}$)	10.35 (23%) [7.79 – 13.72]	7.42 (25%) [5.62 – 10.24]	7.57 (10%) [6.50 – 8.45]	6.30 (18%) [4.99 – 7.56]	8.42 (5%) [8.12 – 8.93]

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets.

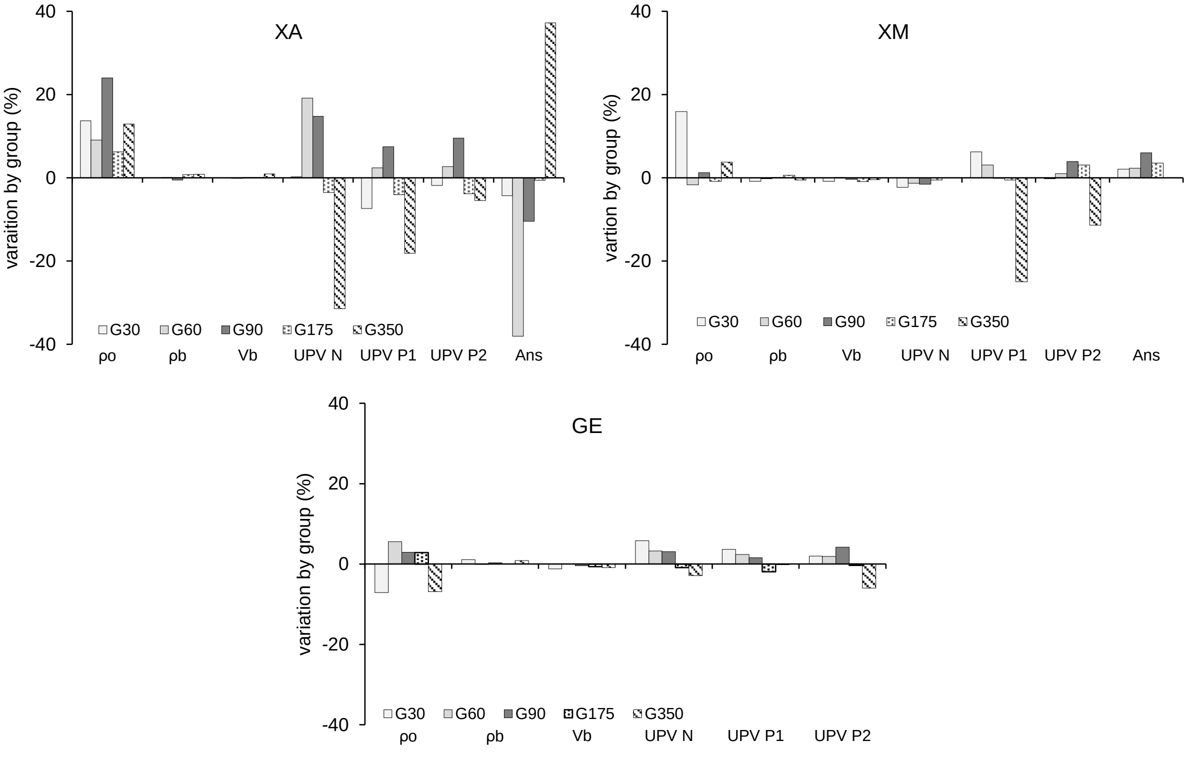


Fig. 8.18 – Physical parameters variations by groups of specimens tested for frost resistance (from initial to each group final cycle).

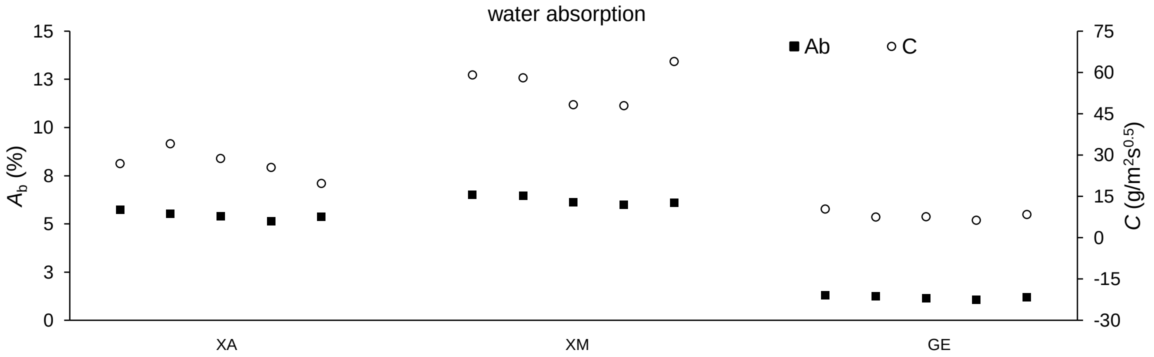


Fig. 8.19 – Water absorption results of each group of specimens tested for frost resistance.

8.2.3 Damage identification by dynamic elastic modulus variation

To calculate dynamic modulus variations (E_d), G350 specimens were monitored for UPV behaviour throughout the testing. Readings were performed along the three directions (N, P1 and P2), as shown in Fig. 7.2. Such a continuous monitoring allowed a global overview on the propagation of internal discontinuities, associated with the freeze-thaw cycles. The type and origin of such discontinuities requires additional research on the topic, however, literature points out to damage such as the formation of microcracks, grain breakdown or to porous and pre-existent voids widening, as probable outcomes of frost weathering [178,233,252]. Repeated freeze-thaw cycles, are known to set in motion a combination of physical mechanisms such as ice crystals expansion associated with hydric pressure, ice front movements inwards or even clays swelling, responsible for causing stress over the structure of rocks [178,233,252]. When such damage overpasses the material strength, it leads to mechanical damage [178,233,252]. In addition to these mechanisms, and as observed on XL and XR specimens, lamellar disaggregation caused by such type of stress plays an important role in increasing the amount of internal discontinuities present on foliated rocks. G350 UPV time variation diagrams are shown in Fig. 8.20, whereas results for all tested groups and respective variations are presented in Table 8.4 and Fig. 8.18.

As observed, Fig. 8.20 G350 UPV variation diagrams show a three branches non-linear progression, consistent with the type of non-linear behaviour previously observed for m_d and ρ_o time variation diagrams. Although the different tested rocks show slight differences regarding their UPV propagation intensity, all present a consistent negative trend. Therefore, a progressive loss of UPV, indicating an increase on the specimens' internal discontinuities levels, is common to all directions and to all G350 specimens. Diagrams show an initial branch characterized by lower UPV variations, that for most specimens seems to last for the duration of the short-term exposure period (90c). The following shorter branch shows sharper UPV variations, and precedes a final and longer branch, again characterized by lower UPV variability. The latter branch starts for most specimens around cycle 175. The middle branch seems to be shorter for GE granites, and longer for all N direction measurements. Such results show that for the tested rocks, internal discontinuities propagation is not uniform throughout different freeze-thaw exposure periods, and clearly are influenced by phenomena that required further analysis.

Martínez-Martínez et al [257] points to two mechanical phenomena to explain such non-linear behaviour. On one hand, ice action and thermal expansion mismatch, caused by rocks mineral crystals simultaneous expansion and contraction on different directions (stronger on anisotropic rocks), responsible for a type of damage progression that halts as rocks accommodate to the cyclic thermal regime [257]. On the other hand, to an initial phase of microcracks formation (micro-decay), frost originated fatigue and micro-shock cause stress accumulation, that ultimately results into microcracks coalescence and the formation of macrocracks (macro-decay) [257]. To be noticed, a gain of UPV propagation speed was observed by the first check point (15c). The precise origin of such phenomena also requires further research. Therefore, and with the exception of the latter observation, results regarding UPV variation behaviours observed for the tested rocks are consistent with the results obtained by Martins et al. [224] for granites tested for frost resistance. A closer look to UPV G350 variation diagrams for XA specimens (N – 2147 m/s; P1 – 3596 m/s; P2 – 4299 m/s), the diagrams show a stronger N variation in comparison with P1 and P2 variations (N – -25%; P1 – -5%; P2 – -3%), indicating a higher increase of discontinuities following foliation direction. Regarding XA P variations, although showing higher intensity, they resemble GE granite P variations.

Analysing XM specimens UPV time variation diagrams, these show that intense discontinuities formation on N direction made UPV reading impossible from cycle 145 onwards (1148 m/s; -20% var.). Nonetheless, discontinuity formation on P direction seems less intense, only failing for P1 direction at cycle 275 (1464 m/s; -29%), and for P2 direction at cycle 305 (2262 m/s; -19% var.). Causes for such frost damage effect over XA specimens are consistent with the higher level of visually identified damage, and with the apparent higher susceptibility of the rocks fabric and foliation to freeze-thaw cycles.

Regarding GE specimens UPV time variation diagrams (N – 1993 m/s; P1 – 2626 m/s; P2 – 2762 m/s), although slightly stronger on N direction (bedding orientation), final variation is very similar on all three (N – -3%; P1 – -6%; P2 – 0.001%). Nonetheless, cycle 350 show on N and P1 variations an unexpected increase of variability of unknown causes. Such results may indicate that for GE granite, under frost weathering, internal discontinuities may be uniformly distributed without a strongly prevailing orientation, contrary to the tested schists. Analysing UPV for each group of specimens, see Table 8.4, G30, G60, G90 and G175 show consistent average UPV values, followed by a significant UPV propagation drop on all G350 groups. Such results were expected taking into to consideration G350 longer exposure to freeze-thaw cycles. Analysing groups' UPV variations in Fig. 8.18, schists show a stronger UPV variation, as expected, with a clear three direction anisotropy, whereas for the granite, variation is lower and shows a two-direction variation, with P2 presenting higher variations in comparison with N and P1.

As observed in Fig. 8.18, a positive tendency is clear for G30, G60 and G90 groups results (short-term exposure period), therefore consistent with the behaviour observed on G350 UPV diagrams first branches. A negative tendency was also observed for G175, consistent with G350 UPV diagram second and third branches. Negative tendency results are consistent either with the second or final branches.

Taking into consideration the effect of frost damage over schists anisotropy, XA (≅ 30% ANs) and XM (≅ 50% ANs) specimens show consistent results throughout the testing. XA G350 results show a possible effect of long-term exposure to freeze-thaw cycles over this rocks anisotropy (50% ANs). XM G350 anisotropy scale was unavailable. Taking into consideration the results obtained for the UPV analysis performed on specimens tested for frost weathering, one can conclude that the freeze-thaw cycles caused an increase on the amount of internal discontinuities. As expected from the previous physical parameters results, GE specimens show a more predictable and consistent UPV variation, indicating a more evenly distribution of damage, and a lower susceptibility to such type of frost weathering. Regarding schists, UPV results show a more intense propagation of internal discontinuities caused by frost weathering intensification over these rocks anisotropic behaviour. Therefore, higher loss of UPV propagation on N direction show a concentration of discontinuities on specimens foliation layers (weakness plans [216]). Pre-existent weathering, as shown by XM specimens results, should be taken into consideration analysing the UPV propagation velocity. As for the dynamic elastic modulus (E_d), it was calculated for the three directions, using individual UPV readings, and by applying the following equation (results presented in GPa):

$$\mathrm{Ed} = \frac{\rho_o V_p^2}{F} x 10^{-9} \qquad \text{(Eq. 8.1)}$$

being: ρ_o – apparent density (kg/m^3); V_p – P-waves (m/s); and F – correction factor calculated by the equation (results without metric scale):

$$F = \frac{(1-v)}{(1+v)(1-2v)} \qquad \text{(Eq. 8.2)}$$

being: v – Poisson coefficient (GE – 0.25; XA and XM – 0.15 [259,260]).

According to the NP EN 12371:2006 standard, specimens are considered damaged if the dynamic elastic modulus variation surpasses 30%. G350 E_d time variation diagrams are presented in Fig. 8.21, whereas groups results are presented further on, along with the static elasticity modulus (E) and strength (R), in Table 8.5. Analysing G350 E_d time variation diagrams, it is noteworthy their resemblance with the previously presented UPV variation diagrams, with the same type of trends and similar three-branches organization. Therefore, a consistent negative trend was also obtained for all specimens, meaning a consistent increase on rocks deformability throughout the frost resistance testing.

Analysing Fig. 8.21 diagrams, the first initial branch means a more stable and with reduced changes to rocks deformability, followed by stronger E_d variations due to deformability increases, prior to a more stable and longer final phase. Analysing Table 8.5 average, minimum, and maximum E_d values for the different groups, these show a clear negative tendency, indicating an increase on deformability on all tested rocks. Table 8.5 N direction E_d results for XA specimens (G30 - 20.5 GPa; G350 – 11.03 GPa) show the stronger increase of deformability among the tested rocks (-46% var.), whereas GE specimens (G30 – 10.8 GPa; G350 – 8.6 GPa) show the lowest one (-14%). In this comparison, XM specimens were not considered since no reliable UPV values were obtained for G350.

Therefore, E_d variation results in Fig. 8.21, clearly show that all tested rocks were damaged during the freeze-thaw cycles, regarding this specific criterion. Results also show that with E_d damage on three directions, poorly-defined foliation schists show higher susceptibility to frost damage, in comparison with the tested granite. XM specimens show the highest susceptibility to E_d freeze-thaw caused damage, being the first reached damage on all three directions (N – 105c; P1 – 145c; P2 – 175c). Although early E_d damage was observed on P2 direction, XA specimens required higher freeze-thaw exposure to become fully damaged (N – 215c; P1 – 275c; P2 – 45c). As expected, GE specimens E_d damage was only observed in parallel to the bedding direction (N – 210c), therefore confirming this type of rock lower susceptibility to freeze-thaw damage.

8.2.4 Damage identification by strength and deformability analysis

To determine the effect of frost weathering over the mechanical features of the tested rocks, specimens were tested for strength (R) according to NP EN 1926:2000 [217] and analysed for deformability based on static (E) and dynamic (E_d) elastic modules. Therefore, each group of specimens were oven dried and tested under dry mass conditions (m_d), following the procedures presented on Section 7.3.1. As previously explained, due to availability limitations, specimens were tested according to their bedding orientation (N direction). Results are presented for each group R, E and E_d in Table 8.5 and Fig. 8.22. Analysing average, minimum and maximum results shown in Table 8.5, one can observe that for XA and GE rocks, to an initial mechanical performance improvement, a consistent mechanical performance drop followed. Such type of variation is consistent with the previously reported non-linear physical parameters performance time progression variation.

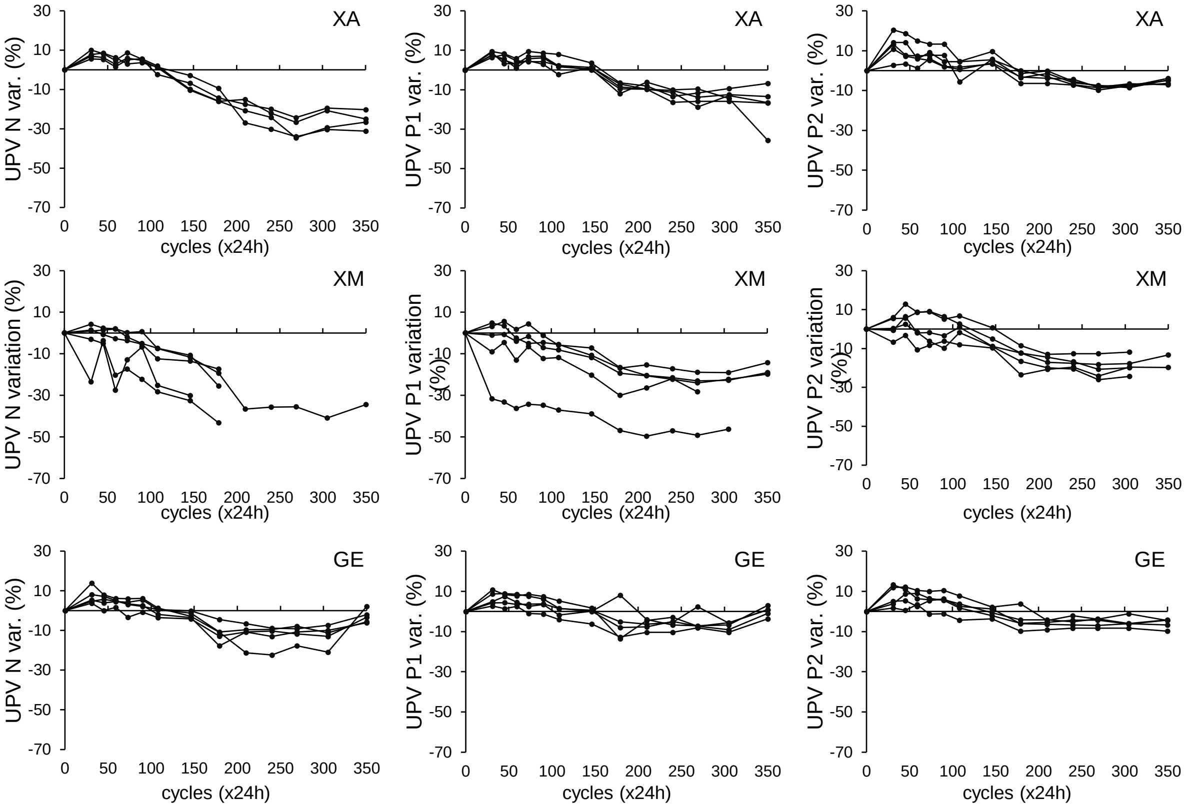


Fig. 8.20 – UPV time variation of G350 specimens

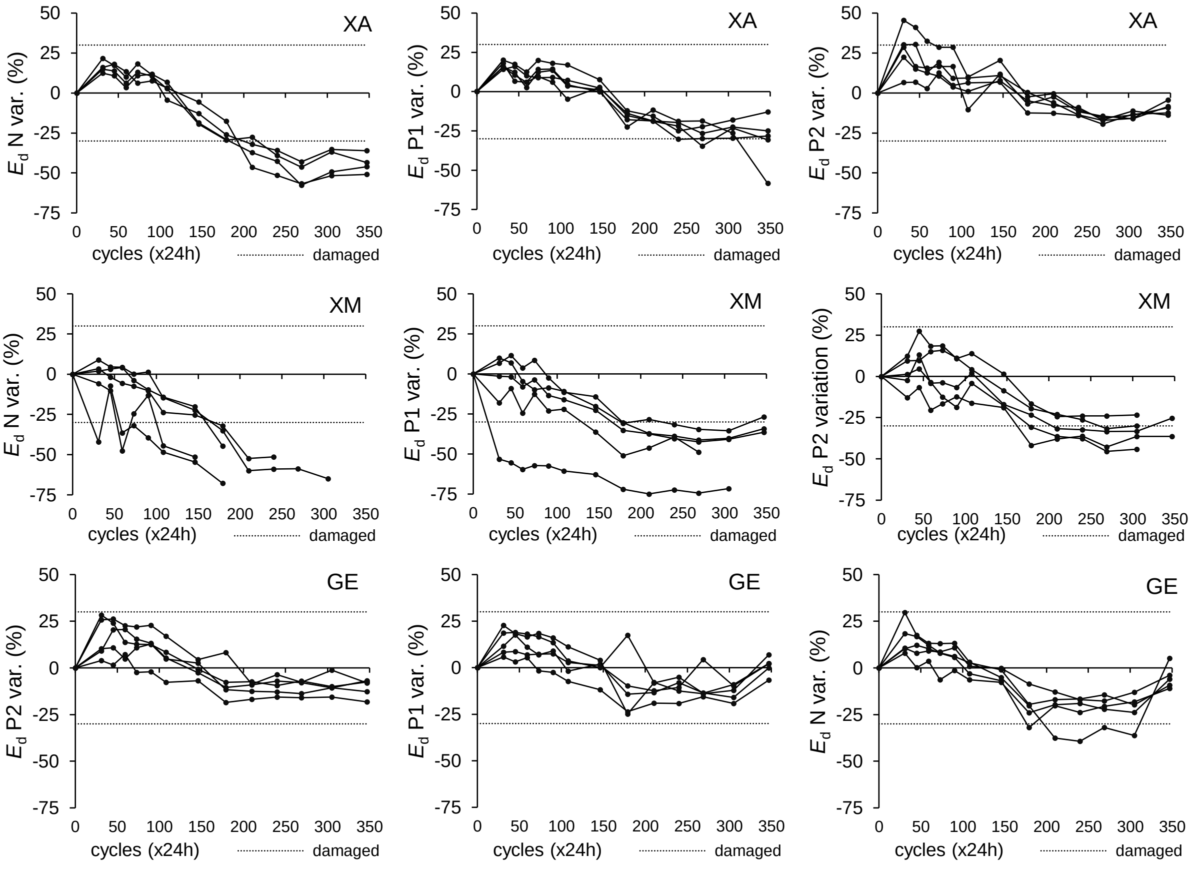


Fig. 8.21 – Elastic modulus time variation of G350 specimens.

The initial mechanical performance improvement for XA and GE groups (G30 – G60 var.) show an average positive variation of ≅ 15%, being higher for GE E variation (27.7% var.). Analysing XA (R – -17.8%; E – -34%; E_d – -54%) and GE (R – -11.4%; E – -8.9%; E_d – -24.8%) groups mechanical performance drop (G60 – G350 var.), higher variability is clear regarding XA specimens, being more stable regarding GE results. For both rocks, E_d results variation seems to show a stronger effect of freeze-thaw over this parameter. Analysing results for XM groups, in Fig. 8.22 a much more linear variation throughout the testing can be observed. Still, an initial mechanical performance improvement (< 3%) was also observed (G30 – G90 var.) and was followed by a mechanical performance drop (R – -7.8%; E – -10.5%; E_d – n.a.). As explained in the previous section, due to the lack of UPV information regarding XA G350 specimens, it became unfeasible to calculate E_d.

Comparing the three analysed mechanical parameters, Fig. 8.22 show similar trend for the three, although results show a stronger effect of frost weathering over rocks deformability. Therefore, higher variability regarding rocks E_d variations can be observed for the three tested rocks, particularly regarding both E and E_d elastic parameters results for XA specimens. As expected, E_d presents higher values in comparison with E, with E_d/E average comparison ratios significantly higher for schists in comparison with the granite (XA – 4; XM – 6.2; GE – 1.4). These results are consistent with Ruedrich et al. [233] observation regarding limestones under frost resistance testing. According to the author [233], the use of E_d values to assess mechanical damage caused by frost weathering should be considered with care. According to Jimenez et al.[252], E_d results are unreliable regarding clay-bearing rocks, point to E as the most reliable method to assess these type of rocks deformability. As shown in Fig. 8.23, only between R and E, both determined by uniaxial compression testing, clear linear correlations were found for XA and XM groups, being only acceptable for GE groups. No acceptable correlation was found regarding E_d. In Fig. 8.24, the stress-strain diagrams for XA, XM and GE G30 and G350 are presented. Analysing the diagrams and comparing with the reference results presented on Section 7.3.1, no significant changes to pre-peak and post-peak behaviours can be observed. The same was observed regarding failure modes.

Analysing the tested rocks mechanical decay, the stronger decay and deformability increase shown by XA schist, are consistent with the previously presented open porosity increase and UPV velocity variations values, thus showing a strong effect of frost weathering over this rock. Results for XM schist lead to the same conclusions as for XA schists. However, this schist lower initial strength and deformability, may have conditioned the frost damage progression. Regarding GE mechanical decay, the lower strength loss and deformability increase were expected due to this rock initial higher strength and stiffness, in comparison with the tested schists. However, the observed strength decay is not consistent with the obtained open porosity results. Nonetheless, GE decay can be explained by its UPV results [224] that show a consistent progression of discontinuities formation inside specimens. XM less evident mechanical decay can be explained by this rock low initial R and E. Based in the above-mentioned conclusions and taken into consideration Martins et al. [224] mechanical frost damage assessment on granites, the tested rocks were considered as damaged by frost weathering. It was also concluded that the damage level is stronger on schists than on the granite.

Table 8.5 – Mechanical characterization of groups of specimens tested for frost weathering.

XA	30c	60c	90c	175c	350c
R (MPa)	40.00 (17%) [34.29 – 47.72]	46.43 (20%) [36.27 – 55.08]	35.46 (2%) [35.03 – 35.89]	35.83 (21%) [24.27 – 42.55]	38.15 (24%) [26.67 – 48.73]
E (GPa)	5.54 (14%) [4.93 – 6.38]	6.36 (32%) [4.48 – 8.50]	4.43 (4%) [4.30 – 4.56]	4.24 (21%) [3.57 – 5.67]	4.19 (26%) [2.65 – 5.24]
E_d (GPa)	20.54 (15%) [16.49 – 24.21]	23.75 (19%) [18.56 – 30.84]	23.11 (9%) [20.00 – 26.10]	20.53 (16%) [16.10 – 23.73]	10.71 (21%) [8.09 – 13.58]
XM	30c	60c	90c	175c	350c
R (MPa)	15.04 (13%) [12.97 – 17.15]	13.64 (8%) [12.70 – 15.08]	15.26 (12%) [12.10 – 16.74]	15.58 (15%) [12.46 – 18.34]	14.07 (9%) [12.70 – 16.65]
E (GPa)	0.74 (11%) [0.66 – 0.84]	0.67 (29%) [0.43 – 0.90]	0.76 (18%) [0.62 – 0.92]	0.76 (14%) [0.60 – 0.85]	0.68 (13%) [0.58 – 0.79]
E_d (GPa)	4.80 (33%) [2.58 – 6.67]	4.92 (23%) [3.38 – 6.26]	5.10 (16%) [4.19 – 6.18]	4.65 (16%) [3.74 – 5.80]	n.a. n.a.
GE	30c	60c	90c	175c	350c
R (MPa)	73.28 (19%) [60.37 – 94.34]	84.67 (18%) [63.89 – 99.53]	83.82 (10%) [73.72 – 90.81]	80.91 (23%) [64.69 – 109.44]	74.98 (12%) [59.77 – 81.61]
E (GPa)	6.39 (26%) [4.97 – 8.98]	7.97 (21%) [5.78 – 10.25]	7.85 (17%) [6.14 – 9.17]	8.28 (20%) [6.28 – 10.21]	7.26 (16%) [5.63 – 8.60]
E_d (GPa)	10.0 (21%) [7.49 – 12.96]	11.43 (33%) [5.36 – 15.27]	10.73 (13%) [9.00 – 12.05]	10.98 (27%) [8.14 – 14.30]	8.60 (26%) [6.22 – 11.22]

Note: Coefficient of variation (CoV) is indicated in percentage inside rounded brackets; Range values [min. – max.] is indicated inside rectangular brackets.

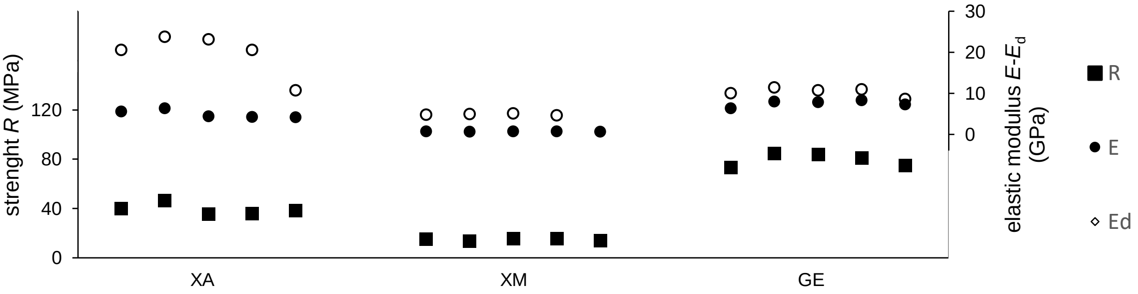


Fig. 8.22 – Average *R*, *E* and E_d results for groups of specimens tested for frost damage.

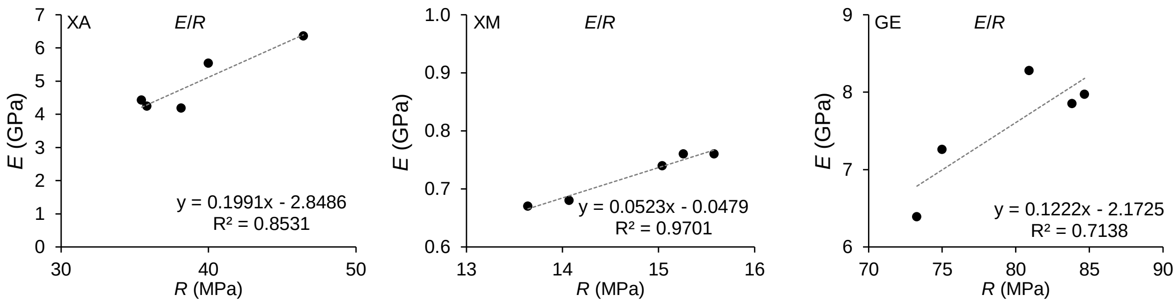


Fig. 8.23 – *R* and *E* correlations for the tested rocks.

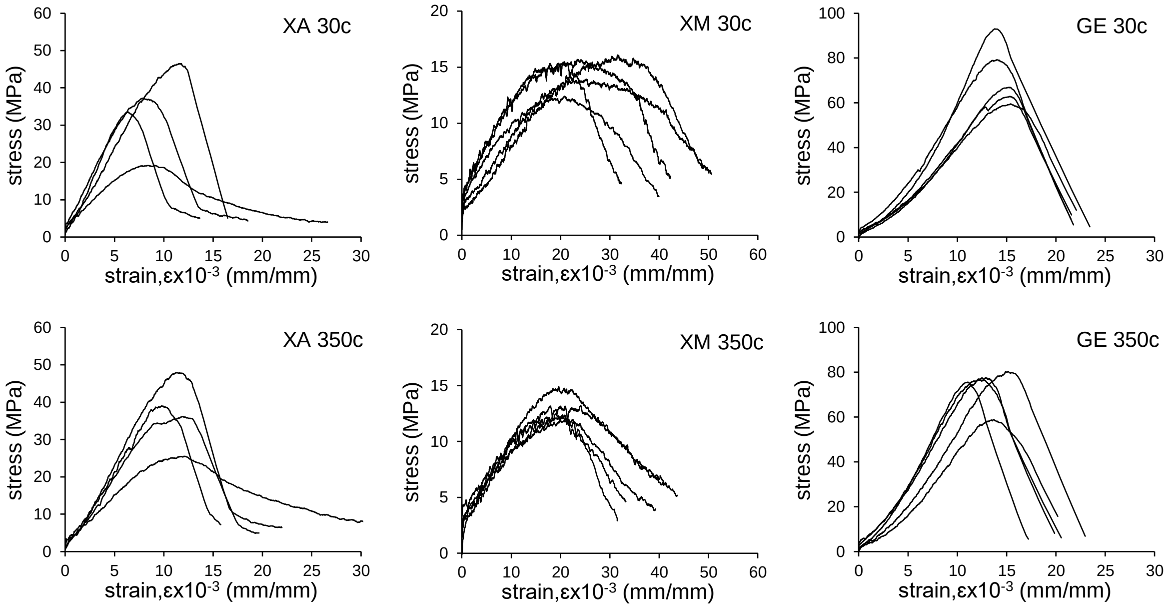


Fig. 8.24 – Stress-strain diagrams from groups of specimens tested for frost resistance.

8.2.5 Frost resistance assessment

Based on the results of the identification and technological frost resistance assessment criteria established by NP EN12371:2006 [255], it was concluded that all tested rocks were damaged by frost weathering, however showing different levels of susceptibility. A summary of the frost weathering assessment is presented in Table 8.6. For a better comparison between the tested rocks, a frost resistance index was prepared and applied. Therefore, to each criterion of the followed standard damage criteria, a rate of 5 was given if verified and 0 if not: A – visual identified damage; B – apparent volume variation; C – elastic modulus variation. A was rated from 0 to 6 according to the level of damage (LD) identified. C was rated from 0 to 3 according to the number of specimens' directions with damage. To B and C, the S and L indexes were attributed if damage was respectively reached during short-term exposure (2) or long-term exposure period (1). Taken into consideration that all rocks reached mechanical damage and that the analysis was based in qualitative yes or no criteria, it was not included in the index calculation.

Table 8.6 – Frost weathering testing and rating results according to NP EN 12371:2006 identification criteria [255]

Rocks	A - Damage assessment through visual inspection (≥ 2 specimens showing LD3*)	B - Apparent volume variation (≥ 2 specimens showing more 1% variation)	C - Elasticity modulus variation based in UPV (≥ 2 specimens showing more than30% variation)			Final Frost damage index (A + B + C)**
			N	P1	P2	
XL	LD4 [9c] Final: LD6 [25c]	n.a.	n.a.	n.a.	n.a.	Non-resistant A6 + Bs + C3s (35)
XR	LD4 [9c] Final: LD6 [50c]	n.a.	n.a.	n.a.	n.a.	Non-resistant A6 + Bs + C3s (35)
XA	LD3 [75c] Final: LD3 [75c]	0,32% – 1,05% [275c]	-82.10% – -27.67% [215c]	-34.68% – -18.59% [275c]	6.81% – 41.00% [45c]	Moderately resistant A3 + BL + C3L (22)
XM	LD3 [30c] Final: LD4 [175c]	-1.00% – 0.48% [305c]	-48.44% – -14.18% [105c]	-62.85% – -14.19% [145c]	-41.85% – -16.55% [175c]	Moderately resistant A4 + BL + C3L (23)
GE	not verified Final: LD1 [9c]	-0.39 – -1,85% [305c]	-37.57% – -12.93% [210 cycles]	not verified	not verified	Highly resistant BL + C1L (13)

Note: Number of cycles to reach damage verification criterion is indicated inside rectangular brackets. *for LD reference see Table 8.1. ** all specimens were considered to have reached mechanical damage, therefore, it is not considered in the index calculation.

Regarding frost weathering for well-foliated XL and XR, due to their catastrophic damage identified by visual inspection, and very fast progression rate that made all other assessment criteria unfeasible, these rocks were rated as Non-resistant to frost damage and considered highly susceptible to damage under such type of environmental conditions. It was clear that lamellar disaggregation plays a very important role on rocks with very poor resistance to freeze-thaw cycles.

Regarding results for the poorly-defined foliation XA and XM schists, it became clear that these rocks offer a certain level of frost weathering resistance when exposed to short-term periods of freeze-thaw cycles. However, for long-term exposure periods, durability decay was considerable in both rocks and thus, requiring protection. Regarding results for the tested GE granite, it became clear that this rock is highly resistant to frost damage, with only very light damage being observed for long-term exposure to freeze-thaw cycles. Therefore, this rock is considered as suitable for the environment it has been used (highland sub-region).

8.3 Final remarks

As shown from the above presented experimental campaign, schists are considerably less durable in comparison with granites when facing salt and frost weathering. It became clear that due to higher levels of porosity and lower strength resistance, schist specimens are susceptible to damage caused by crystallization phenomena from both salts and ice. However, the type of damage observed for the schists tested for salt damage shows a strong chemical action of salt over the schist structure, causing very intense superficial disaggregation. To be noticed, at the exception of the strongest tested granite, on all other tested rocks, salt weathering caused both structural and superficial damage, whereas frost weathering caused damage seemed to be more of structural origin.

It also became clear the strong effect of anisotropy and parameters such as mineral arrangement or foliation over both types of weathering. On well-defined foliation schists, the regular planar internal structure of the rocks seems to facilitate water mobility, therefore, the penetration of salts inside the material. Crystal expansion and clay swelling on the interface of such planar structures causes rocks to split.

Lamellar disaggregation was proven to be the most destructive structural damage mechanism observed on schists, being caused by both types of weathering. The same type of phenomena was observed for pre-existing cracks and voids.

As for superficial damage, faces and foliation interfaces delamination was proven to be the most intense superficial damage caused by frost weathering, whereas intense powdering was by far the strongest superficial damage caused by salt weathering. The latter seems able to cause full destruction of fine-grain schists, confirming the fieldwork observations.

Poorly-defined foliation schists, due to higher planar irregularity and medium-grain seems to better withstand stress caused by crystallization phenomena. As it was proven, these schists irregular fabric is less susceptible to water penetration and lamellar disaggregation. The medium-grain showed higher resistance to salt caused superficial damage, for shorter exposure periods.

As for the granites, as expected, the higher resilience shown to both types of weathering are consistent with a good resistance to very harsh natural context where the source stones were collected from. A more compact, heterogenous coarse-grain internal structure was proven more effective against water penetration, and therefore, against salt and frost damage.

The obtained results confirm the need to protect the schists from water penetration, and if unfeasible, to allow it to evaporate freely, being the use of vernacular mortars, a suitable way found by masons to perform such type of protection. Despite the higher resilience of granites, long-term exposure to both types of weathering are known to cause damage, as it was confirmed by the fieldwork observations. On both cases, preventing access to salt sources, either from contact with livestock, sea spray or air pollution seems fundamental to ensure the durability of stone masonry.

Chapter 9

ANALYSIS OF TWO CASE STUDIES

In this chapter, two examples of the application of methodologies for heritage preservation and reuse are presented based on case studies.

The first case study deals with the difficult problem of conciliating contemporary needs and vernacular heritage preservation, in this specific case resulting from the upgrade of a rural path into an urban road. As in most cases, the existing farm wall, not seen by the community and authorities as a valuable asset, was demolished to enlarge the existing channel. The process of selection and construction of a new farm wall is discussed here. A initial synthesis of the results were discussed by the author elsewhere [142,143]. The second case study deals with the effects of rural abandonment over endangered vernacular heritage, with limited reuse possibilities. Based on case studies and on the efforts of a multi skill research team, the preservation possibilities of the highland endangered corbelled dome heritage are discussed ahead. To address the topic, a preservation methodology was design and is presented. Initial results were published by the author and members of the research team elsewhere

[105,106,155,261–263]. In the following sections, a synthesis of results from the produced work on both case studies is presented, being complemented by the databases presented on the previous chapters.

9.1 Farm walls rebuilding methodology

During the fieldwork observations, it became clear that one of the main challenges and threats to local vernacular heritage, particularly to farm walls, concerned the progressive landscape conversion from purely rural to low-density urban territory. In this process, intense since the 80's of the 20th century, rural roads and paths, both showing a typically 2 to 3 m width and fully adapted for pedestrians use and animal-drawn vehicles, were and still are being progressively converted into contemporary roads or into urban streets, prepared for all sorts of automobiles, and resulting into channels with at least 6 m of width.

As it was seen all throughout the survey area during the exploratory visits, high risks of cultural value loss are associated to this type of very damaging operations. Vernacular farm walls are generally demolished and replaced by very uncharacteristic new farm walls, generally built using unappropriated contemporary building techniques (e.g. hollow cement blocks masonry) [32]. Similar issues such as modifications of property limits, rehabilitation interventions on vernacular buildings following standards applicable to new buildings, the low protection level given to vernacular heritage by the territory management legal framework, or growing difficulties in finding qualified masons, were some other significant challenges involved in this topic.

As it was shown on Chapter 2, it is only admissible to rebuild heritage in very specific circumstances [23]. However, such type of non-protected heritage suffers from a severe lack of cultural value recognition from local communities and territory management authorities, particularly when confronted with contemporary needs considered priorities. Therefore, and for being an unavoidable situation, the heritage preservation problem was addressed from its macro scale, meaning, from the landscape cultural value preservation perspective. The work carried out enlighten the community and local authorities to the advantages of addressing such type of issues from a wider and global heritage point of view and showed that it was possible to achieve a balanced cost/benefit solution for the problem. The opportunity was given to the author to follow the wall rebuilding process. Based on the information presented on the previous chapters, the methodology presented in Fig. 9.1 was prepared and implemented. However, technical decisions were taken either by the contracting authority or by the contractor.

As for the intervention objectives, they were set by the contracting authority, the Barqueiros civil parish council, and were used to set priorities in the decision-making process, and to guide the context analysis. After selecting the new farm wall to build, its construction was monitored. Such monitoring continued for three years after the conclusion of the work. It was possible to assess results and to establish maintenance recommendations. Intervention results and improvement recommendations are discussed ahead.

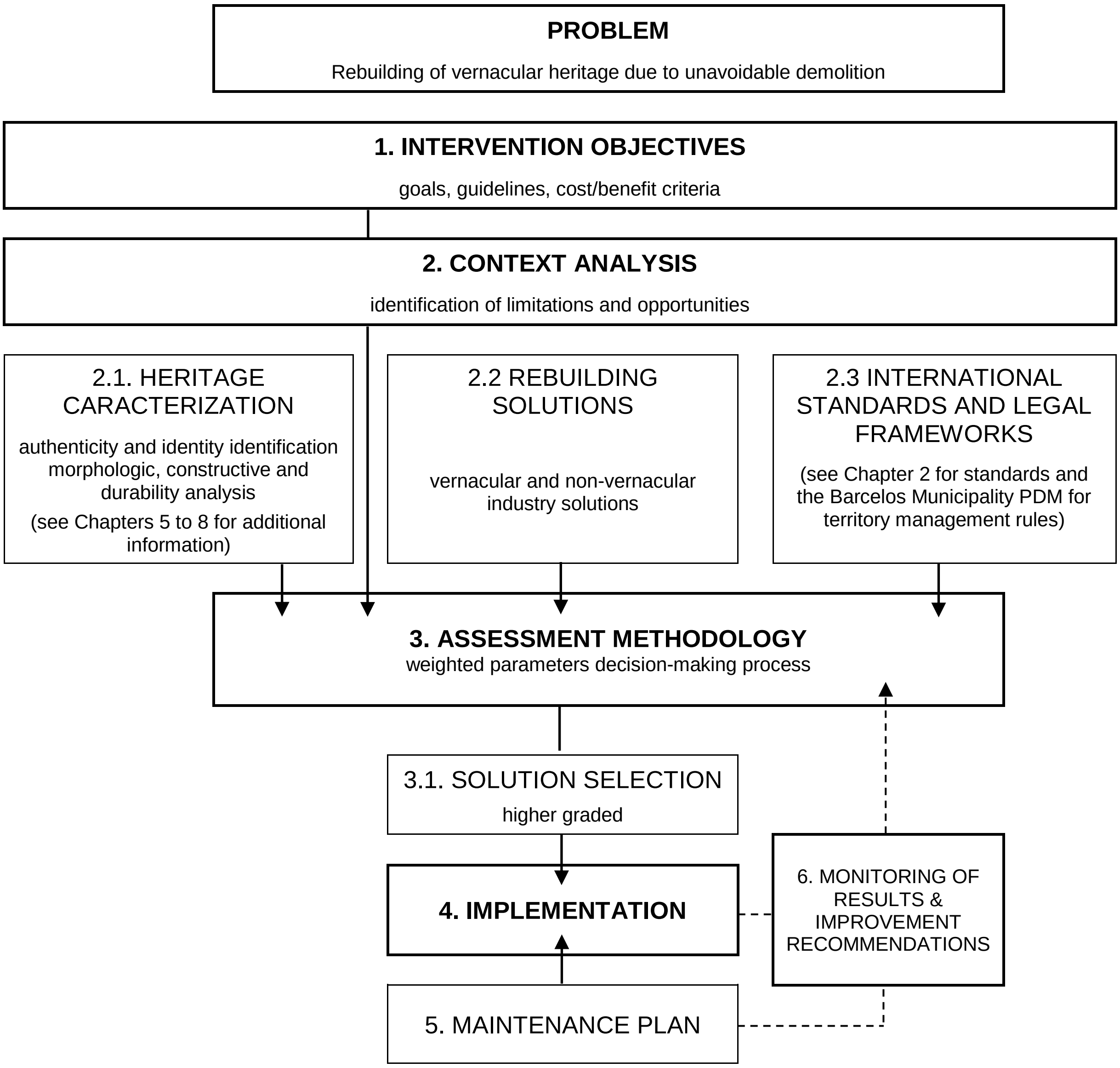


Fig. 9.1 – Schematic representation of the method followed to address the rebuilding intervention of a vernacular farm wall.

9.1.1 Context analysis

The vernacular farm wall demolished in this intervention was a 115 m long stretch of a full protection boundary high farm wall with an average height of 2 m and an average thickness of 0.5 m. To correct the farmland slope, the demolished farm wall had retaining functions to an average height of 0.8 m, measured from the foundation upwards from the road side (see Section 5.4.2 for additional typological and morphological information). As shown in Fig. 9.2, the case study farm wall was the boundary wall of a farm, next to a large farmhouse compound, formed by a farmstead divided into a courtyard and large-size farmyard. The dwelling building was located at the upper-floor of the main building and was divided into a *"bourgeoise"* style area connected to a courtyard with a 19th style garden, and a humbler section opened to the farmyard (see Fig. 9.2c). Large-size two-storey drying granary and the dwelling building, all with ground-floor agrarian compartments, gave the farmyard an L shape configuration. Both courtyard and farmyard were enclosed by high boundary farm walls to farmland and road sides. The compound and farmland are surrounded by roads, originally rural dirt paths, that from 80’s onwards were progressively converted into urban paved roads (see Fig. 9.2a and b). The farmhouse kept active farming until the late mid-20th century. As for the origin of the farm, first documental evidences point to the mid-18th century, period when this area was first referred to as having farms [119].

Fig. 9.2 – Images from the case study farm wall and its context: (a) view of the vernacular farm wall before the intervention; (b) aerial view of the farm; (c) view of the farmstead and its buildings (the farmstead enclosing walls were demolished).

a) *Constructive characterization of the demolished farm wall*

The existing farm wall was built according to the local building tradition described for load-bearing walls on Chapter 6. It was built with local schist stone blocks and soil mortar for bedding, as shown in Fig. 9.3. Regarding the stones, although a wide diversity of schists was identified among the farm wall demolished materials, well-defined foliation XO and poorly-defined foliation XM schists were the most representative ones (for both rocks physical, mechanical and durability information see Chapter 7 and Chapter 8). As for the mortars, two types of soil bedding and pointing mortars were used in different stretches of wall. Granitic residual soil (orange and yellowish shade), or *“saibro”*, was the prevailing type of used mortar, whereas mortar made of clayey soil with kaolin (whitish shade) was used on smaller sections of the wall [126,264,265]. Both types of soil are available at the farm and were prepared by simply adding water. Regarding the cross-section, it matches the typical regional mortar bonded cross-section, described on Section 6.1.2 (see group M walls ahead). However, as shown in Fig. 9.4a, b and c, different thickness and slight facades misalignments observed were the outcome of slight cross-section variations and irregular superficial masonry textures. Regarding the foundation, a direct and shallow foundation was used (average of 0.3 m deep), see Fig. 9.4d. Nonetheless, some short stretches of wall showed a wider than the cross-section foundation (average of additional 0.10 m to road side).

Fig. 9.3 – Images from the case study farm wall building materials: (a) well-defined foliation XO schist stones; (b) clayey soil gathered from the farm; (c) mix of both on the vernacular farm wall cross-section.

Fig. 9.4 - Images from the case study constructive irregularities: (a) deformed cross-section built with granitic soil; (b) cross-section built with clayey soil mortar; (c) stretch of farm wall with terrain retaining functions; (d) deep repairing intervention; (e) wall section show different cross-section thicknesses; (f) superficial masonry texture irregularities; (g) area with different types of foundation building quality (rebuilt area of the farm wall).

As for fragile points reinforcements, several types of capstones were identified. Causes for the constructive diversity observed were attributed to over time deep maintenance and to several partial repairs and reconstructions of collapsed sections of farm wall. Therefore, different masons' skills, available raw materials or lack of economic resources may explain such diversity and differences on construction quality.

For a wider analysis regarding the case study constructive features and its context, a short survey was performed on the settlement farm walls. By knowing them, it became possible to establish authenticity and identity criterion for the planned intervention. Results showed the existence of two groups of farm walls, being the most representative farm walls built with soil mortar, (see group M examples in Fig. 9.5), and the less representative dry-stack farm walls (see group D examples in Fig. 9.5). Examples of walls from group M were found from small-size to high farm walls, whereas examples of walls from group D, predominate small to medium-size walls. The two cross-section types listed above are shown in detail in Fig. 9.6, and their main building features are listed in Table 9.1 (see additional information on Section 6.1.2). To be noticed, the survey was carried out on collapsed walls, therefore, the ratio between mortar, stone and voids seen on cross-sections and superficial masonry textures may have been slightly affected by environmental actions.

Examples from group M were all double-leaf walls (see cases M1, M2 and M3), and presented a poor inner core infill of soil mortar and debris with a considerable percentage of voids [175]. As seen, group M walls showed lower levels of deformation when compared with examples from group D, which indicates a superior structural performance. The survey allowed concluding that the main causes for damage seen on group M walls have human origin and are due to bad interventions, partial demolitions, lack of maintenance and vibrations and impacts resulting from vehicles. As seen, other causes of damage may be attributed to differential settlements, located deformations and partial collapses caused by trees.

Considering now cross-sections from group D walls, for which four main types were identified as shown in Fig. 9.6, they present high variability and percentage of voids, and very heterogeneous inner cores. Leaves and stones blocks show insufficient interlocking, leading to the poor structural performance and durability observed during the field survey [166].

Regarding group D examples, constructive solutions using both types of schist were not common, and walls using poorly-defined foliation schists were restricted to the availability of outcrops of this type of rocks. The single-leaf cross-section was the most common dry-stack solution identified (see cases D1 and D2). Double-leaf walls with debris filling the inner core were only observed for high farm walls (see case D3) and showed stability problems. Cases D4 had a very restricted use, mainly for partitioning purposes. It depended on obtaining either large plate shaped well-defined foliation schist blocks or larger and heavier poorly-defined foliation schist blocks. Finally, damage observed on group D walls was frequently related to cases of out-of-plane deformation and cross-section disaggregation, mainly due to poor maintenance and lateral overload caused by trees.

Fig. 9.5 – Examples of farm walls with mortar (group M) and dry joints (group D). Average height (H) and thickness (T) dimensions are presented in each image.

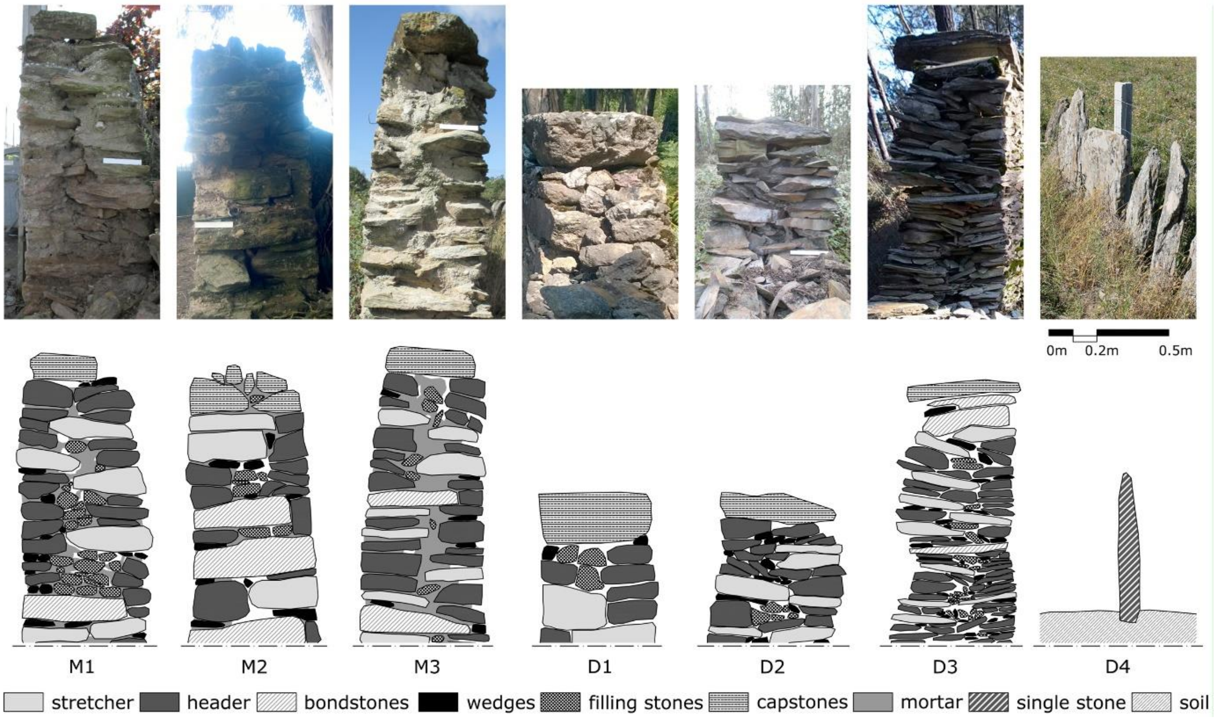


Fig. 9.6 – Cross-sections analysis of the farm walls examples of M and D groups.

Table 9.1 – Main constructive features of cross-sections from groups M and D.

Main features	Group M			Group D			
	M1	M2	M3	D1	D2	D3	D4
Rock type	Mixed well-defined and poorly-defined foliation schists			Poorly-defined foliation schists	Well-defined foliation schists	Well-defined or poorly-defined foliation schists	Well-defined or poorly-defined foliation schists
Number of leaves	Double			Single	Single	Double	Single stone
Mortar	Earth mortar			-	-	-	-
Inner core	Mortar and debris			-	-	Debris	-
Locations	Farmhouses, farmland			Farmland forestall areas	Farmland forestall areas	Forestall areas	Inside farmland and farmhouses
Morphologies (%)* (see Table 5.4)	Used in farm walls of all morphologies (≈ 60%)			Small (≈ 10%) medium-size (≈ 2%)	Small (≈ 17%) medium-size (≈ 8%)	High (≈ 2%)	Small-size (≈ 1%)
Typologies (see Table 5.3)	Used in farm walls of all typologies			Management, animal intrusion	Management, animal intrusion	Management, animal intrusion	Partitioning
Representativeness (%)*	Very high (≈ 60%)			Medium (≈ 12%)	Medium (≈ 25%)	Very low (≈ 2%)	Residual (≈ 1%)

* based on the amount of farm walls observed during the fieldwork survey

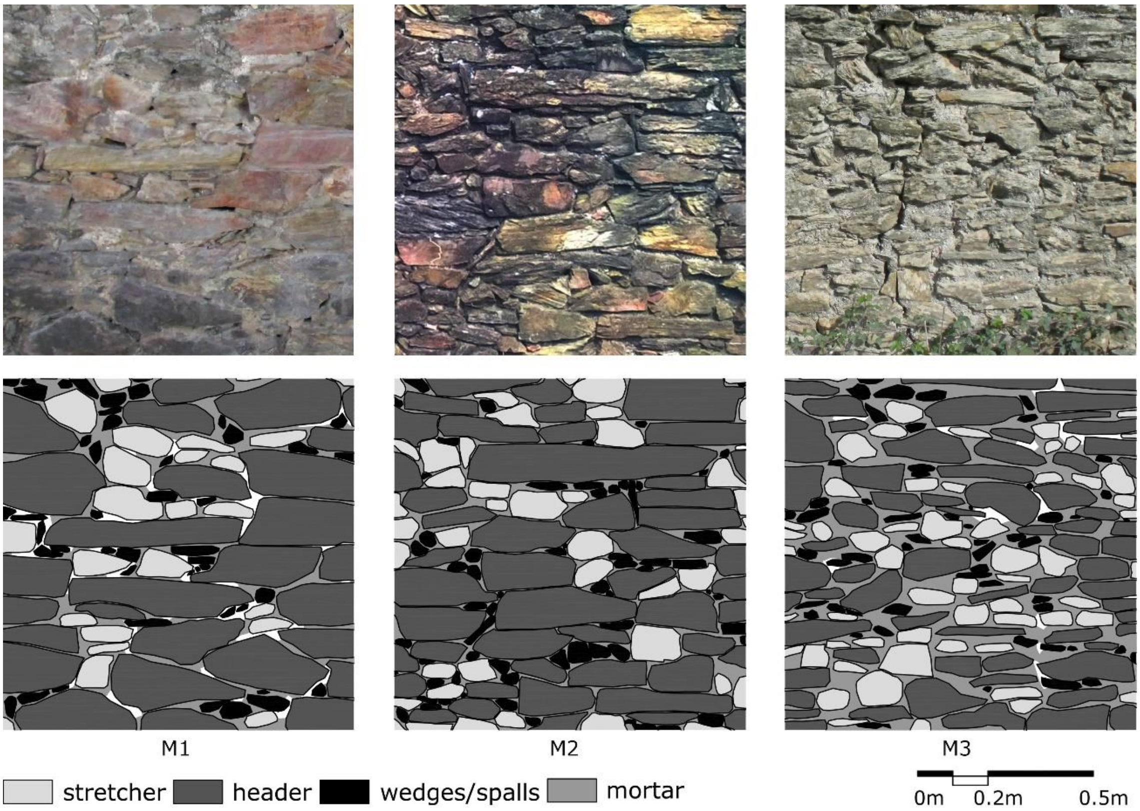


Fig. 9.7 – Superficial masonry texture analysis of the farm walls examples of group M.

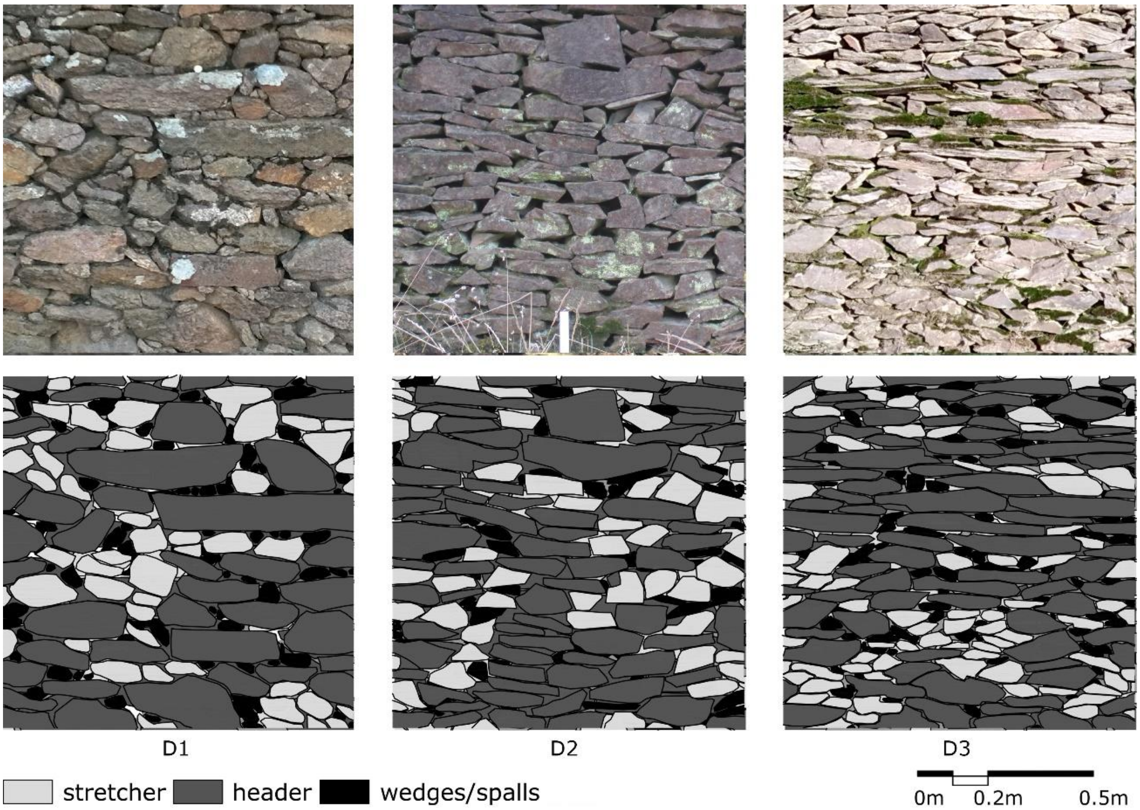


Fig. 9.8 – Superficial masonry texture analysis of the farm walls examples of group D.

Regarding superficial masonry textures, as respectively shown in Fig. 9.7 and Fig. 9.8, these were graphically analysed based on the elevation of a representative portion (1 m^2) of the road face of each group M and D examples. As observed, some irregularities in farm walls faces facing the farmland were frequent, being mainly caused by using poorer hammer-dressed stone blocks on that side, superficial masonry textures were very similar on both faces. To be noticed, due to their very low representativeness in the study area and the very basic single stone cross-section, the case D4 is not represented.

From the analysis, examples from both groups M and D show that masonry textures are very heterogeneous and present irregular arrangements, mainly caused by high geometrical irregularity and dispersion of schist stone blocks. The joints' irregular patterns are also the outcome of the bedding process, made as much as possible in regular horizontal rows and with misaligned vertical joints. As for the visual appearance, diversified colours and patterns associated with schist surfaces features were common. As for mortars in the joints and their appearance, it varies from whitish, ochre, and yellowish shade, to a wide variety of colours and textures associated with overwhelming biological colonization.

By statistically comparing the superficial masonry textures of groups M and D, see Fig. 9.9, one can conclude that on both groups, header stone blocks (placed longitudinally) are in larger number than stretcher stone blocks (placed transversally). The difference between header and stretcher stone blocks in group D examples (54% and 23%, respectively) is lower than in group M examples (59% and 16%, respectively). As observed during the field survey, dry stack walls with higher percentage of stretcher stone blocks showed higher stability in comparison with dry stack solutions with lower percentage of stretcher stone blocks. Based in this observation, one can conclude that a higher use of stretcher stone blocks improves the overall stability of farm walls from group D.

To be noticed, the pointing mortar on group M walls reduces the percentage of the visible voids in comparison with examples belonging to group D. In the latter, about 1/6 of superficial masonry texture area are voids. As observed, on group D walls, the absence of mortar also led to a higher use of wedges in comparison with group M walls (7% and 5%, respectively).

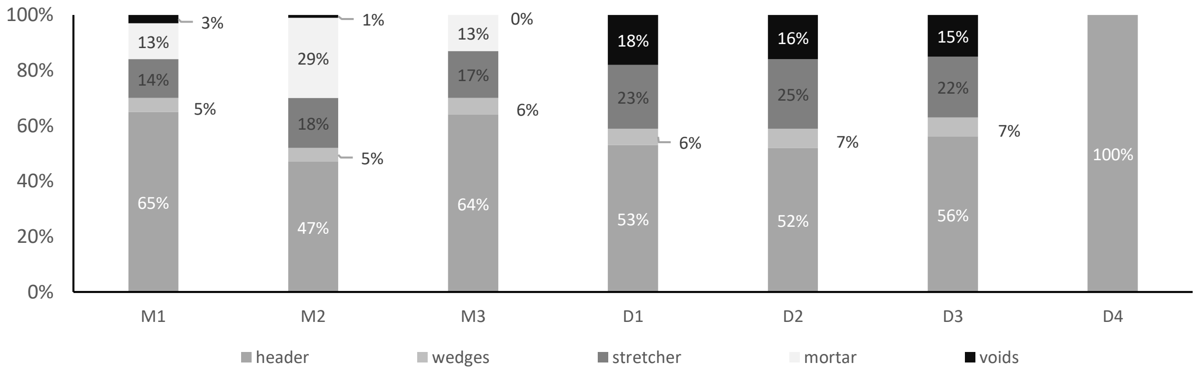


Fig. 9.9 – Analysis of the texture of the farm walls for groups M and D groups (values given in percentage).

b) Damage identification on the vernacular farm wall

Visible damage in the farm wall to demolish and its causes, were identified by visual inspection. A synthesis is presented in Table 6.3 and Fig. 9.10. It is worth noting that, according to witnesses, no maintenance has been performed in this wall for the past 40 years. Identified structural damage was mainly related with foundation settlements and opening of joints, causing deformations and partial collapses along the years. The most threatening deformation identified, corresponding to an out-of-plane top deformation of about 0.2 m, was originated by a foundation settlement caused by a poor intervention to correct the road's slope.

Due to the absence of any kind of render, non-structural damage caused by weathering and biological colonization (small and medium-size biological species) was strong, but not to the point of becoming a structural hazard. As expected, superficial damage is overwhelming, however, due to good water sorption conditions [216], low levels of visible salt or frost damage were detected, being the few cases seen always located at the lower half of the wall. Therefore, the visual inspection analysis made it clear that lack of maintenance, and poor human interventions on the wall and road were the main causes for the detected structural damage.

Table 9.2 – Damage causes and types found in the schist farm wall under study [36].

Damage causes			Damage types	
Human actions	Structural	Non-structural	Masonry walls	Materials
• Lack of maintenance [d; f; g] • Building mistakes and poor interventions [b; d; e] • Accidents and impacts [f]	• Soil and foundation settlements [a; c; e] • Loss of monolithic behaviour (leaves detachment) [b] • Unforeseen or excessive loads [b]	• Natural decay [h] • Weathering and environmental agents [h; i] • Biological colonization [g; h; I; j]	• Cracks, opening of joints [c; e; f; g] • Compatibility joints between wall stretches with slightly different masonry texture [e] • Large out-of-plane deformations (20 cm outwards) [a], small localized deformations [b] • Capstones disaggregation [g], located disaggregation and loss of material due to impact [f] • Partial collapses (later rebuilt) [e; f]	• Cracks, deformations, expansions, crushes, schist lamellar breakdown, material detachments [h; j] • Abrasion, erosion, granular disintegration by powdering or sanding [h; j] • Superficial deposits (e.g. crusts, film, or patina), salt damage (e.g. efflorescence and sub florescence), colour changes [h; I; j] • Bedding mortar disaggregation [g] • Superficial changes due to biological colonization (algae, lichen, moss, plants) [h; j]

Note: see Fig. 9.10 for examples of damage causes and damage types, references inside rectangular brackets.

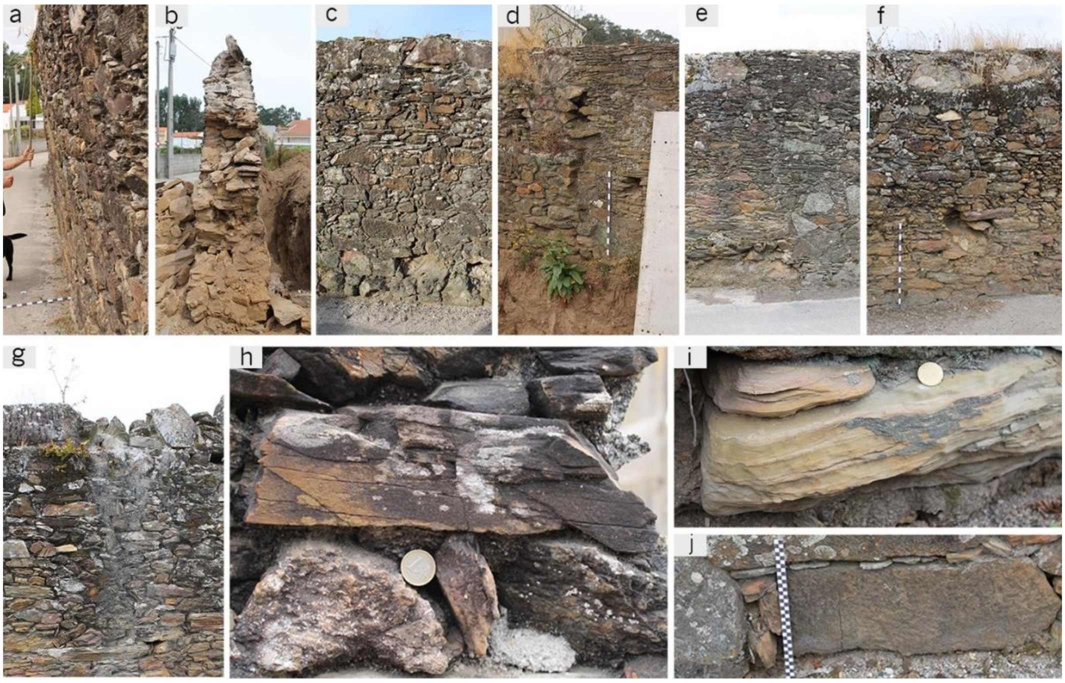


Fig. 9.10 – Examples of damage identified prior to reconstruction of the wall (see also Table 9.2).

9.1.2 Rebuilding solutions analysis

The information presented next regarding possible wall rebuilding solutions was gathered by interviews with local contractors and were confirmed by fieldwork observations. The information was sorted first by building materials, and secondly by compatibilities with authentic vernacular farm walls. As shown in Fig. 9.11 and in Table 9.3, three mains groups of solutions built by local contractors were identified: *i)* vernacular farm walls or Type 1 walls (see case A in Fig. 9.11); *ii)* non-vernacular farm walls or Type 2 (see cases B and C in Fig. 9.11); and *iii)* mixed systems farm walls or Type 3 (see cases E and D in Fig. 9.11).

Vernacular farm walls or Type 1 walls follow the vernacular building tradition and were the only type of farm wall built until the mid-20th century, being the technique used nowadays for maintenance or small repairs. As advantages, Type 1 farm walls show: *i)* an extremely high authenticity level; *ii)* full compatibility with existent heritage; and *iii)* a perfect integration into the landscape. As for main disadvantages: *i)* the growing difficulty in getting specialized masons; *ii)* long construction time; and *iii)* higher building cost related to workforce.

Non-vernacular farm walls or Type 2 walls, became prevailing from the mid-20th century onwards. They are built with contemporary building techniques, using industrial materials and reinforced concrete framed systems. As mains advantages, Type 2 farm walls show: *i)* reduced thickness (average of 0.25 m); *ii)* high availability of specialized builders and materials; *iii)* shorter construction time; and therefore *iv)* lower building costs or very favourable time/cost relation. As main disadvantages, one should point out: *i)* lower durability; *ii)* the loss of authenticity (non-vernacular materials and systems); and *iii)* the loss of identity (negative visual impact on the landscape) and arguable aesthetic aspect. Mixed farm walls or Type 3 walls are the outcome of combining vernacular building features with new materials and techniques. Their compatibility with authentic walls, advantages and disadvantages are very variably.

Table 9.3 – Main building features and construction parameters of common farm wall rebuilding solutions used in the survey area.

Building features	TYPE 1	TYPE 2		TYPE 3	
	A	B	C	D	E
Materials	Local stone (schist) and soil (bedding mortar)	Reinforced concrete combined with hollow ceramic bricks	Reinforced concrete	Reinforced concrete combined with hollow ceramic bricks and covered with local stone	Local stone (schist) and mortar (soil mixed with a small percentage of cement)
Foundation	Direct shallow and wider than the cross-section	Direct shallow and wider than the cross-section (mix of mortar and stone)			
Cross-section	Single or multi-leaf with bedding mortar (from 0.45m to 0.60m)	Single-leaf with bedding mortar (± 0.2 m)	Monolithic (approx. 0.20 m)	Double-leaf (first leaf like solution B, second leaf in structural stone with mortar)	Double-leaf with bedding mortar (approx. 0.45 m)
Masonry texture	Irregular and horizontally oriented; mortar joints	Coursed rows	None or artificially made	Coursed rows	Irregular and horizontally oriented; mortar joints
Reinforcements	Stone blocks overlapping at the inner core; full stretcher stone blocks	Reinforced concrete piers (approx. every 5m)	Steel bars	Steel bars and cement mortar bounding between leaves	Mortared stone blocks overlapping at the inner core; full stretcher stone blocks
Capstones	Stone capstones	Concrete capstone	Non-existent	Concrete or stone capstones	Stone capstones
Finishing works	Joint's pointing with mortar and/or wedges	Cement mortar coating	Non-existent	Cement mortar coating on the inner face	Joint's pointing with mortar or wedges
Building speed (3 men team)	3 m^2/day	8 m^2/day	7 m^2/day	3 m^2/day	6 m^2/day
Cost	60 €/m^2 to 120 €/m^2	35 €/m^2 to 50 €/m^2	80 €/m^2 to 100 €/m^2	120 €/m^2	120 €/m^2
Representativeness	Very low	Very high	Low	Medium (urban context)	Low

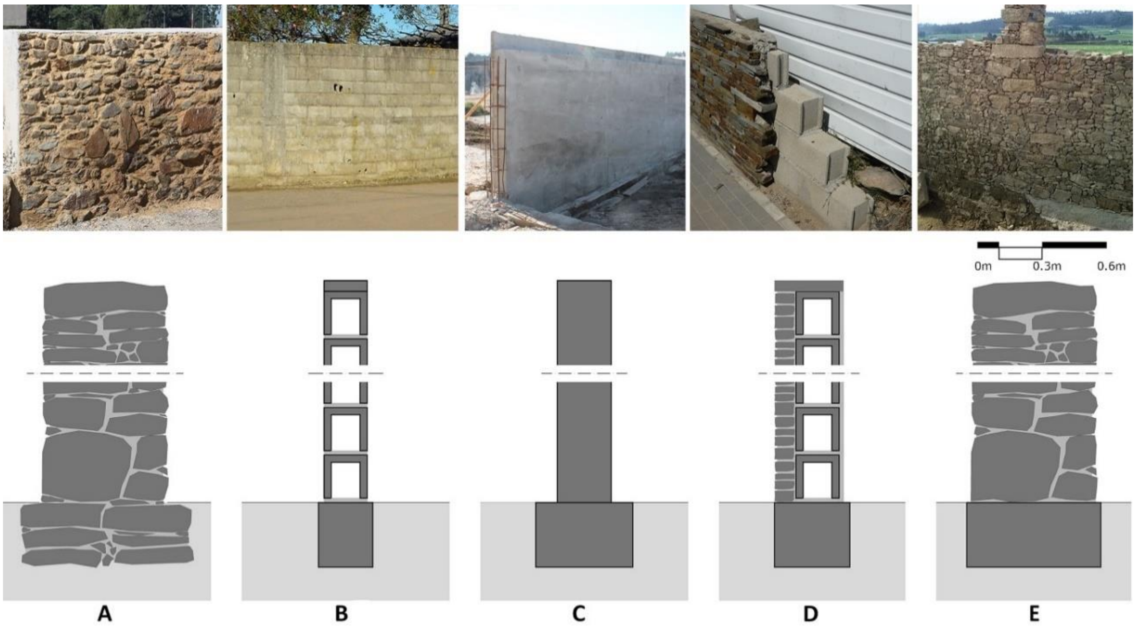


Fig. 9.11 – Common farm wall rebuilding solutions used in the survey area (with typical cross-sections).

9.1.3 Assessment methodology and solution selection

The decision-making process for selecting of the new farm wall solution followed a quantitative and qualitative weight-based methodology, see Table 9.4. Therefore, the new farm walls construction parameters presented in Table 9.3 were quantified and graded accordantly to four different parameters (P1 to P4), rated from 1 to 5 (1 – non-complying; 5 – fully complying). The selected parameters, defined in a qualitative basis, were selected accordantly to the area renovation intervention guidelines set up by the contracting authority. Their weight in the decision-making process was defined by their priority in the intervention objectives, as follows: *i)* preserving local landscape's heritage value, by ensuring visual compatibility with authentic vernacular walls (P1 - 0.4); *ii)* complying with a moderated budget (P2 - 0.3); *iii)* reusing of the demolish materials as much as possible, to reduce costs with new materials and waste disposal (P3 – 0.2); and *iv)* maximum rebuilding time of three months (P4 – 0.1). The final grade F_G was obtained by summing all the parameters.

Table 9.4 - Quantitative analysis of farm walls rebuilding solutions.

Parameters [parameter's weight]	Analysed rebuilding solutions (parameter's grade)				
	A	B	C	D	E
P1 – Authenticity compatibility [0.4]	Very high (5)	Very Low (1)	Very low (1)	Medium (3)	High (4)
P2 – Rebuilding cost [0.3]	120 €/m^2 (1)	50 €/m^2 (5)	100 €/m^2 (3)	120 €/m^2 (1)	100 €/m^2 (3)
P3 – Materials reuse [0.2]	Very high (5)	Very low (1)	Very low (1)	Medium (3)	Very high (5)
P4 – Rebuilding time [0.1]	4 months (1)	1 month (5)	2 months (4)	4 months (1)	3 months (3)
F_G – Final grade	3.4	2.6	2.2	2.2	3.8

Analysing the information presented in Table 9.4, one has: *i)* as for the authenticity compatibility requirements (P1), solutions A (5) and E (4) show a high grade and solution D (3) shows an acceptable grade, whereas solutions B (1) and C (1) show very low grades; *ii)* although solutions B (5;5) and C (3;4) show very good grades for parameters P2 and P4, their very low grades for P1 and P3 (1;1) makes them, from a qualitative point of view, not desirable solutions; *iii)* considering parameters P2 and P4, solutions A (1;1) and D (1;1) show the higher building cost and exceed the available time frame, being solution E (3;3) the most balanced one for the combination of both parameters; and *iv)* as for parameter P3 and from a qualitative point of view, the high grade assigned to solutions A (5) and E (5) indicates a possible decrease in the final cost by reusing the demolished stones (not quantified). Considering the quantitative analysis and the qualitative remarks, one can conclude that solution E (F_G = 3.8), chosen by the contracting authority, seems to be the recommended rebuilding solution in face of the established criteria.

9.1.4 Key building features of the selected farm wall solution

The rebuilding of the farm wall following solution E took place from mid-April to mid-July 2013. The construction followed the main traditional methods (see Section 6.1), improved with some contemporary construction features, as described following and shown in Fig. 9.12. A backhoe loader was used for the excavation, terrain preparation and cleaning works. The shallow foundation was built with poor concrete mixed with schist stones, and casted using a metallic formwork, see Fig. 9.12a and b. The wall was built using a bedding mortar made of soil mixed with a small amount of ordinary Portland cement, with low sulphate contents (CEM II/B-L 32.5 N), and water with the ratio of 1:20:8. An auxiliary timber formwork was used to accelerate the building of the wall by assisting to both faces' vertical alignment, see Fig. 9.12c and d. Nonetheless, guidelines were placed to assist levelling of the top rows, see Fig. 9.12e. The formwork was disassembled and reassemble as each stretch of new wall was concluded, see Fig. 9.12h.

The demolition of the existing farm wall was done simultaneously with the advance of the timber formwork. Demolished materials were kept next to the formwork, easing the construction process, see Fig. 9.12f. The connection to the existent wall was made without the assistance of the timber formwork, see Fig. 9.12g The masonry joints' pointing was performed on both faces of the farm wall, but only using spalls, see Fig. 9.12i. The final task was to correct the terrain slope, see Fig. 9.12j.

Fig. 9.12 – Different steps of the rebuilding of the farm wall: (a) and (b) shallow foundation construction; (c) cross-section of the double-leaf wall; (d) timber formwork and scaffolding; (e) bedding of a layer of stone blocks; (f) new wall and nearby materials from the demolished wall; (g) connecting of the new wall with the existent wall; (h) moving of the formwork; (i) pointing of the open joints with spalls; (j) correction of the terrain slope.

9.1.5 Monitoring of results and improvement recommendations

As positive aspects of the rebuilding intervention and the solution chosen, one can see that the rebuilt wall (see Fig. 9.13) is similar to the demolished one in what concerns geometry and visual aspect. A substantial gain in execution costs and time was achieved due to the use of contemporary construction techniques and of the demolished material's reuse, that balance favourably the high workforce cost required by the solution adopted (see Table 9.3 for construction time need by a three-man team). As for the new farm wall cross-section, the inner core has a low voids percentage in comparison with the demolished wall, which results from the construction technique adopted. An improved structural performance and durability is expected. Structural performance gain is also achieved with the type of foundation built, that shows higher resistance to soil settlements and to disaggregation caused by vibrations induced by passing vehicles.

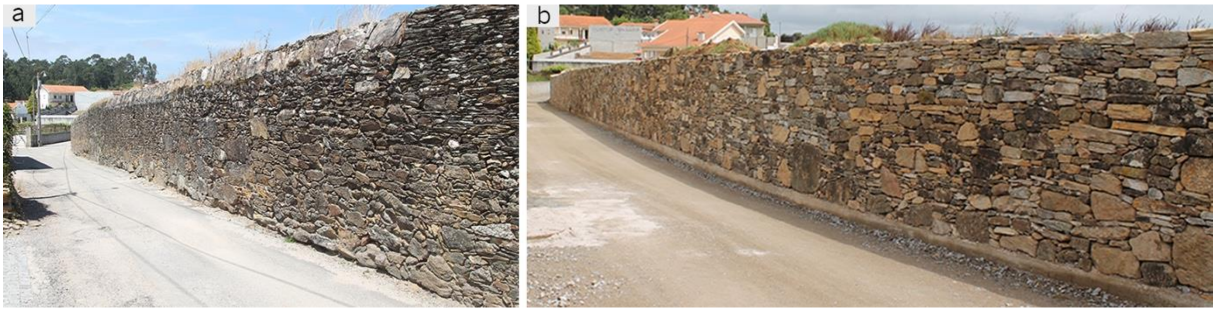


Fig. 9.13 – Rebuilding of the farm wall: (a) prior to demolition; (b) new rebuilt wall.

As less positive aspects resulting from the intervention, one can point out the use of different masons' teams by turns, with different skills levels, that influenced the wall's building quality by increasing its heterogeneity. The use of the timber formwork to assist in the vertical alignment of the wall resulted in a decrease of the percentage of levelling wedges used but increased the percentage of masonry texture's voids. Therefore, in comparison with the traditional methods, the new method used on the new farm wall caused inferior superficial texture quality. Due to the very irregular geometry of the original schist blocks, only an average percentage of 70% could be reused, while the reuse of original soil mortar was not possible. The pointing technique based only in spalls increased the percentage of masonry texture's voids in comparison with the demolished wall. Therefore, a negative effect over the durability of the new wall is expected. As a more general observation regarding the construction technique use and its applicability to other similar cases, it should also be noted that the time and cost benefits associated might not be directly applicable to smaller walls due to machinery and formwork operation costs. Three years after the conclusion of the rebuilding process, the new farm wall does not show any deformation, joint opening phenomenon, or stability problem. Still showing a different aesthetic aspect of "new", the superficial masonry texture is progressively acquiring the aspect of the surrounding farm walls due to biological colonization. As one can observe in Fig. 9.14, a granite capstone was added later, changing the final aspect of the wall.

As seen in Fig. 9.15, some maintenance is already required to correct some minor superficial masonry texture damage and to eliminate some small-size biologic species that are colonizing the new masonry texture. By these observations, it was concluded that no maintenance has been yet performed on the new farm wall.

Considering the above, it was recommended to future similar interventions, to adopt a more effective pointing process, either by using soil mortar or by increasing the number of inserted spalls. The implementation of a proper maintenance and monitoring plans is considerate a priority to prevent or to minimize damage. Additionally, following international heritage preservation guidelines [49], lime-based mortars should be used instead of cement-based ones, in order to prevent future chemical incompatibility with the schist blocks.

As final notes, the five rebuilding options proposed in this work demonstrate the overwhelming predominance of the construction of non-vernacular walls in the study area, mostly due to constraints such as cost and execution time, but also caused by the disappearance of specialized workers and, with them, the empirical knowledge associated to vernacular construction. Although clearly identified as a new wall, the rebuilding solution adopted represents a good example of compromise between the landscape's heritage value preservation and the observation of contemporary society's needs, setting an example of vernacular and contemporary building technique's combination, able to be used when the preservation of vernacular structures is no longer an option.

Fig. 9.14 – Aspect of the wall in late 2016.

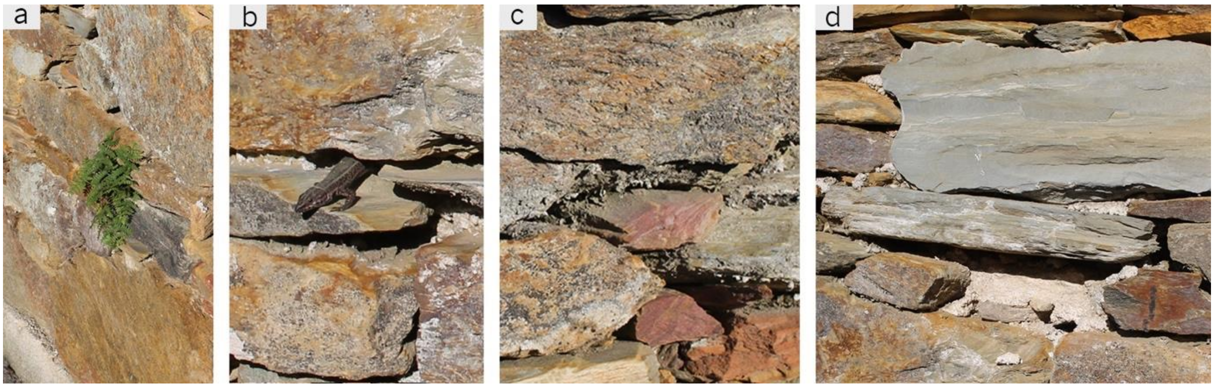


Fig. 9.15 - Minor damage observed in late 2016: (a) colonization by small-size vegetation; (b) colonization by small reptiles; (c) dirt deposits and colonization by algae and fungus; (d) loose spalls and minor masonry texture disaggregation.

9.2 Vernacular corbelled dome heritage preservation methodology

Corbelled dome heritage can be defined as one of the most intuitive types of construction found among both monumental and vernacular heritage. From a constructive point of view, corbelled dome structures can be described as resulting from overlapping stone or adobe blocks, forming horizontal rings or layers of masonry, jutting toward the centre and around a central axis until meeting at the top [107,266]. In Fig. 9.16, some examples from the Iberian Peninsula corbelled dome structures are shown. According to the scarce existent scientific literature on the topic, corbelling behaviour is based on the balance achieved by the combination of vertical transfer of forces to dome’s base and on horizontal actions caused by overlapping stone blocks’ interlocking and friction [267]. As for the applicability of the corbelling principles, examples can be found for domes, to arches and vaults construction. However, considered of less relevance by the scientific community, the structural behaviour of corbelled domes is still less studied and known in comparison with other vernacular structural systems.

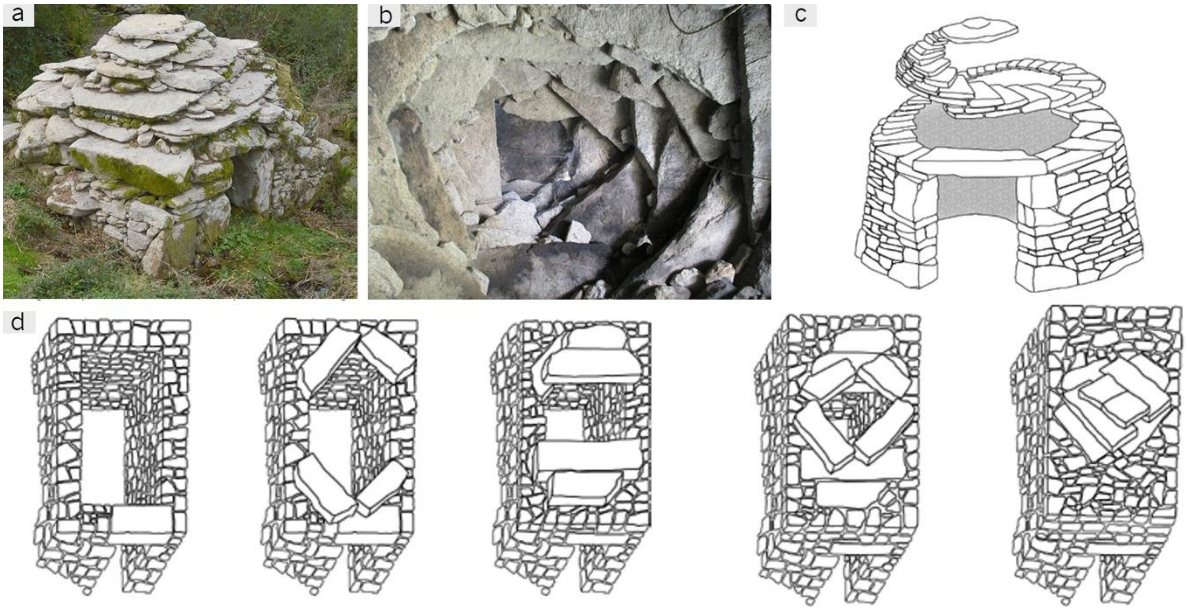


Fig. 9.16 – Images and schematics of corbelled dome structures: (a) external view of building B11; (b) intrados view of building B7 corbelled dome; (c) schematic representation of the construction process of a corbelled dome with spiral form named *“caracoles”*, Andalusia, Spain (drawing by Vegas et al. [268]); (d) schematic representation of the construction process of a rectangular corbelled dome structure (drawing by Vegas et al. [268]);

Being most of these vernacular architecture examples very authentic context adapted responses, corbelled dome heritage morphologies and typologies are found all around the world, built in different materials and using different corbelling systems [42]. Being generally related to traditional agrarian life styles, most existing corbelled dome heritage in Southern Europe is without use and in an advanced stage of abandonment [42]. Although being a fundamental part of specific forms of rural cultural identity, the loss of knowledge and recognition concerning these vernacular forms of heritage, placed them in an endangered position. With the strong rural exodus of the past decades, which resulted in the ending of the highlands traditional agro-pastorist and vertical transhumance ways of life, the corbelled dome heritage built on the temporary mountain range settlements, particularly in the ones located in the most isolated locations, have been suffering from lack of use and severe absence of maintenance. A considerable part of these vernacular structures are already taken by vegetation [139]. Without close contact with the territory, lacking documental information, and with the loss of the old generations, a part of these structures is facing oblivion. Simultaneously, temporary mountain range settlements located in less remote mountain range plateaus, are losing their authenticity and identity due to harmful interventions caused by lack of knowledge about these building specificities (local communities) and cultural value (authorities). To answer/react to such challenges and by understanding the full potential of such forms of vernacular heritage (cultural - economic - touristic), this research performed an attempt to recover part of the Iberian Northwest vernacular corbelled dome heritage knowledge and invested in enlighten society to its high cultural value. Therefore, by understanding this specific vernacular heritage as part of a complex cultural, social, ethnographic, and historic identity, which shaped the landscape into specific human occupation systems (explained on Chapter 4), a research plan was set and implemented. Its main goal was to allow an overview on the architectural and constructive diversity of the corbelling phenomenon at the highland sub-region, whose cultural transhumance phenomena stretches throughout the transboundary mountain range region surrounding and including the Gerês-Xurés Transboundary Biosphere Reserve [124].

The research work gathered as much as possible the endangered vernacular knowledge and developed a preservation plan with recommendations for highland corbelled dome buildings and sites safeguarding. Therefore, a multi-skill research group was set together, combining different research expertise and local partners with intimal knowledge about the territory: *i)* University of Minho - Institute for Sustainability and Innovation in Structural Engineering (ISISE) (coord., the author); *ii)* Vigo University - Applied Geotechnologies Research Group (AG – Dr. Belén Riveiro); *iii)* University of Porto – Faculty of Architecture/Centre for Studies in Architecture and Urbanism (FAUP-CEAU, arq. Fernando C. Barros); and *iv)* the support of Arcos de Valdevez Municipality (local partner). To carry out the study, a methodology was prepared, and it is presented in Fig. 9.17.

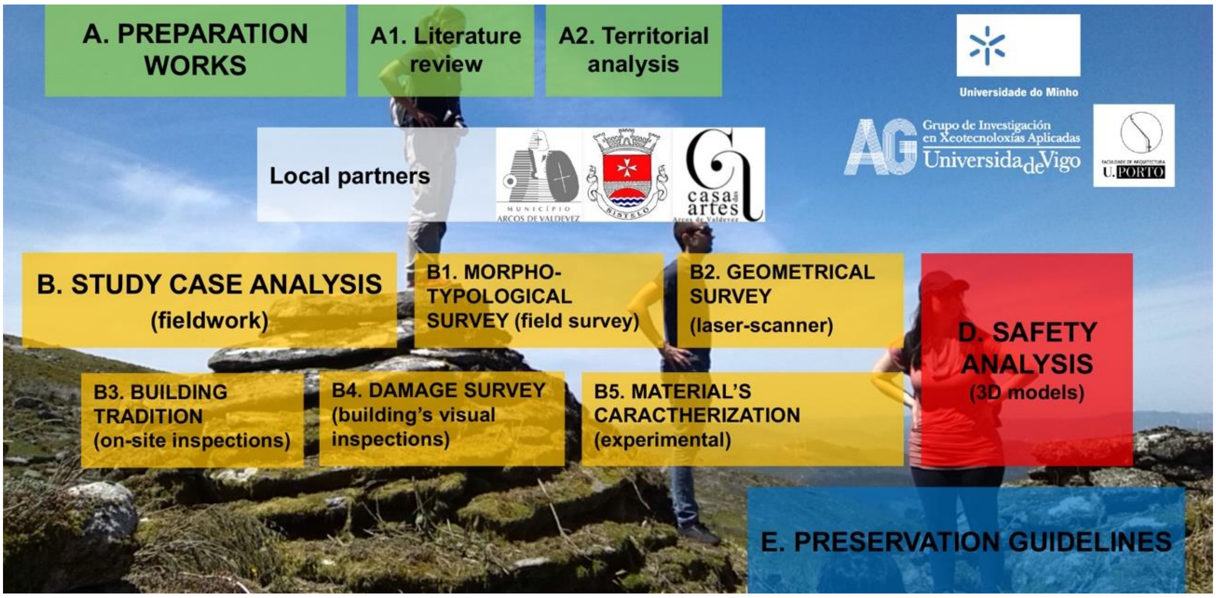


Fig. 9.17 – Methodologic chart for the *"brandas"* research campaign (started 2014)

Taking into consideration the complexity of the topic, the extensive and harsh landscape to study, and the different needs and skills from the research group partners, the research was divided into a macro scale analysis, concerning the territory and its occupation (see results on Chapter 4 and Section 5.4.3) that included literature review on the different topics associated to the task, and on a micro scale analysis, by performing a detailed survey on specific case studies, presented in this section.

As for the different analysis levels, the research started by a first phase of exhaustive literature and documental review, complemented by exploratory visits. The latter were fundamental to obtain an on-site overview on the still existing corbelled dome vernacular heritage, its state of conservation and basic architecture and constructive features. A second phase was implemented, using case studies to conduct several types of surveys (geometric, constructive, and dynamic identification surveys) and analysis (morphological, typological, damage identification). Simultaneously, field interviews among the local community were conducted, and stone blocks of representative granites, used to build the case studies. On the third phase, the experimental characterization of the collected materials was performed(see Chapter 7 and Chapter 8). As part of the task, the dynamic identification of corbelled dome buildings was performed to support future mathematical analysis with numerical models of the corbelled dome structures.

The final phase concerns the elaboration of a preservation plan with guidelines and recommendations, based on the best international good practices on the topic. Following the development of the several research tasks, a strategy for enlighten the local and the academic communities (both national and international) to the topic was implemented through a series of publications and conference participations [105,106,155,261–263]. To be noticed, several other forms of corbelled dome heritage are still identified for future study, and for being a still undergoing research, the structural safety analysis of the corbelled dome buildings is still under preparation. Therefore, the definitive version of the preservation guidelines overshoots the time frame of the present thesis and may suffer slight adjustments in future publications.

9.2.1 Corbelled dome heritage context overview

Although the precise origin of the corbelling constructive knowledge is still uncertain, the megalithic times and Mesopotamian civilizations (around 6000 years) are pointed by several authors as its most probable origin [107,269]. Juvanec [267] points to corbelling building techniques as an intermediate solution between the pillar and lintel, and the arch and dome systems and, therefore, to probably have preceded these technologies in many cultures. From the literature review, it became clear that corbelled dome structures are found all around Europe. Mecca et al. [42] extensive survey on the topic showed the very strong presence of such type of buildings around the Mediterranean. As shown in Fig. 9.18, examples are found from simple dwellings built in adobe (e.g. *“beehive”* houses, Syria), to basic farmers and shepherds stone shelters (e.g. *“cabane”*, France), to larger and elaborated houses (e.g. *“trullo”*, Italy) [42].

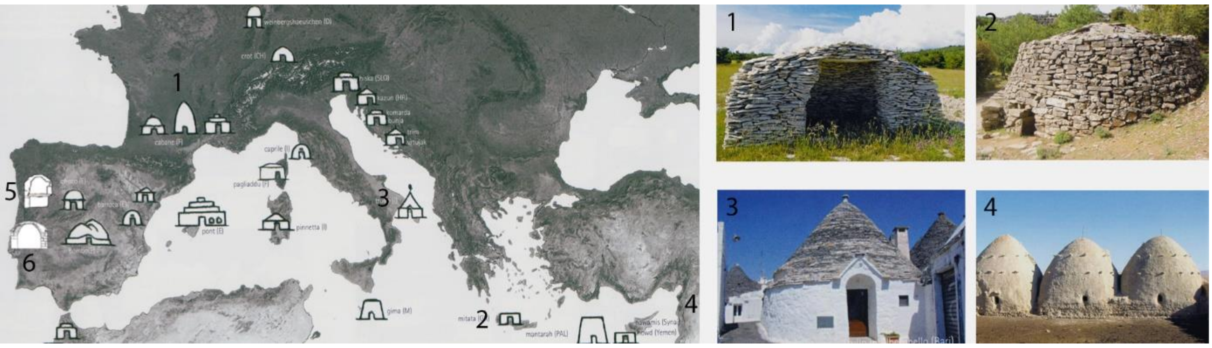


Fig. 9.18 – Corbelled dome heritage around the Mediterranean. Original map from Juvanec, published in [42], with the added Portuguese corbelled dome heritage examples (5) *"abrigos"* or *"cortelhos"*, and (6) *"safurdas"* or *"fornos"* (after Oliveira et al. [10]). Other examples: (1) *"cabane"*, France; (2) *"mitata"*, Crete; (3) *"trullo"*, Italy; (4) *"beehive"* houses, Syria [42].

Based on existing literature on the topic, two main families of corbelled dome buildings can be identified [42,266]. The first and smaller group refers to corbelled dome buildings with mound, such as the Mycenaean (Greece, 14th century B.C.) or Populonia *"tholoi"* (Italy, 7th century B.C.). As shown from the Portuguese ample presented in Fig. 9.19, the best-known examples of such type of buildings are from monumental and archaeological origin and are related to ancient cultures ceremonial and funerary rites.

The second and larger group concerns corbelled dome buildings without mound (see Fig. 9.18 for examples). Most known examples show a non-monumental origin, being related to agro-pastorism and transhumance traditions, but also for other uses such as for housing or complementary infrastructures [42]. Due to their high morphological, typological and constructive diversity and inventiveness, one can assume very pragmatic origin for corbelling techniques, most resulting from the combination of factors such as farming needs, climate and available local materials [266]. In comparison with buildings from the first group, buildings from the second group were built closer to our time.

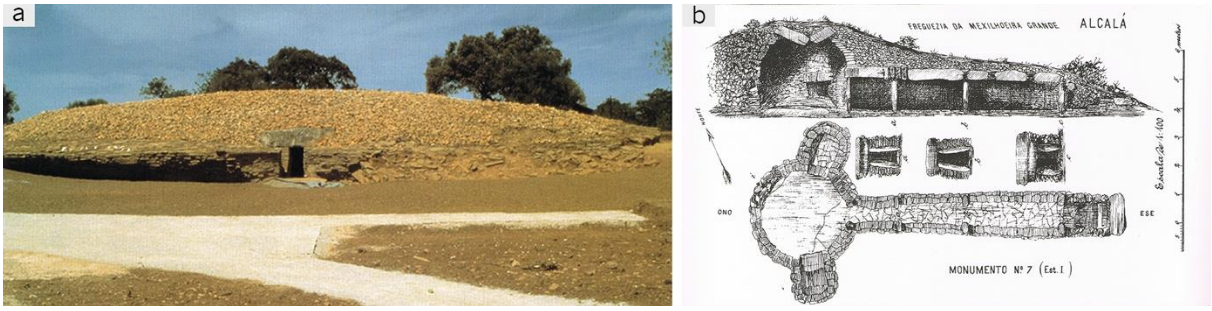


Fig. 9.19 – Alcalar *"tholoi"* (Portimão Municipality, Portugal) [270]: (a) image from the main building; (b) based plan and elevation drawing by Estácio da Veiga (1889).

As for the Portuguese context, very few examples of the first group are known. As for examples from the second group, according to the studies of Oliveira at al. [10], these were mainly farming and transhumance support buildings, being either built isolated or in small groups. As for corbelled dome permanent housing buildings, no examples were seen during the fieldwork or are reported by the existent studies [10,107]. Other types of reported typologies of buildings, such as mills or ovens, were identified during the survey [106].

A first morphological categorisation regarding vernacular corbelled dome structures in Portugal was presented by Oliveira et al. [10]. As shown in Fig. 9.20, the vernacular corbelled dome heritage identified in the author's [10] studies was divided into corbelled dome structures in which the corbelled dome's intrados is part of the walls (6), either starting from the ground (6.1) or from the wall's section (6.2), and structures with the corbelled domes starting from the top of the walls (5).

Besides the reported constructive distinction regarding the relation between corbelled domes and walls, and the clearly distinct aesthetic of buildings from both groups, buildings from the second group are clearly smaller. However, they are the only known examples of two-storey Portuguese corbelled dome buildings. From a functional point of view, although on both groups prevails the agro-pastorist uses, as it was observed during the field survey and also reported by Oliveira et al. [10], examples from the second group were also used as temporary farmers/shepherds shelters (see Section 5.2.3). On both groups of buildings, it was common to cover the domes with earth. Taking into consideration the above-mentioned morphological categorisation, the corbelled dome buildings existing at the highlands belong to the second morphologic group identified by Oliveira et al. [10].

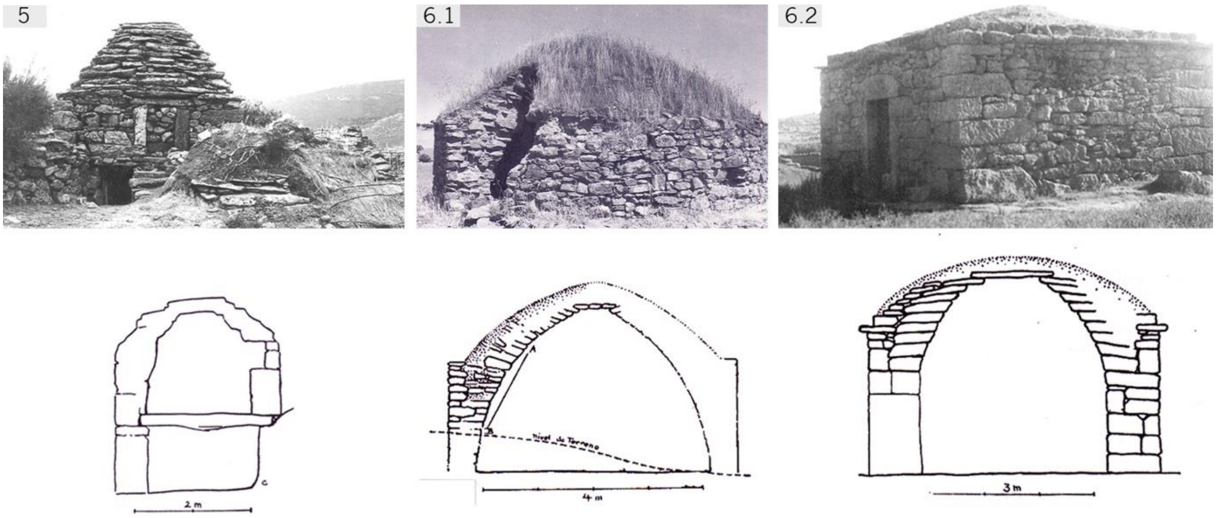


Fig. 9.20 – Portuguese corbelled domes' buildings morphological groups as presented by Oliveira [10].

9.2.2 Fieldwork survey

Considering the results from the first phase of the research, the Peneda mountain range, in Arcos de Valdevez municipality, was selected for more accurate exploratory visits. During these visits, the *"branda"* of Alhal (740 m above sea level) and the *"branda"* of Gêmea (1010 m above sea level), both having as base settlement the *"lugar"* of Padrão (495 m above sea level), of the village of Sistelo (300 m above sea level) were identified for a detailed analysis, due to their remarkable and well preserved corbelled domes structures. Both "*brandas"* are examples of mixed or simultaneous pasture and farming temporary mountain range settlements (see Section 5.4.3). For its closer proximity to the base settlement (Padrão), farmers and shepherd would go and return from the *"branda"* of Alhal during the day in short roundtrips (< 20 min. walk), whereas going from the first to the second *"branda"* would take longer (≅ 1 h and 30 min.). Therefore, at the *"branda"* of Alhal, corbelled dome buildings were built only for livestock sheltering, therefore, there were no two-storey farmers/shepherds’ shelters.

The existing *“branda”* houses, although some show a fireplace, according to witnesses, these building were used as stables and for storage. However, at the *“branda”* of Gêmea, the need to stay for longer periods of time lead to the construction of complex groups of corbelled dome buildings formed by several one-storey livestock shelters, one two-storey farmers/shepherds’ shelter, one gable house and private corrals. Without automobile access and with a narrow climatic window (April – May and September – October), the field survey campaign was divided into different visits performed during one-year time (2014).

On the first visit to *“branda”* of Gêmea, two complex groups of buildings were selected as case studies. The detailed survey was performed on two groups of corbelled dome buildings, named Group A (41º58’26.6” N 8º19’29.3” W), see Fig. 9.21, and Group B (41º58’19.5” N 8º19’30.2” W), see Fig. 9.22. Each group is formed by eight one-storey livestock shelters, one two-storey farmers/shepherds’ shelter, one *“branda”* house, and private enclosed corrals (see Section 5.4.3, for general buildings’ morphological and typological information).

Fig. 9.21 – Different views from case study buildings from Group A (Padrão, *“branda”* of Gêmea, Peneda mountain range).

Fig. 9.22 – Different views from case study buildings from Group B (Padrão, *"branda"* of Gêmea, Peneda mountain range).

On the second visit, see Fig. 9.23, with the support of the local partner and the Equipa de Sapadores Florestais do Gabinete Técnico Florestal do Município e da Associação Floresta Atlântica, the site was cleared from all large and medium-size vegetation that was blocking paths and access to buildings or conflicting with the laser scanner's visual range. During the cleaning operation, a third large group of buildings was discovered, see Fig. 9.41c. The laser scanner surveys and visual inspections were performed on the third visit, see Fig. 9.24a to c. During a fourth and final visit, the buildings' dynamic identification was performed, along with complementary laser scanner surveys, see Fig. 9.24e and f. Visual inspections and photographic surveys were performed on all visits.

Fig. 9.23 – Images from the cleaning operation: (a) cleaning works by the Equipa de Sapadores Florestais do Gabinete Técnico Florestal do Município e da Associação Floresta Atlântica; (b) Group B before the cleaning operation; (c) Group B after the cleaning operation (photos from Fernando C. Barros).

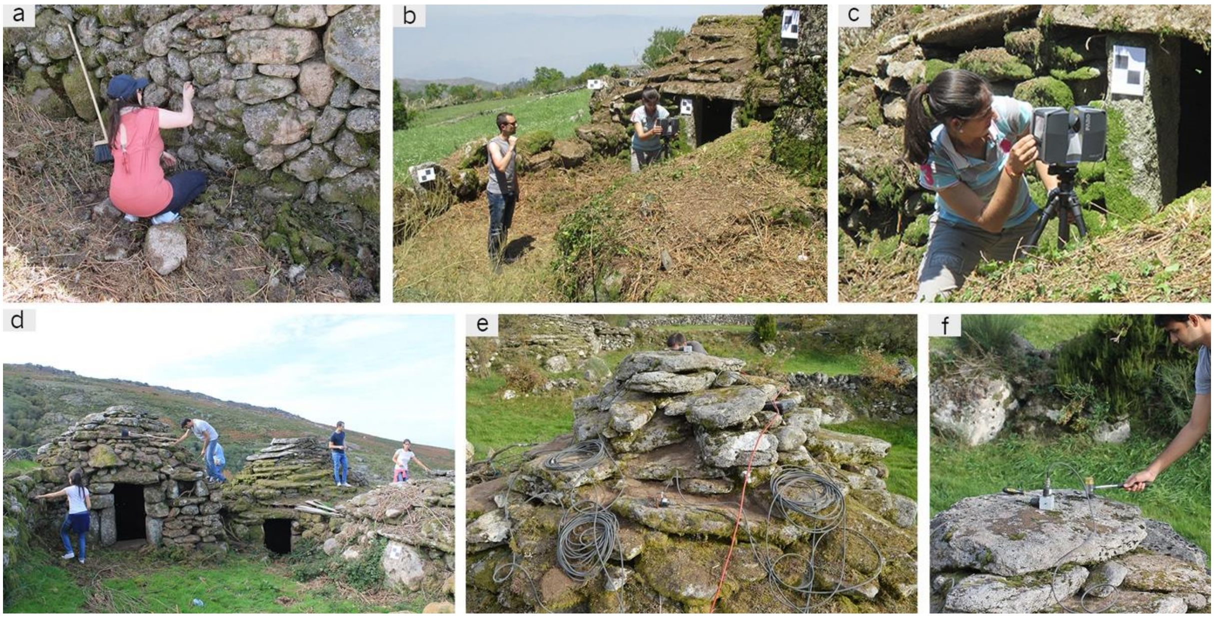


Fig. 9.24 – (a), (b) and (c) images from the laser scanning survey; (d) visual inspection and preparation for a laser scanning and dynamic identification surveys; (e) and (f) images from the dynamic identification survey.

a) Laser scanner survey

Due to the extremely high geometric irregularities shown by the selected corbelled dome buildings, the use of conventional geometric survey techniques was ruled out for being considered ineffective for the aimed level of accuracy. Therefore, to achieve the required detailed and accurate 2D/3D documentation of buildings, laser scanning technology was selected for the digital recording. Laser scanning is a remote, non-destructive technology that is able to automatically record millions of 3D coordinates of an object's surface [214]. Depending on the equipment, the accuracy of the measurements can reach up to a few millimetres. Due to the limited access to the corbelled dome buildings, only static scanners were used. Therefore, a Faro Focus 3D® scanner was used for the survey works, which measures distances using the principle of phase shift at a wavelength of 905 nm. This device measures distances in a range of 0.60 – 120 m with a point measurement rate of 976.000 points per second. It has an accuracy of 0.015° in normal lighting and reflectivity conditions. The field of view extends 300° vertically and 360° horizontally with a 0.009° of angular resolution and the returning intensity is recorded in 11-bit format. Additionally, this laser scanner includes a double compensator in the horizontal and vertical axes. The field works consisted on the recording of 3D images of the constructions from both their exterior and indoor faces. To align all the point clouds in a common coordinate system, artificial targets were needed. To achieve an easier registration process, the scanner was levelled during the recording of all the point clouds. This operation also guarantees that the final point cloud is levelled. During the scanning, angular resolution of the scanner was set to 6 mm at 10 m for the indoor scans, and 3 mm at 10 m for exterior point clouds. Due to the complex geometry of the constructions, a large number of scanner positions were required to complete the exterior and indoor scanning of all constructions. For Group A, a total number of 29 scanner positions were required, whereas 26 scanner positions were required for Group B. The time required for scanning each group of corbelled dome constructions did not exceed four hours.

The information collected was afterwards analysed to allow the extraction of very dense point clouds. As expected, after edition became possible to create several different types of images and to gain access to different levels of information, that were invisible using conventional survey methods, see Fig. 9.25 and Fig. 9.26. However, to create any type of image, the huge amount of points produced from the scanning works had to be post-processed in order to optimize the point clouds and remove redundant data. Such operation is also fundamental to allow an ease handling of the point clouds and to perform the documentation in an efficient manner.

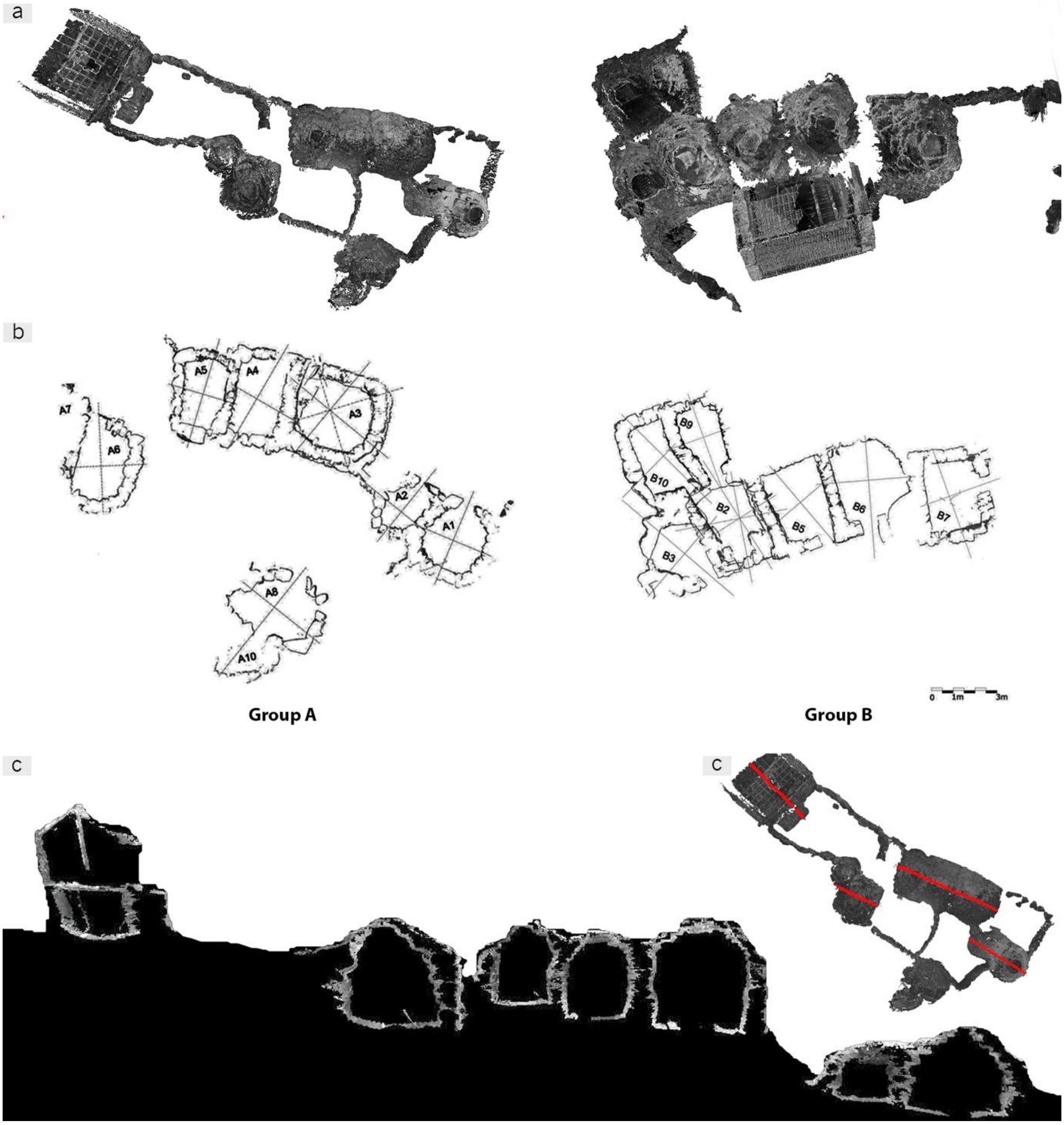


Fig. 9.25 – Different images and types of information resulting from the laser scanning (images created using *RiscanPro®*): (a) aerial view of the point clouds; (b) base plan horizontal sections; (c) group and individual cross-sections and elevations (Group A example).

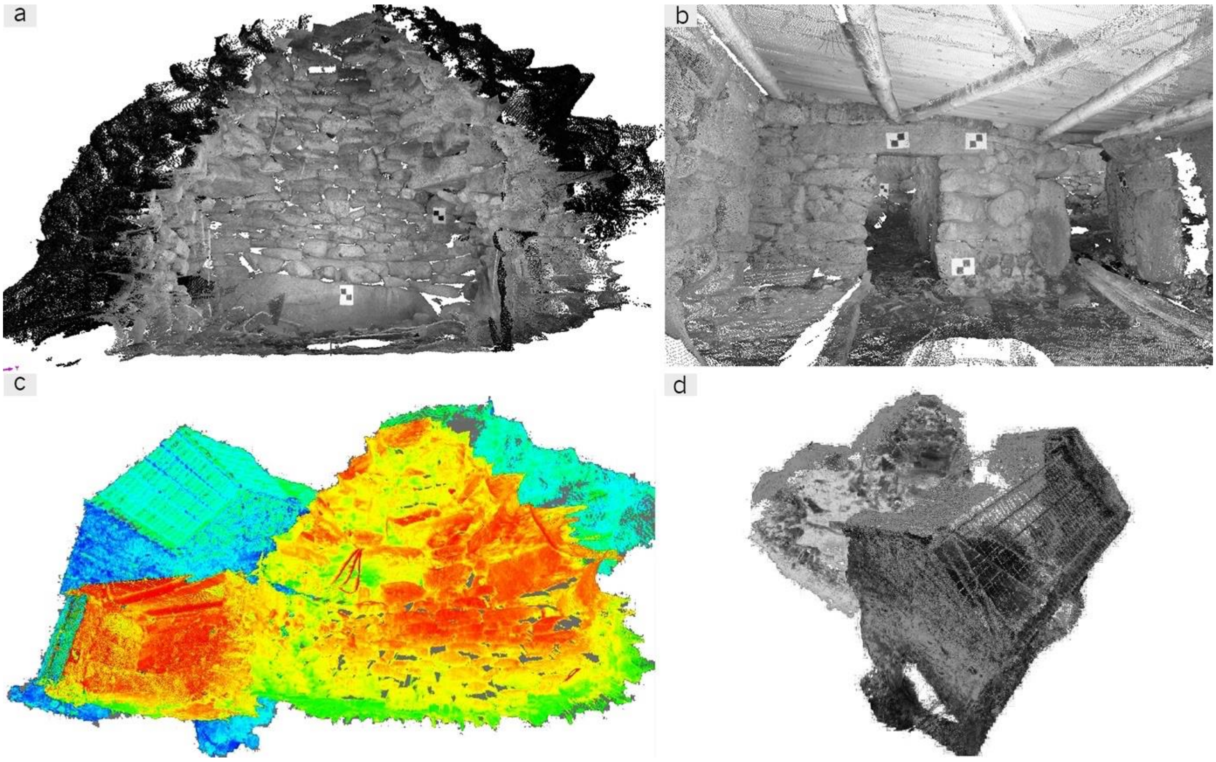


Fig. 9.26 – Examples of perspective images created from the point clouds using *RiscanPro*® (Group B examples).

The first task consisted of performing the alignment of different scanner positions using the coordinates of the artificial targets measured in the field. Next, noisy points of non-desired objects such as vegetation were removed from the point cloud. The following step consisted of the segmentation of the point cloud into three main features: *i)* ground points (that are lately used to define the Digital Terrain Model (DTM)); *ii)* buildings; and *iii)* enclosing walls. To optimize the density of the point clouds and to remove redundant points, a spatial filtering was applied using octree structures. The parameter for this filter was the size of the minimum cube in the octree structure, which was set as 1 cm for the buildings and enclosing walls, and 25 cm for the ground (that define the DTM). Once the point cloud of each individual building was segmented, cross-sections of three orthogonal reference planes were extracted to perform the building's dimensional analysis, see Fig. 9.30. As for the images processing software, *RiscanPro*® and *CloudCompare*® were both used to create the final images of the point clouds, see Fig. 9.28 and Fig. 9.29. Also, as shown in Fig. 9.27, from the point clouds data, mathematical models will be developed to be used for the future structural safety analysis.

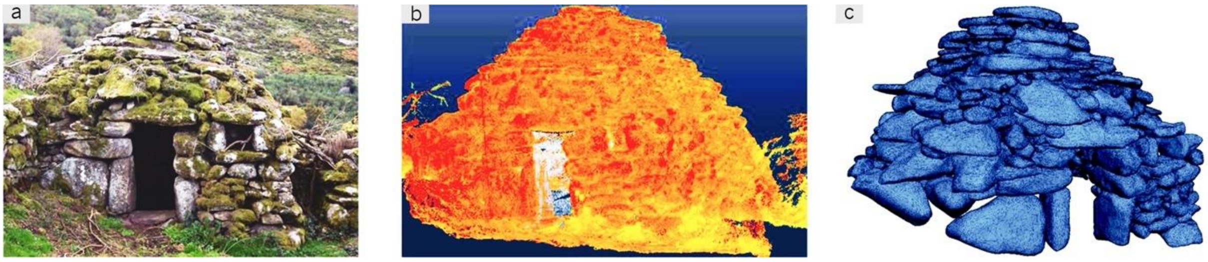


Fig. 9.27 – Sequence of task for the safety analysis: (a) inspection and dynamic identification of case study under analysis for structural safety; (b) point cloud created by laser scanning (author Dr. Belén Riveiro); (c) mathematical model based on the point cloud (author Dr. Belén Riveiro).

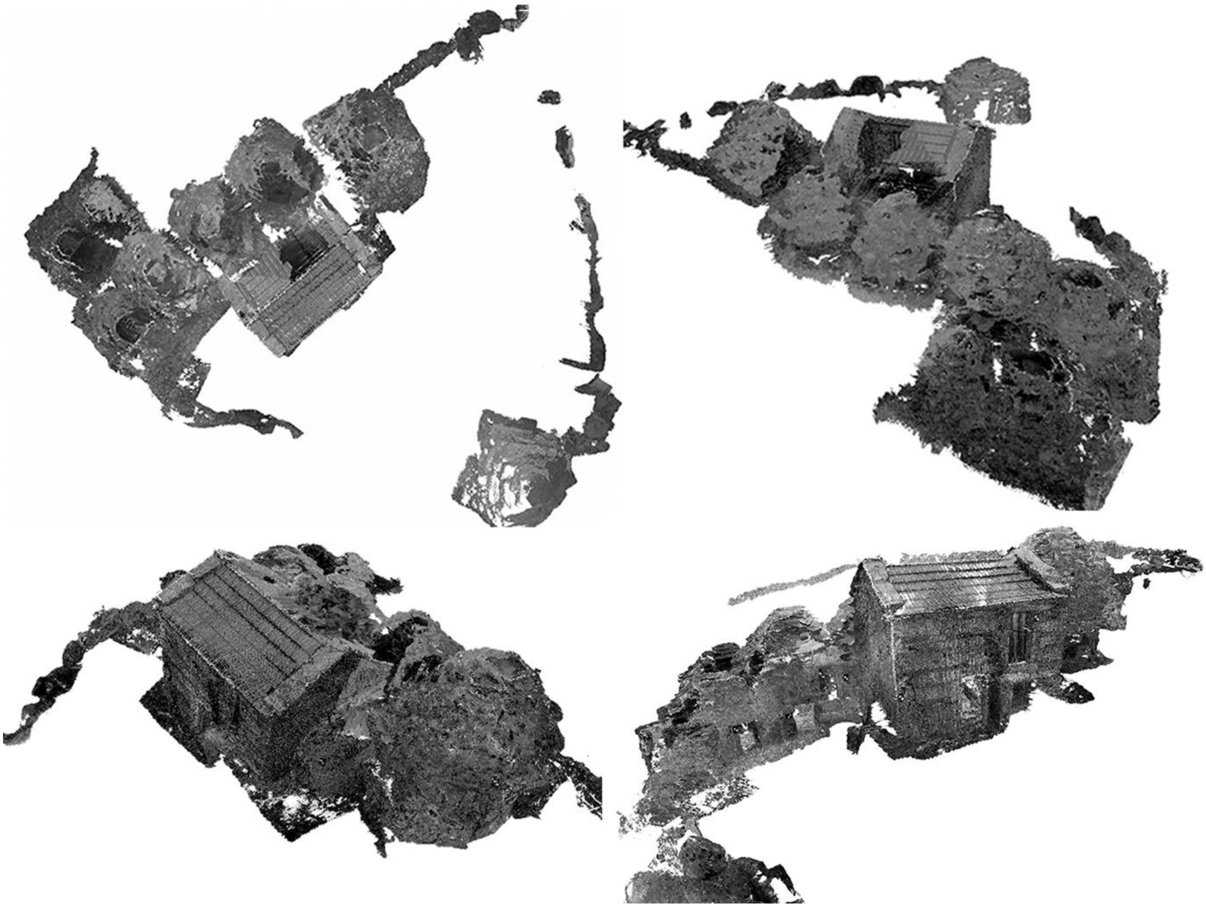
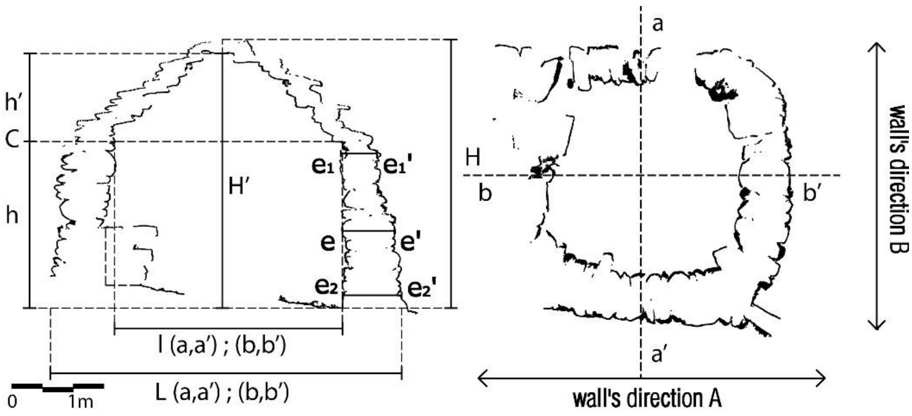


Fig. 9.28 – Examples of images (aerial and perspective views) from Group B buildings created using *RiscanPro*® software.

Fig. 9.29 – Examples of images (perspective and axonometric views) from Group A buildings created using *CloudCompare*® software.

9.2.3 Analysis and discussion of the fieldwork results

As for the territory and the vernacular corbelled dome heritage typological analysis, results were presented previously in Chapters 4 and 5. As shown in Fig. 9.30, the 3D models where analysed according to geometrical parameters such as vertical and horizontal dimensions and ratios, gathered from walls and corbelled domes' accurate base plans sections and elevations. Complementary data was collected during the field survey using conventional methods.



h/h' – wall's/dome's average height; H/H' – internal/external total height; $e_n e_n$' – cross-sections width; l/L – internal/external axis; aa'/bb' – axis direction (referring to the door); F_{cu} – corbelled dome's rows; PO – door's average dimensions; P^{im} – base plan configuration; A^T – gross built area; A^I – usable internal area; A_p – wall's gross built area, being PA for direction A and PB for direction B; V_P – estimated wall's volume; P^e/P^i – external/ internal built perimeter.

Fig. 9.30 – Schematic representation of the type of measurements performed on the 3D point cloud models.

a) Geometric and morphological analysis

Geometric and morphological information collected from the 3D models and the field survey was organized for analysis into two groups of parameters, being Parameters 1 vertical morphological parameters, and Parameters 2 horizontal morphological parameters. Individual buildings average results are presented in Table 9.6 and Table 9.7 for Group A buildings, and in Table 9.8 and Table 9.9 for Group B buildings.

For each group, comparison ratios are presented in Table 9.5. By analysing the above-presented ratios computed, the following conclusions can be extracted:

- *i)* Group B has larger buildings than Group A;
- *ii)* Farmers/shepherds shelters are the highest buildings (H) and the only ones with two-storeys. However, they are not the buildings showing the larger gross built area (A^T);
- *iii)* Concerning the base plan's shapes (P^{im}), the majority show an axial, therefore, rectangular tendency organization. Only smaller buildings presented circular shaped base plans. From these results and the field observations, one can conclude that the analysed buildings are

tendentially rectangular shaped with rounded corners;

iv) By comparing rectangular and circular shaped buildings showing the same dimensional range of horizontal axis, rectangular buildings show higher gross built area;

v) Each individual building from both groups is organized accordingly to a predominant internal axis ($l_{aa'}$ or $l_{bb'}$), being larger on the transversal direction to the entrance on Group A buildings ($l_{aa'}$ 2.76 m > 2.36 m $l_{bb'}$) and larger on the parallel direction to the entrance for Group B buildings ($l_{aa'}$ 2.28 m < 3.01 m $l_{bb'}$). The external axis follows the same tendency. Group B buildings show a higher variation between larger and smaller axis (1.3) in comparison with Group A buildings (1.1). Reasons for the presented axial variations between both groups may be explained by the geometry and size of property. As observed in the images, Group B buildings are all built inside a large corral. As for Group A buildings, these are built in a small and narrow property, with buildings placed with entrances facing the road. Therefore, one can conclude that the construction and organization of the group was adaptable to the geometry of the privately-owned property;

vi) Regarding walls, Group B wall's ($L_{aa'}$/h=1:2) are slenderer then Group A walls ($L_{aa'}$/h=1:1.5), showing considerably lower slenderness in comparison with walls of *"branda"* house buildings ($L_{aa'}$/h=1:10). Therefore, *"branda"* houses represented an optimization regarding the used soil for buildings;

vii) Despite the apparent vertical shape imposed by the corbelled domes' conic geometry, a closer look at the ratio between buildings' axis (L) and total height (H), shows an average ratio (L/H) of 1:1. Applying the same criterion to the wall's height (h), an average ratio (L/h) of 1:2 was obtained. As for the ratio between the corbelled domes' span (l_n) and height (h'), average ratios results (l/h') vary from 1:2 to 1:3. One can conclude that the studied buildings are horizontal shaped buildings;

viii) Dividing the wall's gross built area (A_p) with the building's gross built area (A^T), an average ratio (A_p/A^T) of 1:1/2 was obtained, showing that 50% of the studied buildings' gross built area is masonry walls (mass and voids). These results show that the analysed corbelled dome buildings are in fact heavy mass buildings;

ix) Applying the same calculation, comparison ratios by building show that walls on parallel direction to the entrance (A_{PB}) have higher gross area in comparison with walls on transversal direction to the entrance (A_{PA}). However, such results are misleading due to the fact of buildings being considerate individually in the analysis, when in fact, as shown in Fig. 9.31, the group organization is based on sharing load-bearing walls among buildings. Therefore, analysing results in such a way, with higher number of isolated buildings (4 nuclei), Group A results show lower walls' gross area optimization (0.33 A_{PA} < 0.37 A_{PB}) in comparison with Group B, with less isolated buildings (1 nucleus and 3 isolated buildings). These result show that group solutions represented a considerable gain in building resources management.

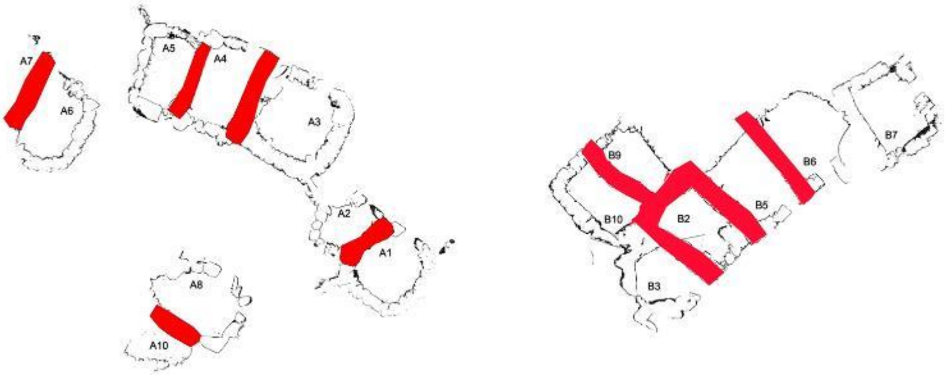


Fig. 9.31 – Analysis on groups shared load-bearing walls.

Table 9.5 – Parameters 1 and 2 comparison ratios.

	Wall's slenderness		axis/ wall's height		axis/ total height		corbelled. domes span/ int. height		wall's area/ gross built area		
	h/e	H/e	$L_{aa'}/h$	$L_{bb'}/h$	$L_{aa'}/H$	$L_{bb'}/H$	$l_{aa'}/h'$	$l_{bb'}/h'$	A_P/A^T	A_{PA}/A^T	A_{PB}/A^T
Group A	1.53	4.36	2.07	1.83	1.21	1.06	2.95	2.47	0.52	0.33	0.37
Group B	2.20	5.18	1.83	2.27	0.95	1.18	1.82	2.47	0.49	0.27	0.40

Table 9.6 – Group A individual buildings Parameters 1 analysis.

Parameters 1	H (m)	H' (m)	h (m)	h' (m)	F_{cu} (un)	L_{aa}' (m)	L_{bb}' (m)	l_{aa}' (m)	l_{bb}' (m)	e_1e_1' (m)	ee' (m)	e_2e_2' (m)	PO (m x m) (un)
A1	2.71	2.56	1.68	0.88	8	3.50	3.40	2.80	2.70	0.37	0.60	0.75	1.05x0.55
A2	2.30	2.15	1.33	0.83	4	2.90	2.15	2.40	1.65	0.55	0.55	0.55	1.05x0.60
A3*	4.15	4.00	2.35	1.65	9	3.95	4.35	3.10	3.50	0.60	0.85	1.00	1.15x0.65 1.26x0.60
A4	3.15	3.00	1.73	1.28	10	3.80	2.50	3.30	2.00	0.75	0.80	1.00	1.05x0.60
A5	2.65	2.50	1.71	0.79	7	3.70	2.35	3.10	1.75	0.50	0.60	0.75	1.00x0.60
A6	2.85	2.70	1.79	0.92	9	3.80	2.70	3.20	2.10	0.50	0.80	0.80	1.00x0.60
A8	2.45	2.30	1.35	0.95	6	2.80	4.00	2.30	3.50	0.40	0 ,60	0.60	0.85x0.65
A10	1.95	1.80	1.20	0.60	3	2.40	2.20	1.90	1.70	0.50	0.50	0.50	0.85x0.70
Avg.	2.78	2.63	1.64	0.99	7	3.36	2.96	2.76	2.36	0.52	0.67	0.74	1.00x0.60
CoV (%)	24%	25%	22%	33%	36%	17%	29%	18%	33%	23%	21%	26%	-
min.	1.95	1.80	1.20	0.60	3.00	2.40	2.15	1.90	1.65	0.37	0.50	0.50	0.85x0.65
max.	4.15	4.00	2.35	1.65	10.00	3.95	4.35	3.30	3.50	0.75	0.85	1.00	1.26x0.60

Note:* two-storey shelter; A7 and A11 not included on Avg; CoV and min. and max. values calculations.

Table 9.7 – Group A individual buildings Parameters 2 analysis.

Parameters 2	P^{im}	A^T (m^2)	A^I (m^2)	A_P (m^2)	V_P (m^3)	A_{PA} (m)	A_{PB} (m)	P^e (m)	P^i (m)
A1	RC	13.25	6.10	6.59	11.071	4.07	3.98	13.14	9.00
A2	RC	8.37	2.90	5.05	6.6913	2.71	3.79	10.70	6.44
A3*	RC	19.97	9.42	9.35	23.692	5.55	6.66	16.51	11.42
A4	RC	15.64	7.00	8.15	14.059	7.94	5.49	15.37	10.57
A5	RC	11.76	5.25	5.95	10.175	4.01	4.88	12.90	8.91
A6	RC	14.23	6.40	7.47	13.334	4.00	5.49	14.20	9.86
A8	RO	14.94	7.33	6.91	9.3285	4.79	3.27	14.39	-
A10	RO	7.50	2.50	4.30	5.16	2.215	3.49	10.17	10.25
Avg.	RC	13.21	5.86	6.72	12	4.41	4.63	13.42	9.49
CoV (%)	-	31%	39%	24%	49%	40%	26%	16%	17%
min.	RO	7.50	2.50	4.30	5.16	2.22	3.27	10.17	6.44
max.	RC	19.97	9.42	9.35	23.69	7.94	6.66	16.51	11.42

Note:* two-storey shelter; ; A7 and A11 not included on Avg; CoV and min. and max. values calculations; RC - rectangular shape; RO rounded shape.

Table 9.8 – Group B individual buildings Parameters 1 analysis.

Parameters 1	H (m)	H' (m)	h (m)	h' (m)	F_{cu} (un)	L_{aa}' (m)	L_{bb}' (m)	l_{aa}' (m)	l_{bb}' (m)	e_1e_1' (m)	ee' (m)	e_2e_2' (m)	PO (m x m) (un)
B1**	5.00	-	-	-	-	3.40	4.85	2.85	4.30	0.55	0.55	0.55	1.50x0.80 (2)
B2*	4.00	3.85	2.73	1.13	11	2.88	3.90	2.18	3.20	0.60	0.70	0.80	1.00x0.80 1.20x0.70
B3	2.75	2.60	1.65	0.95	8	3.10	3.30	2.40	2.60	0.50	0.70	1.00	1.00x0.60
B4	2.95	2.80	1.40	1.40	9	2.40	3.60	1.80	3.00	0.60	0.60	0.60	1.10x0.60 (2)
B5	3.42	3.27	1.45	1.82	10	3.10	3.05	2.40	2.35	0.60	0.65	0.70	1.40x0.70
B6	3.55	3.40	1.50	1.90	10	3.50	3.90	2.80	3.20	0.60	0.65	0.70	1.40x0.80
B7	3.36	3.21	1.30	1.91	11	2.83	3.66	2.23	3.06	0.60	0.60	0.70	1.15x0.60
B8	2.85	2.70	1.70	1.00	8	3.62	4.15	2.92	3.45	0.50	0.50	0.50	1.30x0.70
B10	2.65	2.50	1.70	0.80	6	2.00	3.70	1.50	3.20	0.50	0.50	0.50	1.10x0.70 1.30x0.70
B11	1.45	1.30	-	-	5	2.30	2.50	1.90	2.10	0.60	0.70	0.70	1.00x0.60
Avg.	3.19	3.04	1.68	1.36	9	2.93	3.66	2.28	3.01	0.56	0.61	0.69	1.20x0.70
CoV (%)	15%	15%	27%	34%	19%	18%	10%	21%	12%	9%	13%	24%	-
min.	2.65	2.50	1.30	0.80	6.00	2.00	3.05	1.50	2.35	0.50	0.50	0.50	1.50x0.80
max.	4.00	3.85	2.73	1.91	11.00	3.62	4.15	2.92	3.45	0.60	0.70	1.00	1.00x0.60

Note: * two-storey shelter; ** *"branda"* house; B1, B9 and B11 not included on Avg; CoV and min. and max. values calculations

Table 9.9 – Group B individual buildings Parameters 2 analysis.

Parameters 2	P^{im}	A^T (m^2)	A^I (m^2)	A_P (m^2)	V_P (m^3)	A_{PA} (m)	A_{PB} (m)	P^e (m)	P^i (m)
B1**	RC	16.50	9.00	6.29	28.975	-	-	-	-
B2*	RC	15.93	7.23	7.65	8.6395	4.21	7.06	15.45	10.63
B3	RO	12.25	4.82	7.01	6.6595	4.06	5.50	13.20	8.30
B4	RC	11.00	4.60	6.04	8.036	2.42	5.25	13.00	8.50
B5	RC	17.24	7.85	8.90	16.198	4.38	6.76	16.05	11.10
B6	RC	18.70	9.50	8.64	16.416	4.38	5.76	16.30	11.70
B7	RC	15.25	6.80	8.09	15.452	4.94	4.44	15.20	10.20
B8	RC	15.00	10.10	4.41	n.a.	n.a.	n.a.	n.a.	n.a.
B10	RC	13.16	5.30	7.16	12.522	3.69	5.50	14.26	9.70
B11	RC	5.80	3.99	1.57	n.a.	n.a.	n.a.	n.a.	n.a.
Avg.	RC	14.82	7.03	7.24	12	4.01	5.75	14.78	10.02
CoV (%)	-	26%	31%	32%	35%	20%	16%	9%	13%
min.	RO	11.00	4.60	4.41	6.66	2.42	4.44	13.00	8.30
max.	RC	18.70	10.10	8.90	16.42	4.94	7.06	16.30	11.70

Note: * two-storey shelter; ** “branda" house; B1, B9 and B11 not included on Avg; CoV and min. and max. values calculations; RC - rectangular shape; RO - rounded shape.

b) *Building technique analysis*

The building technique analysis was performed based on on-site observations using conventional geometrical surveys and the 3D models. The first observations revealed that local masonry was built using local available granite stones, either gathered during the process of preparing the land for farming or pasture, or by extracting them from nearby rock outcrops. On the case studies, plate shaped granite masonry units were gathered from outcrops. To be noticed that on other observed examples of corbelled dome buildings, parallelepiped shaped stone blocks were used. As for the main dimensional parameters of masonry walls and corbelled domes, these were presented on Parameters 1 and 2 Tables. In this section, an overview regarding stone blocks geometry and distribution in masonry walls and in corbelled domes superficial textures are presented in Table 9.10 and Table 9.11 respectively. Stone blocks were divided into three sizes hierarchy (qualitative) and analysed by their respective distribution on walls and domes (quantitative). For the sake of clearness, being the analysis based on a qualitative criterion, it should be noticed that stone blocks size rating is related to the specific building under analysis, meaning that the same block may be rated differently if on a different building. An example of the analysis performed on a case study of the *“branda”* of Alhal is shown in Fig. 9.32.

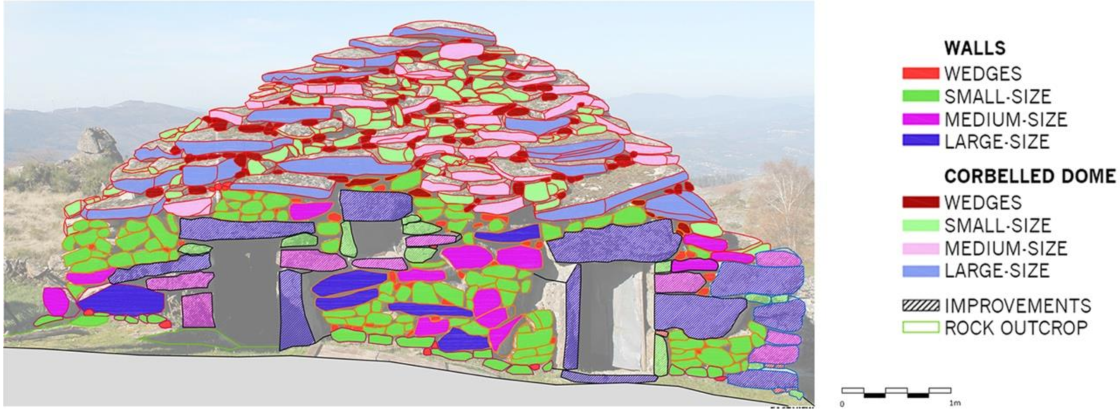


Fig. 9.32 – Example of a statistical superficial masonry fabric analysis performed on a corbelled dome building.

Analysing sizes and distribution of the stone blocks units on Group A and Group B buildings, one can conclude that:

i) Medium-size stone blocks prevail in masonry walls, whereas large-size stone blocks prevail in corbelled domes' masonry;

ii) The shape and dispersion of stone blocks on masonry walls and corbelled domes were restricted by their function. Parallelepiped shaped stone blocks prevail in walls for being larger and heavier, therefore suitable to sustain dome's thrust and to resist horizontal loads. Lighter plate shaped stone blocks were concentrated in corbelled domes, to cover as much horizontal area as possible and with the minimal possible weight. Walls and domes stone blocks horizontal section comparison show that walls' large-size stone blocks are similar in size to corbelled domes' medium-size stone blocks. As for the vertical section, the stone blocks on walls are on an average 50% taller than stone blocks on domes. Regarding the dispersion of smaller stone blocks, results show their slightly inferior use on corbelled domes structure;

iii) As observed, to achieve the domes' cone geometry, larger-size stone blocks were concentrated in the lower half of the structure, becoming smaller upwards until the domes' rows reach the capstone;

iv) By comparison with other observed corbelled dome buildings, it became clear that stone blocks horizontal/vertical proportion influenced decisively corbelled domes height and number of built rows (F_{cu}). Therefore, stone blocks with higher horizontal area allowed lower structures with less rows, see Fig. 9.33a, whereas stone blocks with a parallelepiped shape resulted in taller and heavier structures, with more rows, as shown in Fig. 9.33b. Exceptional cases of megalithic domes, built with just a very large stone block were observed in other temporary mountain range settlements. As for alternative corbelling solutions, a very singular corbelled vault building was found at the *"branda"* of Alhal, see Fig. 9.33c;

v) As for the regularity of walls and domes, it was clear the direct relation between size and regularity of the stone blocks, meaning that as stone blocks became larger and irregular, construction quality seems to decrease.

Fig. 9.33 – External (above) and internal (bellow) view of examples of different corbelled domes identified during the field survey: (a) taller dome built with parallelepiped and irregular shaped stone blocks (*"branda"* of Gêmea); (b) lower dome built with large plate shaped stone blocks (*"branda"* of Gêmea); (c) corbelled vault building with double chamber (*"branda"* of Alhal).

Regarding the construction of the typical corbelled dome building, field observations show:

i) The construction of masonry walls followed local dry stack tradition (see Chapter 6), built without or with a direct foundation, generally with two-leaves cross-section and presenting a very irregular superficial masonry texture with high percentage of voids, see examples in Fig. 9.34. Smaller buildings, due to the average size of the commonly used stone blocks, were frequently built in single-leaf cross-sections. Openings and corners were reinforced with larger stone blocks;

ii) Stone blocks show a very irregular geometry, being bedded, and levelled by a large number of wedges. Therefore, the resulting interface is very irregular and stone blocks and leaves interlocking is poor;

iii) Structural stability of walls was achieved by their low slenderness, heavy mass, and the use of large numbers of stretcher and bondstones, giving walls a certain level of protection against deformations and out-of-plane loads.

iv) From a structural point of view, corbelled domes are structural elements (rounded shape) built on top of the structural box formed by load-bearing walls (rectangular shape). Geometric compatibilization between both masonry sub-structures was achieved by starting the construction of the dome simultaneously from different points along the walls. Near corners of the structural box, larger stone blocks placed over the corner would allow the passage from the base to the dome geometry;

v) Corbelled domes' masonry was built using header stone blocks, overlapping around the central axis by describing an apparent spiral movement that starts from the top of the walls and ends at the dome's capstone. Larger stone blocks were bedded over the middle portion of at least two underneath stone blocks. In this way, stone blocks were supported in an average of 2/3 of their horizontal section but leaving the middle area in cantilever. Any resulting gaps were filled with smaller size stones. Wedges were used to improve the stability of larger stone blocks, but also to give them a slope outward to drain rain water. To do this, wedges were placed by the inside of the dome, over the edge of the supporting units.

Taking a closer look to the structural behaviour of the analysed corbelled domes, it was possible to understand that forces flow through a large number of contact surfaces resulting from the very irregular interfaces and the abundant number of wedges [173]. Simultaneously, through this particular building technique, dome's load is transfer to the walls not only by granite stones under compression, but also by flexural behaviour. By the large number of detected cracked large-size granite stone blocks, loose smaller stones, and crushed wedges, it becomes clear that these massive structures show high resilience to deformation and high capability in achieving new structural balances. As for construction quality, observations showed the prevalence of poorly constructed masonry, although a few cases of improved quality could also be observed.

Table 9.10 – Stone blocks' sizes and distribution on Group A buildings superficial masonry textures.

Buildings	ee' (m^2) Avg	Walls (m) [% of built texture]			Corbelled domes (m) [% of built texture]			F_{cu} (un)
		small	medium	large	small	medium	large	
A1	0.57	- [10%]	0.60x0.60x0.30 [70%]	0.70x0.70x0.40 [20%]	- [10%]	1.00x0.70x0.20 [60%]	1.20x0.70x0.20 [30%]	8
A2	0.55	- [10%]	0.55x0.50x0.45 [70%]	0.80x0.50x0.40 [20%]	- [10%]	0.70x0.50x0.15 [40%]	1.60x0.80x0.20 [50%]	4
A3*	0.80	- [30%]	0.70x0.55x0.30 [50%]	1.20x0.60x0.50 [20%]	- [10%]	0.70x0.50x0.10 [40%]	1.60x0.80x0.10 [50%]	9
A4	0.85	- [30%]	0.70x0.55x0.30 [50%]	1.20x0.60x0.50 [20%]	- [10%]	0.70x0.50x0.10 [40%]	1.60x0.80x0.10 [50%]	10
A5	0.60	- [50%]	0.70x0.55x0.30 [20%]	1.20x0.60x0.50 [30%]	- [10%]	0.70x0.50x0.10 [40%]	2.00x0.80x0.20 [50%]	7
A6	0.70	- [20%]	0.70x0.55x0.30 [40%]	0.90x0.80x0.50 [50%]	- [10%]	0.70x0.50x0.10 [40%]	1.60x0.80x0.10 [50%]	9
A8	0.50	- [10%]	0.50x0.40x0.30 [40%]	0.80x0.50x0.40 [50%]	- [20%]	n.a. -	1.70x0.70x0.15 [80%]	6
A10	0.50	- [10%]	0.50x0.40x0.30 [40%]	0.80x0.50x0.40 [50%]	n.a.	n.a.	2.00x1.10x0.15 [80%]	3
Avg.	0.68	21%	48%	33%	13%	43%	55%	7
CoV (%)	20%	69%	35%	46%	37%	19%	31%	36%
min.	50%	10%	20%	20%	10%	40%	30%	3
max.	85%	50%	70%	50%	20%	60%	80%	10

Note:* two-storey shelter; A7 and A11 not included on Avg; CoV and min. and max. values calculations.

Table 9.11 – Stone blocks' sizes and distribution on Group B buildings superficial masonry textures.

Buildings	ee' (m^2) Avg	Walls (m) [% of built texture]			Corbelled domes (m) [% of built texture]			F_{cu} (un)
		small	medium	large	small	medium	large	
B1**	0.55	- [20%]	0.55x0.30x0.20 [30%]	1.00x0.35x0.20 [50%]	n.a.			
B2*	0.70	- [15%]	0.50x0.30x0.10 [75%]	0.80x0.60x0.40 [10%]	- [15%]	0.70x0.50x0.10 [15%]	1.20x1.00x0.15 [70%]	11
B3	0.70	- [25%]	0.60x0.40x0.15 [65%]	0.90x0.50x0.40 [10%]	- [10%]	0.80x0.70x0.10 [10%]	1.60x0.10x0.10 [80%]	8
B4	0.60	- [20%]	0.40x0.20x0.10 [75%]	0.70x0.40x0.25 [5%]	- [15%]	0.50x0.40x0.10 [70%]	1.00x0.60x0.25 [15%]	9
B5	0.65	- [15%]	0.50X0.30X0.15 [70%]	0.80X0.30X0.20 [15%]	- [15%]	0.70X0.50X0.15 [35%]	1.20X0.30X0.10 [40%]	10
B6	0.65	- [15%]	0.50X0.30X0.15 [70%]	0.80X0.30X0.20 [15%]	- [20%]	0.70X0.50X0.15 [50%]	1.20X0.30X0.10 [30%]	10
B7	0.60	- [20%]	0.60x0.15x0.10 [70%]	0.60x0.60x0.20 [10%]	- [20%]	0.70x0.40x0.15 [75%]	1.10x0.80x0.35 [15%]	11
B8	0.50	- [20%]	0.60x0.50x0.20 [30%]	1.00x0.70x0.50 [50%]	-	0.90x0.60x0.15 [30%]	1.70x0.70x0.20 [60%]	8
B10	0.50	- [20%]	0.50x0.30x0.15 [70%]	0.80x0.40x0.20 [10%]	- [10%]	0.60x0.50x0.10 [10%]	1.00x0.70x0.10 [80%]	6
B11	0.67	- [20%]	0.50X0.30X0.10 [30%]	1.20X1.00X0.40 [50%]	- [5%]	n.a. [5%]	1.50X0.90X0.15 [90%]	5
Avg.	0.68	21%	48%	33%	13%	43%	55%	**9**
CoV (%)	13%	19%	22%	91%	29%	70%	56%	19%
min.	0.50	15%	30%	5%	10%	10%	15%	6
max.	0.70	25%	75%	50%	20%	75%	80%	11

Note: * two-storey shelter; ** *"branda"* house; B1, B9 and B11 not included on Avg; CoV and min. and max. values calculations.

Fig. 9.34 – Examples of masonry walls' superficial textures, seen by the inside of buildings.

9.2.4 Damage survey

Damage identification during the survey was performed by visual inspection, being complemented with observations performed in other nearby *“brandas”.* The information was organized into three groups according to damage causes and risk level for buildings’ structural safety. Table 9.12 shows a synthesis of the most representative damage causes and damage types.

Table 9.12 – Synthesis of *"branda"* of Gêmea damage mechanisms and damage types [36,174].

Damage causes			Damage types	
Human actions	Structural	Non-structural	Masonry walls	Materials
• abandonment and severe lack of maintenance	• differential soil settlements	• natural ageing	• opening of joints, deformations	• fractures, material crushing and detachment
• poor construction quality	• loss of monolithic behaviour (leaves’ detachment)	• weathering and environmental agents	• loose shims and smaller masonry units	• abrasion, erosion, granular disintegration (weathering)
• poor interventions	• loss of masonry interlocking	• biological colonization (small/medium-size species)	• walls and corbelled domes’ masonry fabric disaggregation	• superficial deposits (e.g. crusts, film, or patina), colour changes and soil deposits
• surrounding terrain changes	• unforeseen or excessive loads (vertical/horizontal)		• wall in and out-of-plane deformations	• humidity and salt damage (from moisture and livestock’s manures)
	• large-size species’ biological colonization		• corbelled domes’ deformations due to masonry units’ sliding or rupture	• superficial exfoliation and material loss (freeze/thaw and salt damage)
			• walls and domes partial or totally collapsed	• superficial changes due to biological colonization (alga, lichen, moss, plants)

a) Structural damage

Although corbelled domes and masonry walls are part of the same structure and fully built with the same type of materials, both show some specific types of structural damages. Being fully supported over the masonry load-bearing walls, corbelled domes structural safety depends of walls’ structural performance. Taking into consideration the previously described structural behaviour and its nature of assembled work [186], corbelled domes are highly sensitive to masonry walls’ structural instability. It is noteworthy that the observed examples of buildings with larger and heavier corbelled domes showed improved durability and were the best-preserved structures identified. However, as shown in Fig. 9.35, among buildings with smaller corbelled domes, thus lighter structures, several cases of buildings in ruins due to the collapse of domes were identified. Although was not the case on the *“branda”* of Gêmea, it was a common circumstance on other *“brandas”* visited during the exploratory visits. Therefore, corbelled domes collapses were identified during the fieldwork survey as the most representative cause for buildings’ ruin, being two types of structural failures observed. As for the most representative case, corbelled domes lose their structural equilibrium and typically collapse inward of buildings, see Fig. 9.35a. In the most severe cases, dome’s collapse causes masonry walls to disaggregate and collapse outwards (push-over effect), see Fig. 9.35b. On the second case, the domes' collapse is a consequence of masonry walls severe rupture and collapse, see Fig. 9.35c. By losing their support, the corbelled dome collapse is immediate. On a few cases of buildings showing total ruin, and except for megalithic corbelled domes, it was not clear which of the structural elements collapsed first, see Fig. 9.35d. In less severe cases, such as partial corbelled domes rupture or when not causing severe damage to walls, buildings would become deactivated, but if masonry walls were still stable or could be repaired, the dome could be rebuilt. On cases were buildings became irrecoverable, by observing several ruins with a considerable amount of missing stone blocks, it became clear that the reuse of stone blocks was a widespread practice. Cases of structural damage with lower risk level are generally related to deformations caused by damage and/or instability of the walls or caused by over time structural instability related to stone blocks dislocations or failure. Due to very irregular interfaces and extensive use of wedges, the large stone blocks of the domes showed a higher exposure to flexural behaviours, therefore to tensile rupture [173]. On the surveyed area, the plate shape of granite stone blocks made them prone to such type of tensile mechanical failure.

Fig. 9.35 - Examples of ruined small-size livestock shelters (*"branda"* of Rio Covo, Sistelo): (a) domes' partial collapse due to masonry unit's rupture; (b) building's corbelled dome in complete ruin (collapsed inward), but showing masonry walls in good condition; (c) masonry walls' partial collapse due to dome's inwards collapse; (d) building in complete ruin (partial reuse of stone).

As for material failure, stone blocks and wedges rupture seemed mostly caused by excessive loads due to corbelled dome's deformations. The process of achieving a new structural balance, resulted frequently on stone blocks cracking, and splitting due to tension concentration points. The new stone blocks arrangement often caused wedges crushing or to become loosen. Examples of typical corbelled domes masonry units' damage observed during the survey are shown in Fig. 9.36.

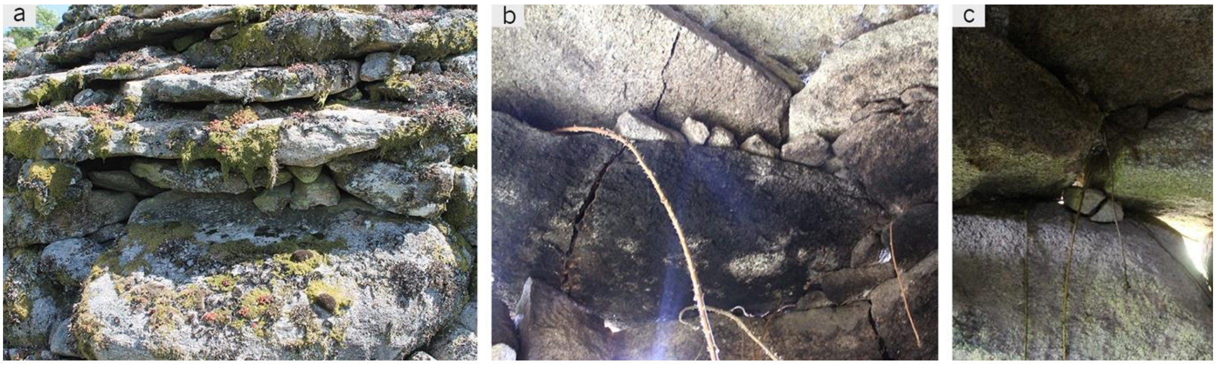


Fig. 9.36 – Examples of corbelled dome's damage: (a) loose and displaced masonry units and shims; (b) large plate-shaped units cracked due to deformation; (c) crushed shim.

As for structural damage on masonry walls, most common causes are related to excessive loads, differential settlements, and loss of cohesion of leaves. As for damage, several types of in/out-of-plane deformations, leaves disaggregation and partial collapses were the most observed cases.

Regarding walls' damage caused by excessive vertical loads, these were either an outcome of corbelled domes structural behaviour changes and/or foundation soil's settlements. Excessive horizontal loads were mainly related to terrain's horizontal loads over walls simultaneously used for terrain retaining purposes. Similar damage caused by vertical and horizontal excessive loads were also seen on groups of buildings to which a new building was added, or cases were a new corbelled dome was constructed over existing structures, by overlapping them, as confirmed by the 3D model, see Fig. 9.37.

As for the damage types identified, these were: *i)* in/out-of-plane deformations, also associated to masonry walls poor monolithic behaviour and poor stones blocks interlocking, that as seen in several cases lead to walls disaggregation and collapses; *ii*) vertical or slight diagonal cracks caused by the opening of joints or fractures on stone blocks; *iii)* crushing of wedges; and *iv)* loose wedges and smaller stone blocks.

Smaller buildings with less massive walls, frequently presented visible damage resulting from construction's poor quality or mistakes, generally related to: *i)* a very high percentage of voids; *ii)* high superficial masonry textures irregularities due to irregular stone blocks; *iii)* very poor interlocking. In these type of buildings, masonry walls' deformations and partial disaggregation was very common [172]. Fig. 9.38 illustrates some examples of typical structural damage on masonry walls.

One can conclude that the main cause of ruin of the analysed vernacular buildings results from corbelled domes collapse. As for the corbelled domes, their structural safety is achieved by their mass and the capability to adapt to instability, higher in domes with more rows. As for structural durability of the masonry walls, it is highly influenced by domes' structural performance. Analysing walls behaviour, it was concluded that as its fabric overall regularity and construction quality decreases, the risk of structural instability due to deformation and disaggregation resulting from poor interlocking, rises [165].

Fig. 9.37 – Laser scanner generated cross-section, showing deformed masonry walls due to overlapping corbelled domes (from left to right).

Fig. 9.38 – Masonry walls' examples of structural damage: (a) vertical cracks (opening of joints and fracture of masonry units); (b) disaggregated and partially ruptured masonry wall; (c) large masonry wall deformation.

b) Non-structural damage

The identified non-structural damage is the outcome of the dynamic and combined influence of all weathering agents present in the survey area environment [198]. By being non-plastered buildings located in a region with a predominantly moderated (7℃ to 12℃ of annual average temperature variation) and humid Atlantic climate (average of 2001 mm and 2800 mm of annual precipitation, 50% concentrated between December and March, with snow) [271], water and temperature, and associated weathering agents, play a key role on stone blocks durability (see Chapter 8 for granite durability). It was also observed that humidity and biological colonization were responsible for the rotting and collapse of the few existent wooden elements. Identified biological colonization can be divided into two groups. The first and of overwhelmingly representativeness, refers to superficial micro-organisms (e.g. algae, lichen, moss) and small-size biological colonization of granite, particularly in faces exposed to the northern direction or areas with high relative humidity. The second and growing in representativeness, refers to medium and large-size vegetal species colonization (e.g. plants, bushes, and trees) caused by soil accumulation on wall's large voids, on horizontal surfaces of domes, or in buildings' soil pavement. The damage related to the first group is mainly due to granites superficial changes (colour and texture changes), but also to less significant chemical superficial damage [198]. As observed, these damages are very intense on walls and domes' external faces, where granite is almost completely covered with colonies, but less significant in the interior (less expose to environmental agents, but higher exposure to moisture and soot). Examples of typical corbelled dome's biological colonization are shown in Fig. 9.39.

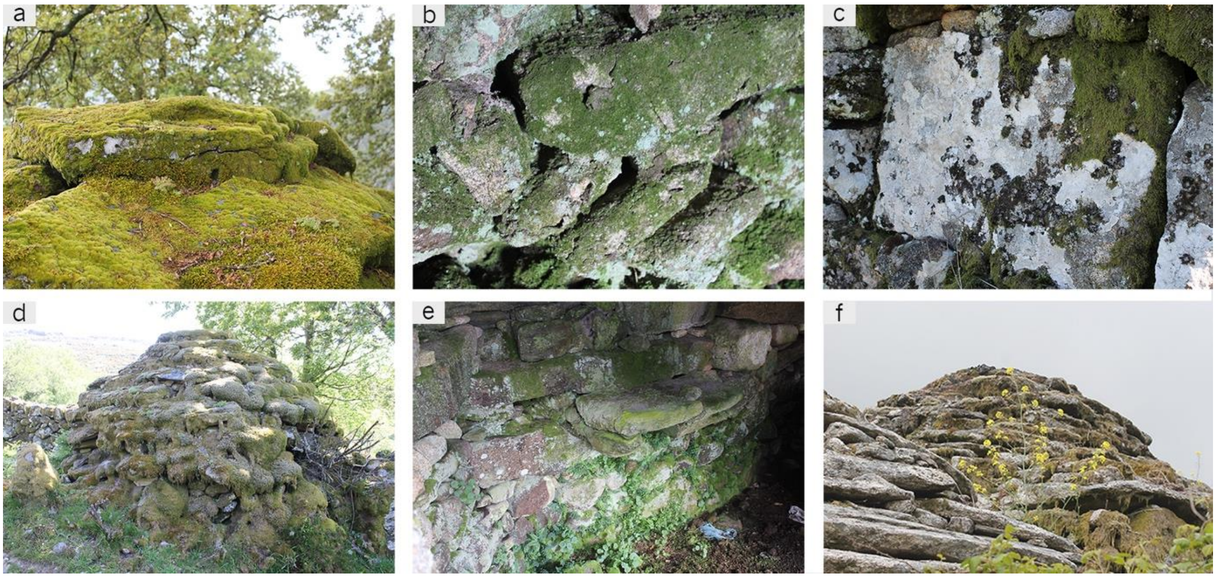


Fig. 9.39 – Examples of typical biological colonization on the surveyed area.

As for the damage of the second group, it poses higher risks to buildings structural safety, and depend of the size of the colonizing species [168]. Several examples of collapsed corbelled domes and disaggregated masonry walls were identified as caused by large-size bushes and trees, either colonizing masonry or growing inside buildings. Push-over actions caused by trees and large bushes were identified as the major cause of *"brandas"* farm walls collapse, and of severe damage on some smaller buildings.

Considering weathering caused mechanical damage, one can identify: *i)* cases of material loss due to stress concentrations; *ii)* superficial damaged caused by abrasion and erosion; *iii)* frost damage caused by freeze/thaw cycles; and *iv)* salts caused damage. Damage related to material loss can be associated to large variety of causes, and it was identified in the field as by: *i)* the rounding and roughening of stone blocks edges and corners; *ii)* superficial material loss (e.g. exfoliation, granular disintegration); *iii)* pitting; *iv)* micro-cracks and *iv)* fracture and rupture of larger pieces of materials. Due to the strong external biological colonization, erosion and abrasion damage was only clearly observed inside buildings. However, its existence on the exterior is almost certain. It is visible on masonry found in areas of physical contact with livestock (pavements, lintels, and jamb stones), areas of strong internal ventilation or, outside buildings on horizontal surfaces that could accumulate water (e.g. staircases and corbelled domes horizontal surfaces). Identified frost damage is related to water penetration on granites superficial imperfections, porous and larger cracks, particularly on horizontal surfaces (see Section 8.2). Salt caused damage was identified inside buildings, concentrated at the lower part of masonry walls (efflorescence), and related to rising dump and contact with livestock manures (see Section 8.1). Fig. 9.40 shows examples of mechanical and chemical damage observed on granites during the fieldwork.

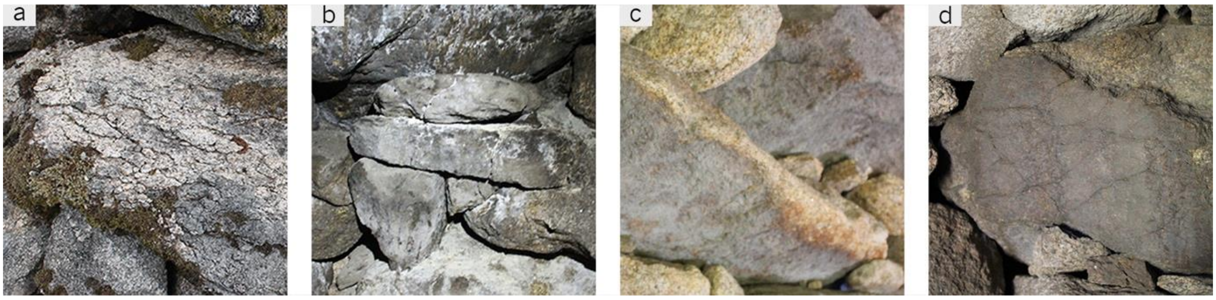


Fig. 9.40 – Examples of granites' mechanical and chemical damages: (a) superficial exfoliation; (b) salt caused damage; (c) humidity stains and masonry units' edges disaggregation; d - superficial chemical damage.

c) Human caused damage

As for the human caused damage, the field survey inspections revealed that it can be divided into two equally high-risk groups, being the first caused by human intervention and the second by its absence.

Regarding the first group, along with poor initial construction quality, some poor interventions and mistakes, that compromise structural safety, were identified during the visual inspections: *i)* added partition masonry walls to existent buildings without any kind of interlocking with the existing walls; *ii)* buildings constructed without proper fragile point's improvement; and *iii)* added new shelters and *"brandas"* houses to existent buildings without proper reinforcement of existent masonry structures. Nowadays, the use of contemporary building materials and very poor planed interventions, lead to the total loss of authenticity and identity of some temporary mountain range settlements, especially on prolonged stay mountain range temporary settlements.

As for the causes of the second group, it is directly related to total or partial abandonment of highland's temporary mountain range settlements, resulting from decades strong rural exodus (see Section 3.6). The exploratory visits revealed that most of the remotely located sites and almost all of the livestock *"brandas"* are facing total abandonment. Closer mixed use *"brandas"* are still in use, although only livestock still uses the shelters and only during the day.

Therefore, it was observed that the severe lack of maintenance allowed the uncontrolled growth of large vegetal species (trees), that in some observed examples caused severe structural damage to buildings. Since repairing works on damaged buildings are not performed, in some cases for decades, some show a very advanced state of ruin. Others are completely covered with infesting vegetation, becoming inaccessible, and therefore risking ruin, and disappearing from the landscape, see Fig. 9.41. As for the sites, the growing large-size vegetation causes the temporary mountain range settlements' roads to become blocked and the destruction of the farm walls. Now, since the studied *"branda"* of Gêmea does not possess any proper access road, except for old mountain paths, or any type of modern infrastructure, severe character losses caused by human interventions on building are a still a non-existent phenomenon. Examples of the above-mentioned human caused damage are shown in Fig. 9.41.

Fig. 9.41 – Examples of human caused damage: (a) and (b) severe and full loss of authenticity of both buildings and site caused by poor interventions ("branda" of Santo António of Vale de Poldros, Monção); (c) group of corbelled dome buildings discovered in "*branda"* of Gêmea during the cleaning operation.

9.2.5 Discussion of results and guidelines proposal

The success of any attempt of preserving and reuse of the fragile and endangered vernacular corbelled dome of the highland sub-region depends on understanding its multi dynamics and perspectives. Therefore, methodologies must be able to operate with this heritage constructive, social, and economic but also historical, ethnographic, and emotional diversity.

Based on the developed research and in the international good practices [3,49], a proper plan of action should attend to: *i)* the vernacular heritage identification and full knowledge focused in its management and monitoring; *ii)* the development of operative tools able to integrate needs and mitigate risks and threats; and *iii)* the technical challenges concerning vernacular heritage preservation and reuse. As a macro scale recommendation, any type of strategy should include the entire landscape and its vernacular human occupation should be considerate as whole, therefore, including the territories on both sides of the Portugal/Spain border.

As for the first topic, vernacular heritage management and monitoring necessarily depend of knowing the heritage at hand. During the research, it became clear the very scarce available information regarding the existent vernacular corbelled dome heritage dispersed in the territory, the very deficient mapping and total absence of information regarding its state of preservation and cases of abandonment. Therefore, a full inventory is seen as a necessary first step, capable of reaching the entire region of the vertical transhumance phenomenon. At this macro informational level, multi-disciplinary knowledge development will allow to launch bridges among different fields of expertise, potential promoters, and territory management authorities. However, such task should be addressed as an opportunity to involve and enlighten local communities to the need of protecting their own vernacular heritage.

Regarding the development of suitable operative tools, it is seen as indispensable to address not only the corbelled dome heritage and sites, but the entire landscape involved in the wider cultural tangible and intangible heritage context. Therefore, such tools should: *i)* identify ownership; *ii)* clearly identity the areas of the different territory management authorities; *iii)* to establish preservation intervention priorities and levels; and *iv)* develop a plan to involve the community in the preservation effort. The analysis of the information collected and developed by the operative tools will allow to hierarchise the territory and its heritage, and to clearly define various levels of protection (macro and micro scale intervention), by distinguishing areas of high sensitivity destined only for preservation and areas with reuse potential.

Regarding the second topic of action, a state of absence of adequate legal frameworks concerning vernacular heritage was recognized. Lack of knowledge of the high cultural, economic, and touristic potential of the landscape and its vernacular architectures seems to be the main reason to the absence of protection measures in the existent territory management plans.

Therefore, a fully effective protection guidelines and strategy, depend of adopting: *i)* a revised legal framework, commonly developed and equally accepted by all involved territory management authorities from both sides of the border, focused on the preservation and able to carefully monitor the reuse of endangered vernacular heritage; and *ii)* the establishment of control mechanisms over the type of intervention and uses allowed in these heritage buildings, based on authenticity and identity criterions.

As for the technical challenges related to the several types of possible interventions on vernacular corbelled dome heritage, taking into consideration this heritage overwhelming diversity (morphological, typological, and constructive), further research is needed to embrace its full knowledge. Therefore, further work is required to determine the adequate techniques to use for achieving structural safety in structures at risk, but also to allow technicians and builders to intervene without threatening its high cultural value.

In this context, technical guidelines must ensure compatibility with the best international practices and international standards presented on Chapter 2. However, a good starting point should pass by excluding the use of non-vernacular materials and construction techniques on mountain range plateau settlements, which can in any way alter basic morphology and aesthetics of buildings and sites. The use of corbelled dome buildings outside their natural use seasons should be conditioned, therefore eliminating the need to improve buildings to unnatural comfort conditions, taking into consideration buildings original design. Nonetheless, such comfort conditions may be allowed on *“branda”* houses if based on renewable sources of energy, therefore, not requiring the implementation of heavy infrastructures with a strong impact on the landscape.

At the temporary mountain range settlements such as the *“branda”* of Gêmea, suitable guidelines should pass by: *i)* avoiding the construction of contemporary infrastructures such as modern access roads, not only to cut on real estate pressure at these locations, but to preserve their natural balance; *ii)* new uses (e.g. tourism or non-traditional farming) should be restricted to specific periods along the year and, when requiring changes to buildings, these should be restrict to a smaller percentage of existent structures, to avoid excessive human pressure on these locations; and *iii)* sites declared as of higher cultural value or as extremely sensitive, should include a maintenance plan for their public roads and spaces, enforced by the local municipalities, to avoid their destruction.

As for the implementation of the above-presented action plan, it is only possible by the will and direct involvement of the competent territory management authorities (local, municipal, and national institution). Such requires the implementing and enforcing of suitable legal frame work and knowledge transfers among all involved. Along with the transfer of technical, legal, or academic and scientific knowledge among potential actors, a significant part of the effort should be put on the involvement of the local community affectively attached and still using the endangered heritage. Such effort should be embraced throughout all steps of the action plan, by keeping in mind that the local community is simultaneously the first to threaten the existing heritage for lack of knowledge, but also the first line of defence against its destruction. A schematic of the above presented action plan is shown in Fig. 9.42.

1. INVENTORY

(of buildings and sites)

- multidisciplinary knowledge production

2. OPERATIVE TOOL PREPARATION

(preservation plan design)

- ownership identification
- mapping areas under different territory management authorities
- preservation priorities and levels
- community involvement plan

3. PROTECTION GUIDELINES AND STRATEGY

(focused on authorities and all involved actors)

- legal framework revision and common adoption
- control mechanisms

4. TECHNICAL GUIDELINES

(multiple intervention scale)

- international standards and good practices

5. PLAN IMPLEMENTATION

(all involved actors)

- suitable legal framework enforcing (by legal authorities)
- knowledge transfer (e.g. publications or training academies)
- community involvement initiatives

Fig. 9.42 – Highland (Entre-Douro-e-Minho) vernacular corbelled dome and mountain range plateaus temporary settlements protection and preservation methodology proposal.

9.3 Final remarks

Although in different contexts and facing distinct types of threats, both analysed case studies are examples of endangered vernacular heritage. Due to the lack of knowledge and cultural value recognition by local communities and territory management authorities, both case studies of vernacular heritage are examples of the severe destruction and loss identity that the Portuguese northwestern rural settlements and landscape are facing since the mid-20th century. The above-presented results showed that there are options to the simple destruction and replacement of vernacular by new without any kind of caution or added value. It is also shown that on both cases, there is still much to gain by investing on preservation, either of buildings and landscape, but also by reusing heritage from an economical point of view.

As shown in the case of the rural landscape preservation by carefully planned vernacular farms wall replacement, a scientific methodologic approach and suitable decision-making process, may be the key for a clear understanding of the economic potential gain associated to heritage preservation. The proposed three-step methodology embraced all the reasonable perspectives involving the intended intervention, by providing valuable information about vernacular heritage value, industry solution and cost/benefits. However, the study also showed the overwhelming predominance of non-vernacular construction solutions, strongly implemented due to constraints such as costs and construction time, but also due to the disappearance of specialized workers. The new farm wall solution presents an acceptable example of compromise between the landscape's heritage value preservation and the observation of contemporary society's needs.

As for the corbelled dome heritage of the highlands, results showed on one hand, the huge diversity and possibilities associated to this very exquisite type of vernacular heritage, that requires multi-disciplinarily efforts to be fully embraced. On the other, the extreme level of abandonment and threats associated to it. It also became clear the complete loss of the knowledge transmission chain.

The short analysis presented in this thesis shows that there is still much to discover regarding the highland transhumance forms of architecture, and the urgency of promoting its protection against the rising of touristic and real estate pressure, which are focused on the present eco and nature friendly tastes of society. However, seeming as a solution for the depressed and abandoned highland territory, without proper management control and rules, will result in the benefit of few and a loss to all the other.

Chapter 10

CONCLUSIONS AND FUTURE WORKS

This thesis addresses the topic of vernacular heritage preservation and rehabilitation. A methodologic approach was presented, focused on guiding researchers and technicians in this hard and complex topic. Taking into consideration the objectives of the work, they were fully achieved as demonstrated in the previous chapters. The Entre-Douro-e-Minho vernacular heritage was analysed and a diversified data base regarding buildings authenticity and identity features, construction, and state of preservation is provided in this document. Experimental data concerning the physical, mechanical and durability characterization of regional schists and granites was also presented. The potential of using LIDAR survey techniques to scientifically analyse vernacular heritage, using corbelled dome heritage as case studies, was also demonstrated. As the arrival point, methodologies for proper intervention and preservation guidelines for vernacular heritage are given in the last chapter. The undertaken research was able to gather, articulate and synthesise dispersed information about distinct types of vernacular heritage from the Entre-Douro-e-Minho region, and to contribute with new knowledge of experimental and scientific character. From this work, important research questions were raised and still require further research. These refer to broader topics such as the impacts of growing touristic speculation over rural landscapes and endangered vernacular heritages, or technical issues, such as the structural retrofitting of vernacular masonry load-bearing walls or the identification of the most suitable techniques to intervene on vernacular structures.

10.1 Conclusions

By performing an initial review on international good practices and reference heritage preservation guidelines, it became clear that the international community is aware of the challenges and economic potential associated to vernacular heritage preservation. Understood as a fragile heritage, the cultural value of vernacular buildings overshoots its immediate tangible value, becoming much richer with its intangible context. Therefore, international good practices dictate that vernacular heritage should be analysed and preserved taking into consideration its specific context, physical features, and above all, the community.

Taking into consideration such position, it became clear that vernacular heritage preservation should not focus on simplified museological perspectives, but it should be able to promote buildings’ reuse as a first step to ensure successful preservation. However, to achieve such goal, a global understanding on the topic must be achieved, by clearly identifying threats and risk involving heritage preservation, and by establishing ways for buildings’ reuse and preservation in the spirit to the best international preservation practices. Therefore, it was concluded that successful vernacular heritage preservation is only achievable by knowledge sharing and by ensuring the participation of the enlarged community involved (e.g. populations, technicians, authorities).

From the analysis of the above-mentioned methodologic tools, it was concluded that after setting intervention objectives (e.g. type of intervention, cost/benefit ratio or timeframe), intervention and preservation methodologies should attend to the following steps: *i)* full and complete characterization of the endangered vernacular heritage, able to assess cultural significance and protect vernacular knowledge for future generations; *ii)* exhaustive analysis of the object, focused on its constructive characterization, state of preservation, structural safety analysis and material characterization; *iii)* context and industry solutions analysis; *iv)* from the variables identified and intervention objectives, to establish and follow a scientifically-based decision-making process to guide the selection of suitable solutions for the problem; *v)* to implement solutions and monitor the process; *vi)* to establish a suitable maintenance plan. However, to the success of such types of methodologies, international good practices point the importance of its flexibility, multidisciplinary, and ability to promote inclusion and interaction among the different actors in the process.

A review on studies addressing the topic of the rural world in Portugal was perform. It allowed to collect information regarding the lost rural realities and its buildings. The analysis of such studies was fundamental to understand the context that gave birth to the still existing vernacular heritage. As expected, most of the existing data refers to buildings’ morphologies and typologies, being technical characterization information regarding vernacular materials and building techniques scarce.

However, from the above-mentioned studies it was possible to conclude that the fading of the traditional way of life and abandonment of rural structures is a long-lasting phenomenon that started from late 19th century onwards. It became clear that the origin of the exceptionally low cultural value recognition presently given by rural populations to their humble vernacular heritage is a consequence of the very harsh and difficult life they symbolize. It was also concluded that vernacular heritage principles and values were manipulated and shaped accordingly to ideologies throughout the 20th century. As for the strong changes to the rural landscape felt in the last decades, it became clear they are in fact part of an evolutive line that started in past centuries with the importation to the rural territory of foreign life styles and models, as proven by the *"bourgeois"* and *"brazilian"* houses.

From a detailed and multidisciplinary analysis of the territory, it was made clear that the Entre-Douro-e-Minho vernacular heritage, although sharing the same basic principles, is strongly influenced by geography. The data base of context information presented in this topic confirms that regional geography (valley and mountain range) shaped two sub-regional cultural identities (lowland and highland), with specific agrarian traditions (intensive polycultivation and agro-pastoralism and vertical transhumance), and different territory occupation strategies (dispersed and concentrated settlements), that had in the farmhouse its main productive and organization cell. As it was shown by the literature review examples and the exploratory visits, all these variables shaped context adapted morphologies, typologies and even construction techniques.

From the detailed morphologic and typological characterization present in this thesis, it is clear the wide diversity of types of vernacular buildings existing in the region. It was concluded that rural houses and farmhouses were designed to assist different regional agrarian strategies, and that there was a direct link between their typologies (humbler or more elaborated) and production output, social structure, and economic capability. However, it was also confirmed that the dwelling's design followed the same basic principles all around the region, with the common areas being the main cell of the house, followed by the kitchen as privileged working space. Private and individual compartment although existing, were secondary in dwelling's design. The extension outwards of the internal routines of the rural dwelling, through porches and balconies, was also identified as a fundamental feature of regional houses. Due to context, the lowland farmhouses protected themselves from the road, whereas at the highland the road was used as an extension of the farmyard. From the exploratory visits was also concluded that vernacular houses and farmhouses were adaptable and flexible structures, growing and shrinking according to needs. Complementary and fundamental to regional agrarian economy, a vast and diversified network of production buildings and infrastructures such as mills, farm walls, irrigation infrastructures, farming terraces or roads, humanized most of the rural landscape.

The study of the highland mountain range plateaus territory occupation with settlements of temporary use, revealed these as a very genuine and exceptional way of using buildings to make productive the most of harsh and difficult environments. In these endangered buildings, the use of corbelling construction techniques and the diversity of existing corbelled dome structures reaches an exceptional level of landscape and heritage cultural value. Complementary to the above-mentioned analysis, vernacular buildings were characterized for their main construction features and durability issues.

Regarding building materials, it was concluded that granites and schists, along with soil mortars, were the main regional material used to make masonry, being timber used to make pavements and roofs. By a criterion of availability, granites prevailed for all types of masonry constructions, being preferred by masons. Although easier to extract, the mineral features and strong foliation exhibited by local schists required extra care on handling and bedding. Being considerate weaker by masons, the use of schists for more demanding and delicate masonry elements was a secondary option. From the performed observations, it was concluded that the structural organization of vernacular buildings is based on constructing an external structural box, made of load-bearing walls reinforced at ground-level by transversal walls (of the same type as the facades), that supported the timber structures of pavements and roofs. Porches and balconies were also built in timber elements, supported also over load-bearing walls or stone or timber pillars. External stairs were always built in stone blocks. Timber was also used to make the frames. The use of stone pavements at the upper-floor was restricted to the fireplace slab, if the kitchen was located at that level. Ground-floor pavements were generally made of compact soil, being timber pavements only seen in more urban or high-status buildings. A few exceptional examples of upper-floor corbelling pavements were observed at the highlands. In this research, the detailed constructive analysis was focused on the load-bearing walls.

Therefore, it was concluded that cross-sections and resulting superficial masonry textures were dictated by the geometry of stone blocks and the use of mortars in the joints. The exploratory visits showed that two-leaves cross-sections with mortar in the joints were the prevailing type of cross-section built in the region, and rubble masonry was the predominating superficial masonry texture. Uncoursed masonries were built when economic capability allowed to get horizontally proportioned stone blocks (improved construction quality), whereas the construction of coursed masonries required ashlars (finest construction quality observed).

Single-leaf dry stack cross-sections were seen on smaller farm walls. Observed two-leaf dry-stack cross-section was related to regular stone blocks or ashlar masonry. It was also a common building technique at the highland, when using larger irregular stone blocks to make very poor-quality masonry buildings such as stables or corbelled dome shelters. As for the corbelled domes, the observed examples were all constructed on dry-stack single-shell masonry.

It was observed that direct foundations were a common solution for higher load-bearing walls, being the smaller ones built without foundation. Extra care was put in the improvement of masonry’s fragile points and capstones construction. Soil mortars (granitic residual soil or clayey soil) were used as render on the facades of dwelling buildings, or farmstead walls facing the road on high status buildings. The use of renders at the highland required extra economic capability, therefore, it was not a common solution. Regarding the state of durability, it was concluded that most of the still existent vernacular heritage show considerable durability problems, being most of the abandoned buildings facing imminent ruin.

Observed structural damage is often related to foundation settlements, deformations of the horizontal structural elements, excessive loads caused by new buildings or by changes in the foundation soil, or the loss of walls’ monolithic behaviour. Cracks caused by the opening of joints and out-of-plane deformations were the most common types of damages observed, whereas ruptures and collapses were mostly seen on ruined buildings and farm walls. The catastrophic collapse of roofs was identified as the most severe type of structural damage in these types of buildings. Most of the times, it immediately disables buildings and strongly accelerates decay on load-bearing walls, by simultaneously inflicting mechanical damage and by increasing walls' exposure to rainwater. Material damage of structural origin, such as cracking and fractures with losses of material, crushing of stone blocks and wedges, or delamination on schists are common. Biological colonization was identified as overwhelming on non-rendered masonry, becoming a structural hazard when caused by large-size species such as trees. Salt damage was frequently seen during the exploratory visits, along with frost damage at the highland.

As for human originated damage, poor maintenance, changes of use, initial building mistakes and poorly performed interventions were identified as causing severe damage on vernacular structures. Losses of authenticity and identity were also identified as resulting from deep changes to vernacular buildings, either by using contemporary industrial materials or by performing poorly planned upgrade operations.

As for the sites, uncontrolled construction and unsuitable legal frameworks were identified as the main causes for the loss of cultural value. It was also concluded that damage resulting from abandonment is concentrated in areas of strong rural exodus or in remote locations such as the highland temporary mountain range plateau settlements, whereas loss of cultural value due to new construction was frequent in areas of intense emigration, or of strong real estate and touristic pressure, such as the coast.

The characterization of regional vernacular stones is one of the main contributions of this thesis. The selection of the types of rocks to test was coordinated with the selection of the main case studies, having been collected among demolished materials. Therefore, granites were selected from the highlands corbelled dome heritage buildings and the schists from the lowland farm walls. Taking into consideration the scarce available literature on the characterization of schists, two well-defined foliation and two poorly-defined foliation schists were selected for testing. The design of the experimental campaign was based on the most common types of physical, mechanical and durability characterization tests performed on rocks, and on acquiring the basic data required to understand these natural materials reactions to service conditions and possible interactions with new ones. Results showed that both types of rocks are strongly influenced by their mineral arrangement and planar structure. Tested granites are coarse-grain rocks with a homogeneous fabric. In comparison with the schist, they presented inferior porosities and higher densities, resulting on lower water absorption, and retaining capability. UPV measurements on granites showed an internal homogeneous fabric and an even distribution of internal voids. It also revealed the presence of a preferred orientation, meaning that from a microstructural point of view, the tested granites are inhomogeneous rocks. Regarding mechanical performance, results showed higher strength, lower ductility, and inferior flexural resistance on both tested granites. For not exhibiting any significantly differentiating behaviour on the three tested direction, the tested granites are here considerate as isotropic rocks.

Results for schists reveal a strong influence of foliation, in these types of rocks named schistosity, over their performance. Results confirmed a strong anisotropy on these rocks, stronger on well-defined foliation schists with fine grain heterogenous fabric. As for the poorly-defined foliation schists, presenting a medium-grain and more heterogeneous fabric in comparison with the previous-mentioned schists, results also revealed anisotropy. In comparison with granites, both schists presented higher porosity and lower density, stronger and faster water absorption capability, and a clear three directions anisotropy. UPV results show significantly different sets of propagation velocities for each direction, revealing a very heterogenous distribution of internal voids, caused by foliation. As for mechanical performance, schists showed inferior strength in comparison with granites, with higher ductility and flexural resistance, especially with load applied transversally to foliation.

The influence of water over the tested rocks was also analysed. As for UPVs, an increase of propagation velocity was observed for granites, as a consequence of internal voids filling with water. However, schists showed a propagation velocity decrease, possibly indicating an interaction of water with internal clays or by causing the widening of the joints between the foliation layers. As expected, water caused a consistent decrease on the mechanical performance of both rocks, stronger in the case of schists.

Regarding durability, schists showed higher susceptibility to salt and frost weathering due to lamellar disaggregation, with higher intensity on well-defined foliation schists. In the case of salt weathering, the intense powdering damage observed in the latter, confirmed the field observations regarding such type of damage. As for poorly-defined foliation schists results, these showed a slightly higher resistance to salts, although still poor. Granites showed a much better resistance to salt damage. Regarding frost weathering, well-defined foliation schists showed no resistance, while poorly-defined foliation schists presented higher resistance to such type of damage. Granites showed almost no susceptibility to frost damage.

From the results of the testing campaign, it was concluded that foliation on rocks consistently affects their performance. Schists' proven anisotropic behaviour confirmed masons' experience acquired knowledge regarding its lower resistance and risks associated to lamellar disaggregation. It was also concluded that rocks showing higher levels of regular foliation show higher exposure to water, therefore, inferior durability.

To contribute to the existing scientific literature on the preservation and rehabilitation of vernacular buildings, the methodologic principles presented in the thesis were demonstrated on two real case studies. Farm walls and corbelled dome heritage were selected for a detailed analysis and addressed with different preservation approaches. Both are examples of endangered heritage, although facing distinct types of threats and challenges. In the first case, to meet the community life standard, it was required to demolishing and replace a centuries-old vernacular farm wall. Therefore, the preservation challenge faced was how to rebuild without causing the loss of cultural value to the landscape and site. A major challenge was the impossibility to simply replicate a similar wall, due to the lack of economic resources and available masons, meaning that an industry solution had to be selected. Following the previously presented methodologic steps, existing vernacular heritage was characterized in detail and its knowledge safeguard, and a compromise solution was found between industrial solutions and vernacular building techniques, by applying a rational decision-making process. The implementation of the solution was monitored, and improvements and a maintenance plan were presented. As for the second case, corbelled dome buildings of a temporary mountain range plateau facing a state of severe abandonment were selected. Given the growing touristic speculation in the region and the absence of any legal framework applicable to the area, preservation guidelines are required. The main challenges to overcome were the very scarce information available, including the lack of information about the distribution of buildings and sites in the territory. The lack of knowledge showed by local populations and the unfamiliarity of the local territory management authorities about such forms of heritage, added complexity to survey. A multi-skilled research team was assembled, and a detail analysis of the vernacular heritage was implemented based on case studies, used as support for developing the preservation methodology and guidelines. Due to the lack of scientific data on these structures, laser scanner surveys were performed to fully understand these buildings complex geometries, and to support a detailed constructive analysis. Analysing the work outputs, it was proven that the selected survey technique is the most suitable one regarding the type of structures under analysis. From the case study results, an important and unique database about such type of structures in Portugal was created. A preservation methodology specific for such type of fragile vernacular heritage was developed. It was concluded from both case studies that vernacular heritage faces considerable threats created by lack of knowledge, and that there are multiple possibilities to conciliate heritage preservation and its reuse without losing cultural value. As final note, with the information and work presented in this document, the objectives of this research were fully achieved.

i) As for the first, a strong contribution for the safeguarding of Entre-Douro-e-Minho vernacular knowledge is given by the data base created, and presented as the different chapters of this thesis, namely: (*a)* regarding rural landscape and vernacular heritage regional context on Chapter 4; *(b)* characterization information regarding vernacular architectures morphologies and typologies on Chapter 5; *(c)* an overview on the main features of the regional building tradition on Chapter 6; and *(d)* about vernacular schist and granite stones scientific characterization on Chapters 7 and 8. By using the reference data presented of the mentioned chapters, researchers and different actors from the field of expertise dedicated to heritage preservation gain a fundamental tool to support authenticity and identity traces identification on rural buildings of the Northwest. Several published papers and attended conferences allowed to share the research results, as required;

ii) As for the second, a decisive contribution was given to technical and scientific literature regarding vernacular schists and granites, by the extensive experimental campaign and its results, discussed on Chapters 7 and 8;

iii) As for the third objective, it was fully achieved by Chapter 6, that presents an overview on Entre-Douro-e-Minho’s building tradition and still existent vernacular heritage overall state of preservation. The data given regarding damage and its causes constitutes a fundamental tool to support field observations and state of preservation assessments;

iv) As for the final and fourth objective, two case studies dealing with different preservation challenges are presented on Chapter 9. With them, two specifically designed preservation and rehabilitation methodologies, supported in the information of the previous chapters, are explained, and are given as methodological examples for future interventions on vernacular heritage buildings.

10.2 Future works

Future works on this topic should focus on complementing the information presented in this thesis, since only a small fraction of the potential of the topic was addressed in this research. Regarding the study of vernacular morphologies, typologies, and construction techniques, it was made clear that there are multiple realities and variations that are still not identified or require further analysis. On a multidisciplinary perspective, the same type of literature review presented in this thesis for the main end-19th and 20th century authors should be extended to the very diversified and barely known universe of smaller, local, or even international authors that addressed the Northwest rural world along the past centuries. For its importance and for the shortage of examples, the same kind of work performed at the *"branda"* of Gêmea should be replicated on other temporary mountain range settlements and other types of vernacular heritage. Such knowledge is fundamental to protect and to share knowledge regarding such type of very fragile and endangered vernacular heritage.

Regarding experimental works, much is still to be done. It is important to include other types of materials, such as other rocks or other varieties of the existent ones, and to extend the tests to soil mortars. Since it was not possible within the scope of the present work, the tested granites and schists characterization data should be complemented with detailed petrographic, mineralogic and chemical information. To determine with precision the influence of weathering over these rocks, samples of undamaged rocks should be collected and tested. With these data, a better understanding on the physical and mechanical alteration sustained by the tested rocks would be possible, along with the creation of behaviour prediction models to determine weathering on rocks under service conditions.

As mentioned in the introduction and during the thesis, some of the ongoing experimental work overshoot the time frame of the present research. Among these, the structural analysis and safety assessment of the corbelled dome structures presented as case studies is a challenging task that poses complex modelling challenges. Other ongoing experimental work refers to a larger ISISE project that involves the testing of schists masonry wallets constructed according to the traditional building techniques described in the thesis, namely two groups of 9 wallets each, divided into wallets with and without rendering and wallets reinforced with commercial grout (3 x 3 x 3). The first group was tested for compression using cyclic loading, and the second group is under accelerated ageing testing with salt (NaCl) and will be loaded later. The testing campaign also addressed the use of sonic tests to analyse such types of masonry, and the experimental characterization of traditional granitic residual soil mortar. The above-presented experimental research is fundamental for the sustainability of the built environment and for the growing rehabilitation industry in search of innovative solutions and products. As final suggestion and important future work, investment should be made on diversifying the methodologies applicable to vernacular heritage buildings. These should also embrace their reuse potential and sustainability assessment, and the definition of specific preservation guidelines for other cases of endangered vernacular heritage such as the mills or the wolf pit traps. In this context, the creation of a nationwide vernacular heritage open-access data base, with the characterization and geolocation of case studies, based in a common checklist of criterion to allow all researchers to give inputs to it, is one of the most important tasks face the challenge of effectively protecting Portuguese vernacular heritage.

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