Natural and Synthetic Consolidants for Earth Heritage: A Review

Telma Ribeiro^{1,2(✉)}, Daniel V. Oliveira², and Paulo B. Lourenço²

¹ Department of Conservation and Restoration, New University of Lisbon,
Lisbon, Portugal

telmachito@gmail.com

² Department of Civil Engineering, University of Minho, Guimarães, Portugal
{danvco, pbl}@civil.uminho.pt

Abstract. Since ancient times, natural products have been used to preserve earthen structures. Old recipes with cactus resin, bee wax, or linseed oil, have passed through generations and, in some countries, are still used nowadays. On the other hand, 20th and 21st centuries brought synthetic products as a solution to restore and conserve historical buildings. Although these synthetic products were extensively studied for stone-based monuments, they are also being used in earth heritage. The act of consolidating a degraded surface is, in conservation field, one of the most sensitive points, since the options available do not offer reliable solutions. Most of the times, the product applied, specifically in earth heritage, do not embrace two of the most important aspects in any conservation procedure: compatibility and reversibility. This paper aims to review the main consolidants (natural and synthetic) commonly used in earth heritage conservation, and also to draw the attention for the importance of a solid diagnosis of the initial state of conservation. With this review, it was possible to understand a lack of homogeneity in the identification of decay phenomena, as well as in recognizing its mechanisms of occurrence, and consequently in choosing the proper consolidant or treatment.

Keywords: Earth heritage · Conservation · Decay phenomena
Natural consolidants · Synthetic consolidants

1 Introduction

Due to its availability, abundance, efficiency, and versatility, earth has been used for centuries as a material for construction. However, it was soon discovered that, even with all its advantages and qualities, structures in earth also showed problems of maintenance and degradation phenomena. To preserve the buildings, natural products were used in two different ways: mixed with the raw material or applied over the surface [1, 2]. Depending on environmental conditions, type of natural products available and empirical experience, the methods for conservation (and consolidation) of earthen buildings vary over time and space showing different techniques and levels of complexity [1, 3, 4]. In more recent years, the use of synthetic products spread into earth heritage conservation raising a lot of questions regarding compatibility, reversibility and durability [5].

The concept of consolidation is defined by the Oxford Living Dictionary [6] as “the action or process of making something stronger or more solid.” In fact, the term consolidation is used, in conservation field, as a procedure or an action to perform when a material shows several degradation phenomena, coherence loss or serious changes in its mechanical, physical and chemical properties [7, 8]. Moreover, the level of decay may not only compromise the material stability but also the historical, artistic or cultural significance [8, 9]. The decision of consolidate a material is always delicate and sensitive and it should consider a number of factors and premises before performing it. Its complexity is also due to the factor (as for all conservation processes) that each case is different, so it is basically impossible to rely on a single “recipe” and apply it on all materials with severe decay phenomena [9]. Nevertheless, before beginning a consolidation process, the following question should be considered: why does this material need to be consolidated? And to answer, it is crucial to understand the decay processes of earth architecture.

2 Earth Heritage Degradation

Any intervention in heritage should always start with a detailed evaluation and assessment of the conservation state [10]. Specifically for deterioration patterns that may indicate the need for consolidation processes, it is crucial to understand first the reasons behind the appearance of such problems. Mapping all degradation phenomena is very important as a first step to identify and comprehend the causes for it [9, 11, 12]. Previous conservation works should also be identify, since, occasionally, products or treatments used in past may be in the origin for some present decay problems [9]. However, to perform such deep analysis it's necessary to follow a criteria and, most important, a terminology for degradation phenomena. In the literature review there are no references to a glossary for identification of decay patterns in earth heritage. Some authors pointed out the importance of earth heritage characterization in terms of state of conservation before intervention, proposing the filling of a form describing sources and causes of current damage and dividing the pathologies in groups – material, structural, surface damage, atmospheric agents, and anthropic pathologies [13, 14].

In the literature about case studies, in general, there is an identification of the main factors that contribute for earthen material degradation, but the deterioration patterns are usually too general. Or sometimes, when presenting the decay phenomena, there is a misunderstanding between factors and pathologies. Terms as damage [15]; erosion, degradation, and dirt [16]; weakness, loss of bonding, and alterations [17]; vulnerability [18]; surface loss, and stains [19]; parasite vegetation [20]; and exfoliation, and cracking [21]; are some examples of lack of homogeneity on identifying decay phenomena. Also, the descriptions are always too vague and brief, drawing more attention to material characterization and intervention itself.

The absence of a global language that specifies a typology of degradation mechanisms, when referring to earth heritage state of conservation, results in a poor initial characterization that can lead to misinterpretation of real decay phenomena. Consequently, treatments and products applied can be used in an incorrect way, or sometimes, used excessively, when preventive measurements could be enough. For example, a

Fig. 1. (a) Fissure in the plaster (Huaycan de Cieneguilla – Peru); (b) network of fissures in the plaster (Nieve nieve – Peru); (c) multiple fissures and fractures with different levels of deepness (Huaca de la Luna – Peru); (d) fissures in decorative layer (Huaca de la Luna – Peru); (e) structural fracture (Burkina Faso); (f) fissures in the joints (Burkina Faso)

common decay phenomenon in earthen buildings is cracking. But there are many types of fractures, so labeling all as cracks may induce in error when choosing the right treatment (see Fig. 1). A crack means a visible separation of a material, but depending on the size, deepness, place of occurrence, number and distribution, it can be categorized into a different typology. For instance, in stone conservation, ICOMOS (International Council for Monuments and Sites) establishes five types of cracks: fracture, star crack, hair crack, craquele, and splitting [22]. This detailed characterization is very helpful during the analysis of the original conservation state in any case study, and produces a solid and complete mapping of all pathologies. Following the same example, during treatment phase, each type of crack means different intervention: it may be necessary a structural reinforcement, or a grout injection, or just a surface treatment. Moreover, an exhaustive identification of all decay phenomena represents accuracy in time and budget planning.

Additionally, the lack of terminology and difficulty regarding the diagnosis of initial conservation state reflects also other important problem: does one understand deeply how this material degrades? What are the common decay mechanisms happening inside the material matrix? What type of chemical, physical and mechanical reactions and transformations occur? There is still a lot of research needed to be done in this area, so treatments can be optimized and, most important, to improve the knowledge about earthen heritage.

3 Consolidants in Earth Heritage Conservation

As mentioned before, to comprehend and recognize degradation phenomena is essential to execute an accurate and correct conservation treatment. Conservation scientists need to fully understand all decay patterns in each case study before starting the intervention [12]. In what concerns consolidation methods, it is even more important to know not only the typology and distribution of a damaged area, but also the origin for such pathology. Therefore, comprehending how earthen material deteriorates is fundamental for choosing the right product to consolidate or for conservation treatment.

Consolidation mechanism means applying a product that should penetrate and interact with the original material matrix. This interaction happens between the binding agent (within the consolidant), usually in a liquid state, and the degraded layer. Through the production of insoluble compounds inside the porous material matrix, the consolidant creates a bond between the capillary walls, reducing the porosity [23].

Compatibility and reversibility are two of the most important aspects to consider when dealing and deciding about introducing a new material over an original and historical surface, and the last one is very difficult to achieve. The Venice Charter (International Charter for the Conservation and Restoration of Monuments and Sites – 1964) declares that “Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience” [24]. Brandi states that any treatment applied in historical heritage should never inhibit or obstruct any future restoration action [25]. Moreover, Plenderleith, the first director of ICCROM, also denoted that in conservation work, there is a dictum that nothing should be done that cannot, if necessary, be undone easily in the future [26].

It is also important to distinguish between stabilization of earth material and consolidation. The first refers to incorporation of new products within the raw mixture, e.g., addition of lime, cement, fibers, resins, etc., with the purpose of achieving a strengthener final earth material. Consolidation refers to an action applied directly in an original degraded layer, using compatible products [27].

3.1 Natural Consolidants: Traditional and Ancient Techniques

The use of natural consolidants and stabilizers started many centuries ago. Populations learned how to improve their earth constructions by observing the nature. It is the case of the epigeal nests (or mounds) produced by termites – amazing constructions that can rise above ground up to 7 m high and are waterproof. Termites mixed soil with their

saliva and excrements producing a strong structure, resistant to humidity and rainfall [2]. Using this knowledge, men and women started to use available or mixed natural ingredients and applied it in their houses and buildings.

Polymers are macromolecules composed by repeat subunits, known as monomers, and the biopolymers have natural and biological origin. When in contact with earth material, biopolymers change the electrostatic charge of clay particles, leading to dispersion. This dispersion effect reduces the water content but does not affect the material porosity, and also improves the adhesion between clay particles and other compounds, namely sand [3, 28]. The polysaccharides family (cellulose, starch, cactus, agave, aloe, algae, and gums) and the protein family (casein, gelatins, and collagen) form a gel with water, being thickening and/or gelling agents, which increases the material cohesion [1, 2, 28].

The use of these natural products as consolidants is often referred in the literature as traditional methods used in the past, but in some regions, especially in Africa and South America, are still being used, see Table 1 [1, 29, 30]. Recipes using natural ingredients can be found in CRATerre compilation [1] and also through oral communication with people involved in earth construction.

Table 1. Some examples of different consolidants tested and/or applied on earthen substrates.

Year	Consolidant		Test method	Application method	Reference
1990	Isocyanate Silanes (tetraethylorthosilicate – TEOS with and without methyltriethoxysilane – MTEOS)	Synthetic	New probes and test walls	Spraying Brushing Bulk infiltration Multiple coating	[33, 34]
1990	Ethyl silicate	Synthetic	(<i>in situ</i>) Tell’Umar (Seleucia) Hatra Ancient City, Iraq	Injection	[5]
2008	Nopal mucilage	Natural	(<i>in situ</i>) Sampling from Nuestra Señora del Pilar mission Mexico	Aspersión	[29]
2011	Potassium silicate	Synthetic	(<i>in situ</i>) Jiaohe Ancient City site China	Spraying Drip penetration	[21]
2014	Alkaline solutions (NaOH and KOH)	Synthetic	New probes (lab)	Impregnation	[35]

Limewash is another traditional product commonly used as a consolidant of earth architecture. J. Canivell et al. affirms that limewash can increase cohesion when the carbonation process occurs inside the material, but alerts also for low level of penetration and need for regular maintenance [31].

These natural products can constitute solutions for desegregation problems in earth buildings, if they were study in a scientific level. More than just apply natural resins, oils or waxes, it is crucial to understand their interaction, compatibility and efficiency with earth material, since they can constitute an important resource to be used as a substitute for some “aggressive” synthetic products. Also, it is important to study their durability and susceptibility to biological attack [27].

3.2 Synthetic Consolidants: Commercial Products

The use of synthetic products started to be commonly used in earth heritage in the last years (See Table 1). These products were and still are used and tested for stone conservation [32], but there is still a lack of knowledge regarding earth heritage.

Two of the most common products used are ethyl silicate and acrylic resin. Ethyl silicate forms silica-gel inside the pores producing a strong bond between clay particles. After the polymerization, a reduction of material inside the porous occur, but without compromising the clay particles bond. In this way there is water resistance, but not water repellency, thus ensuring the vapor permeability [5]. Although this treatment with ethyl silicate seems a viable option, it is completely irreversible and can cause loss of surface material [5, 31].

Organic compounds, such as acrylic resins, constitute another line of consolidant products. These have been proved to be non-suitable products, mainly due to the low permeability of the layers generated on the surface of wall, which drastically changes the hygrometric behavior and consequently weakens the structure due to water ponding [31].

References to other synthetic products can be found in the literature, namely polyvinyl acetate and synthetic resins (acrylics, epoxies, and polyurethanes) but without success. Besides, these products form a film at the surface acting as a barrier to water permeability, increasing the deterioration phenomena [27].

Once again, more research is needed to accomplish successful results with consolidation procedures. The products available denote problems especially regarding compatibility and reversibility aspects.

4 Conclusions

It is clear that there is still a long way ahead to achieve a deep understanding about earthen material degradation. Although a considerable number of publications about earth heritage conservation were made available in the last years, very low has been written about decay mechanisms and how they occur. Chemical, physical and mechanical research is needed in this area and an approach by the conservation science is crucial, not only to interpret the main decay phenomena in earth heritage, but, most important, to create a homogeneous language that can categorize the different

deterioration typologies. Moreover, the lack of a solid and justified diagnosis of the initial state of conservation, together with a detailed mapping of all decay phenomena, can cause a wrong conservation treatment and compromise the historical, aesthetic and social value of heritage.

Regarding treatments, consolidation represents one of the most dangerous one if done without profound knowledge of conservation theory and without scientific background. The number of consolidants available is large, but does not fulfill all that is required for a product with its characteristics. More studies regarding efficiency, interaction, compatibility and durability between consolidants and earthen material are needed to guarantee a successful and harmless intervention in the built heritage.

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References

1. Vissac A, Bourguès A, Gandreau D, Anger R, Fontaine L (2017) Argiles & Biopolymères
2. Fontaine L, Anger R (2009) *Bâtir en terre, Du grain de sable à l'architecture*. Éditions Belin/ Cité des sciences et de l'industrie
3. Eires R, Camões A, Jalali S (2010) Optimização do desempenho de construção em terra com recurso a bio-polímeros. In: Fernandes M, Correia M, Jorge F (eds) *Terra em Seminário 2010; 6º Seminário Arquitectura de Terra em Portugal; 9º Seminário Ibero-Americano de Arquitectura e Construção com Terra*. Argumentum, Coimbra, pp 168–171
4. Eires R, Camões A, Jalali S (2017) Enhancing water resistance of earthen buildings with quicklime and oil. *J Clean Prod* 142:3281–3292. <https://doi.org/10.1016/j.jclepro.2016.10.141>
5. Chiari G (1990) Chemical surface treatments and capping techniques of earthen structures: a long-term evaluation. In: *Adobe vol 90*, pp 267–273
6. English Oxford Living Dictionaries. <https://en.oxforddictionaries.com/definition/consolidation>. Accessed 7 Sep 2017
7. Lampropoulos VN (2016) *Erosion and Conservation of Stone*. Athens
8. Ferreira Pinto AP, Delgado Rodrigues J (2014) Impacts of consolidation procedures on colour and absorption kinetics of carbonate stones. *Stud Conserv* 59:79–90. <https://doi.org/10.1179/2047058412Y.0000000075>
9. Rodrigues JD (2001) Consolidation of decayed stones. A delicate problem with few practical solutions. In: Lourenço P, Roca P (eds) *Historical Constructions - Proceedings of the 3rd international seminar*. Guimarães, pp 3–11
10. Van Hees RPJ, Binda L, Papayianni I, Toumbakari E (2004) Characterisation and damage analysis of old mortars. *Mater Struct* 37:644–648. <https://doi.org/10.1007/BF02483293>
11. Tabasso ML, Simon S, Laurenzi Tabasso M (2006) Testing methods and criteria for the selection / evaluation of products for the conservation of porous building materials. *Rev Conserv* 3630:67–82. <https://doi.org/10.1179/sic.2006.51.Supplement-1.67>
12. Delgado Rodrigues J (2015) Defining, mapping and assessing deterioration patterns in stone conservation projects. *J Cult Herit* 16:267–275. <https://doi.org/10.1016/j.culher.2014.06.007>

13. Canivell J (2012) Characterization methodology to efficiently manage the conservation of historical rammed-earth buildings. In: Mileto C, Vegas F, Cristini V (eds) *Rammed earth conservation*. CRC Press, Valência, pp 283–288
14. Mileto C, López-Manzanares FV, Cristini V, Soriano LG (2012) Restoration of rammed earth architecture in the Iberian Peninsula: ongoing research. In: Mileto C, Vegas F, Cristini V (eds) *Rammed earth conservation*. CRC Press, Valência
15. Mileto C, Vegas F (2017) Proyecto COREMANS: Criterios de intervención en la arquitectura de tierra
16. Vegas F, Mileto C, Cristini V (2014) Constructive features and preservation work of rammed earth architecture: the Islamic tower of Bofilla (Valencia). *J Archit Conserv* 20:28–42. <https://doi.org/10.1080/13556207.2014.886377>
17. Rocha M (2012) The citadel of Reina (Badajoz, Spain)—10 years of interventions on its walls. In: Mileto C, Vegas F, Cristini V (eds) *Rammed Earth Conservation*. CRC Press, Valência, pp 199–204
18. Bertagnin M, De Antoni D (2012) Preventive maintenance of an Himalayan earthen temple and studies on its reduced scale model. In: Mileto C, Vegas F, Cristini V (eds) *Rammed Earth Conservation*. CRC Press, Valência, pp 625–629
19. Graciani A, Martín JJ, Mora GM, Alejandro FJ, Canivell J (2012) Preliminary studies for intervention, interpretation and value enhancement of Tower of Don Fadrique (Albaida, Seville, Spain). In: Mileto C, Vegas F, Cristini V (eds) *Rammed earth conservation*. CRC Press, Valência, pp 345–350
20. Orihuela A, Castillo-Martínez JM (2012) Restoration of the Andalusí wall of the Alcazaba Antigua (Ancient Citadel) of Granada (Spain). In: Mileto C, Vegas F, Cristini V (eds) *Rammed Earth Conservation*. CRC Press, Valência, pp 401–406
21. Li Z, Wang X, Sun M, Chen W, Guo Q, Zhang H (2011) Conservation of Jiaohe ancient earthen site in China. *J Rock Mech Geotech Eng* 3:270–281. <https://doi.org/10.3724/SP.J.1235.2011.00270>
22. ICOMOS, ISCS (2008) Illustrated glossary on stone deterioration patterns
23. Ferreira Pinto AP, Delgado Rodrigues J (2008) The action of inorganic consolidants in limestones. In: 11th international congress on the deterioration and conservation stone, pp 873–880
24. ICOMOS (1964) The Venice Charter 1964. In: 2nd international congress Archit Tech Hist Monum 1–4
25. Brandi C (2006) *Teoria do Restauro*. Edições Orion
26. Siegesmund S, Snethlage R (2014) *Stone in architecture, properties, durability*. Springer, Berlin
27. Correia M, Guerrero L, Crosby A (2016) Technical strategies for conservation of Earthen archaeological architecture. *Conserv Manag Archaeol Sites* 17:224–256. <https://doi.org/10.1080/13505033.2015.1129799>
28. Fontaine L, Anger R, Houben H (2009) Quelques mécanismes de stabilisation du matériau terre, de la terre stabilisée aux composites argiles - biopolymères. In: Achenza M, Correia M, Hubert G (eds) 1st Mediterranean Conference on Earthen Architecture International Conference Mediterra 2009. Edicom Edixzioni, Cagliari, Italy, pp 473–479
29. Martinez-Camacho F, Vazquez-Negrete J, Lima E, Lara VH, Bosch P (2008) Texture of nopal treated adobe: restoring Nuestra Señora del Pilar mission. *J Archaeol Sci* 35:1125–1133
30. Neumann JV, Zavoni EH, Bernal JB, Mehta P (1986) Preservación de las construcciones de adobe en áreas lluviosas. Pontif Univ Catol del Peru, Dep Ing

31. Canivell J, Graciani A (2012) Critical analysis of interventions in historical rammed-earth walls—military buildings in the ancient Kingdom of Seville. In: Mileto C, Vegas F, Cristini V (eds) *Rammed earth conservation*. CRC Press, Valência, pp 289–295
32. Aires-Barros L (2001) *As rochas dos monumentos portugueses, tipologias e patologias -*, vol I. Ministério da Cultura - IPPAR, Lisboa
33. Coffman R, Selwitz C, Agnew N (1990) The Getty adobe research project at Fort Selden II: A study of the interaction of chemical consolidants with adobe and abobe constituents. *Adobe* 90:250–254
34. Selwitz C, Coffman R, Agnew N (1990) The Getty adobe research project at Fort Selden III: an evaluation of the application of chemical consolidants to test walls. In: *Adobe* 90. pp 255–260
35. Elert K, Pardo ES, Rodriguez-navarro C (2015) Alkaline activation as an alternative method for the consolidation of earthen architecture. *J Cult Herit* 16:461–469. <https://doi.org/10.1016/j.culher.2014.09.012>