ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Shivangi Shukla

Seismic strengthening of rammed earth constructions using reinforced coatings

University of Minho

Czech university of Prague

Education and Culture

Erasmus Mundus

SAHC

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DECLARATION

Name: Shivangi Shukla

Email: shivangi.shukla04@gmail.com

Title of the Msc Dissertation: Seismic strengthening of rammed earth constructions using reinforced coatings

Supervisor(s): Daniel V. Oliveira, Rui A. Silva

Year: 2016

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: Universidade do Minho

Date: July 18, 2016

Signature:

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Good, better, best. Never let it rest. 'Till your good is better and your better is best' - St. Jerome

Of course, journey to the best is never alone there are always aims, drives and individuals around who make it happen. In my journey to ‘the best’ there has been a contribution of lot of people, some permanent and some who come as guest stars. My words here cannot express my thankfulness to the best but I express my acknowledgement to one and all who were a part of my journey in SAHC and made this dissertation work possible.

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The reasons which pushed me forward to take this journey up are the emotional support, strength and confidence from my family which I would personify as my parents, my sister and my fiancé. My work and words are incomplete without mentioning my mentors from India, Professor Nalini Thakur, School of Planning and Architecture, New Delhi; Dr. Arun Menon, Assistant Professor, IIT Madras and Krishnachandran Sethumadhavan, structural engineer, who are the reason for me being a SAHC graduate. And here I am looking forward to see the next ‘best thing’ in my life.

ABSTRACT

Earth constructions cover 30% of the total built heritage in the world, some of which are Unesco World Heritage listed. Building in rammed earth consists in compacting layers of moist earth within a formwork to erect walls. Rammed earth constructions are known for presenting high seismic vulnerability, due to their high dead-weight, low mechanical properties (especially very low tensile strength) and poor connections between structural elements. During a seismic event of moderate intensity, the walls tend to fail in their plane and in out-of-plane mechanisms.

In South Portugal, the regions of Alentejo and Algarve are seismically active and a significant part of the built heritage is made of rammed earth. The structural vulnerability of rammed earth buildings puts the heritage and the life of their inhabitants at risk. Hence, the mitigation of the aforementioned risks demands the development of adequate interventions for the seismic strengthening of rammed earth constructions. In Peru, coatings reinforced with geomesh have been used for the strengthening of adobe constructions, where this solution has been shown to be highly effective in increasing their bearing capacity and energy dissipation capacity under seismic loading.

This type of solution can also be applied to rammed earth with the same purpose, nevertheless little investigation has been carried out on its development and validation. Little literature available for conservation principles and structural retrofitting makes it even more challenging. The development of this solution, in this case, needs the investigation of compatible materials and of the characterization of its mechanical behaviour. Proceeding in this way will make possible to create bases for proper design, namely with respect to the development of numerical tools. In this context, the main objective of this dissertation is to contribute for the development of the knowledge on the strengthening of rammed earth walls by means of reinforced coatings.

The proposed objective integrates the following methodology: a) literature review on rammed earth construction, namely focused on their seismic behaviour and intervention approaches, and on the strengthening of masonry with reinforced coatings; b) proposal of an approach for strengthening rammed earth constructions with reinforced coatings within the international principles and guidelines for heritage conservation; c) execution of an experimental program dedicated to the characterization of the behaviour of the solution (individual materials and interaction). The experiments were carried out in the structural laboratory of University of Minho, followed by evaluating the results and discussing the findings.

RESUMO

A construção em terra cobre 30% de todo o património construído no Mundo, onde se inclui alguns sítios listados como património Mundial pela Unesco. Construir em taipa consiste em compactar camadas de terra húmida no interior de um molde para erguer paredes. As construções em taipa são conhecidas por apresentarem elevada vulnerabilidade sísmica, devido ao seu elevado peso próprio, propriedades mecânicas baixas (especialmente uma resistência à tração muito baixa) e fracas ligações entre elementos estruturais. Durante um evento sísmico de intensidade moderada, as paredes de tendem a romper no seu plano e através de mecanismos de rotura para fora do plano.

No Sul de Portugal, o Alentejo e o Algarve são regiões sismicamente ativas, onde uma parte importante do património construído é de taipa. A vulnerabilidade sísmica das construções em taipa põe em risco a sua preservação e a vida dos seus moradores. Assim, a mitigação destes riscos exige o desenvolvimento soluções de reforço sísmico adequadas para construções de taipa. No Perú, têm sido utilizados rebocos armados com geomalhas no reforço de construções de adobe, onde esta solução tem demonstrado enorme eficiência no melhoramento da capacidade resistente e da capacidade de dissipar energia da ação sísmica.

Este tipo de solução pode ser aplicado com o mesmo objetivo, porém tem sido desenvolvida pouca investigação sobre o desenvolvimento e validação da técnica. A pouca bibliografia existente sobre princípios de conservação e reforço estrutural, tornam esta tarefa ainda mais difícil. Neste caso, o desenvolvimento desta solução requer a investigação de materiais compatíveis e da caracterização do comportamento mecânico. Através desta abordagem, tornar-se-á possível criar bases para dimensionamento, nomeadamente no que diz respeito ao desenvolvimento de ferramentas numéricas. Neste contexto, o principal objetivo desta dissertação é contribuir para o desenvolvimento do conhecimento sobre o reforço de paredes de taipa com rebocos armados.

O objetivo proposto será conseguido seguindo a metodologia seguinte: a) revisão bibliográfica sobre construções em taipa, nomeadamente focada no seu comportamento sísmico e abordagens de intervenção, bem como no reforço de alvenaria com rebocos armados; b) proposta de uma abordagem o reforço sísmico de construções de taipa com rebocos armados, seguindo princípios e recomendações internacionais para a conservação do património; c) execução de um programa experimental dedicado à caracterização do comportamento da solução (dos materiais individuais e da sua interação). T Os ensaios foram realizados no laboratório de estruturas da Universidade do Minho, seguindo-se a análise e discussão dos resultados.

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1. INTRODUCTION

1.1 Context

'Build your architecture from what is beneath your feet' - Hasan Fathy

The aforementioned statement, from the great Egyptian architect Hasan Fathy, holds a deep meaning describing his thoughts for earth construction. Though these words came in 20th century, mankind understood the power of earth construction since the inception of human settlements. For millions of years, mankind lived with perfect harmony with nature using locally available natural materials like earth, timber/bamboo, stone, etc. From primitive construction to permanent dwellings in ancient civilizations, raw earth was extensively used for building, while keeping the sustainable balance in the environment. Earth construction techniques have been known for over 9000 years, where earth was used as a building material not only for dwellings but also for religious buildings. The building methods involved were economic, robust and required only simple technology (AEI, 2016).

Nowadays, many countries still present examples of earth constructions, but historically these are associated to dry climatic/arid zones where wood was scarce. Mud bricks and rammed earth were used throughout the ancient Middle East, where Jericho is the earliest city reported to be built with raw earth. The oldest known buildings in RE (rammed earth) are 10,000 years old and were built at Catahyouk, near Konya in Turkey. Now, it constitutes a famous archaeological site with ongoing excavations, where evidences of mud bricks, cob and RE have been found. All dwellings found were load bearing with earthen walls and roofs. Chinese rammed earth buildings are 4500 years old, some parts of the Great Wall of China (UNESCO listed world heritage site) were built in RE over 2000 years ago. Teotihuacan sun pyramid (Mexico) has 70 m tall, 1900-year-old (built between the 300 and 900 AD) and its core consists of around 2 million tons of RE cladded faced with stone. In Spain, RE was also used to build the Alhambra palace and fortress, which is now listed as UNESCO World Heritage site (Ciancio, et al., 2015).

Earth has been used as a building material in many places in the World, namely in Nile's shore in Egypt, the fertile valleys of China, Tibet, Iran, India, Nepal, Yemen or the Andes Mountains in Peru and Europe. The RE technique was brought to Europe by the Romans and Phoenicians and it was used for more than 2,000 years. The grain stores of Ramasseum, in adobe, from 1300BC in the old city of Thebes still exist in Egypt (Anon., 2016). In Northern Europe the oldest mud brick walls are found in Heuneburg, Germany, and date back to the 6th century BC. Bronze Age evidences also showed that earth was used as an infill in timber-framed dwellings in this region. The archival writings of Pliny were referring to the construction of RE forts in Spain by the end of the year 100 BC. In almost all pre-Columbian cultures adobe construction is very common, namely in Mexico, Central America and South America (Minke, 2006). With respect to modern RE constructions, several important architectural examples exist, such as the Rauch house in Austria, with three storey load bearing unstabilised rammed walls, and the Royal Automobile Club in Victoria, which is the biggest modern load bearing RE building in Australia (Ciancio & Beckett, February 2015).

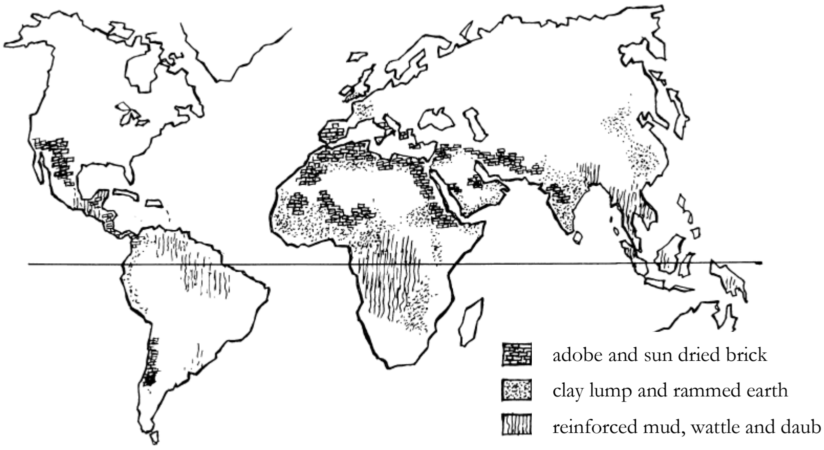


Figure 1: Map of the worldwide distribution of earth construction *(Gramlich, March 2013)*

The worldwide distribution of earth construction is pictured in the map of Figure 1, where it is clear that adobe (mud brick) and RE are the most widely used techniques. In addition, these are techniques used since ancient times, as is evidenced by the adobe dwellings dating from 8000 to 6000 BC, discovered in Russian Turkestan, or the foundations in RE from 5000 BC, discovered in Assyria. The use of adobe and RE continued over the times, where Bam citadel, Iran, presents constructions with 2500 years old, while the fortified city of Draa valley in Morocco, is around 250 years old. (AEI, 2016). The RE technique slowly emerged in many areas of the World, spread by the Spanish conquerors as they settled their colonies. In the Medieval period (13th -17th centuries), earth was frequently used throughout Central Europe as infill in timber-framed structures.

From 15th to 19th centuries RE technique got widespread in France as *Pisé*. In Germany, the oldest inhabited house made in RE walls dates back to 1795 (Minke, 2006). RE construction attained its popularity in the US from 1780 until about 1850 (Anon., n.d.), while in Canada, it emerged in between 1838 and 1841. The period from the 1920s through the 1940s was active for studies on RE construction in the US. Many institutions carried out extensive research on the subject. Houses were built inexpensively under some schemes in association with architects and provided accommodation to low-income families. After the World War II the costs of modern building materials fell and RE became less preferable. In fact, RE construction lost its popularity with the advancement and development of modern building materials in the 21st century, to which also contributed some of disadvantages of these constructions, namely their poor seismic behaviour. The advantages and disadvantages of RE constructions are listed in Table 1.

Table 1: Advantages and Limitations of rammed Earth

Advantages	Limitations
- simple, fast and inexpensive construction - load bearing capacity - sustainable/ recyclable/biodegradable - non-toxic and termite-resistant - non-combustible/resistant to fire - excellent thermal and acoustic characteristics - durable/ long lifespan	- labour intensive, which can result in higher building cost in developed countries - requires using adequate formworks - maintenance demanding construction, especially in the case of unstabilised RE - poor seismic performance of unstabilized RE - susceptible to damage by water/ moisture - additional insulation and vapour barriers required - carbon benefits are reduced with cement stabilisation

Over the time, the RE technique kept developing with the experience and depended on climate/geological conditions of the region, structural stability and diverse building requirements (Schroeder, 2015). In recent years, with the advancement of research and development in structural analysis and material stabilisation, RE construction technique has been able to reclaim its status as a preferable building material. However, the seismic performance of these constructions is still a challenge in the fraternity of structural engineering, conservation as well as architectural designing. It has become a prevalent research topic worldwide and this dissertation is a footstep to contribute to the concerned subject.

1.2 Motivation

The diversity of earthen structures ranges from simple forms of dwellings to massive monumental sites of great intricacy. About 10% of the World heritage list of UNESCO are earthen construction sites (Getty, 2016). According to United Nations, one third of the human population lives in earthen dwellings, in developing countries it is about 50 % and at least 20% of urban and suburban populations residing in earthen houses (AEI, 2016). The last decade has witnessed significant natural calamities, which caused heavy losses in terms of human fatalities, property and heritage loss. Along with natural disasters, the increasing urbanization and modern building technologies are also a great threat to earth constructions. The traditional construction methods and practices are disappearing, and moreover it is also becoming harder to find a skilled labour in the field. Figure 2 shows the twelve major earth construction techniques.

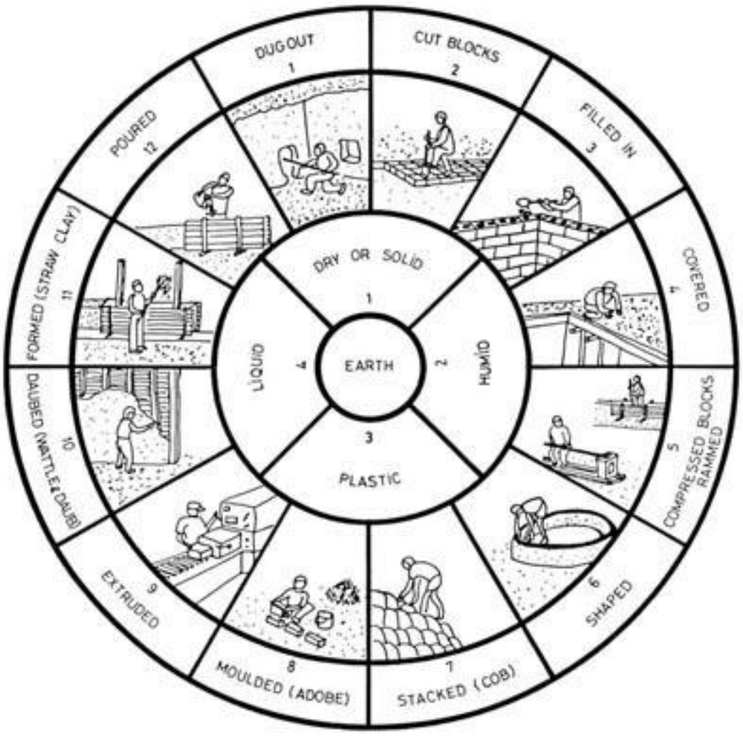


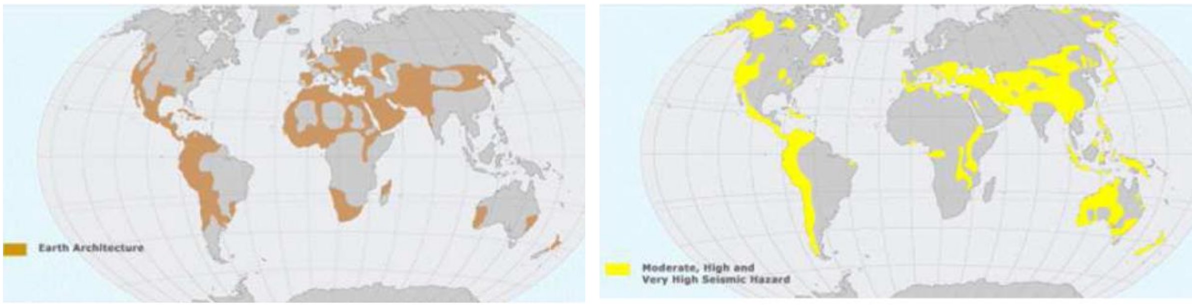
Figure 2: The twelve main techniques for earth constructions (Auroville, 2016).

Risk assessment and disaster management involved with natural disasters (floods/earthquakes) or human impacts is a major concern today. Due to the mismanagement of resources, risk of ecological disasters is also present, moreover it affects the built environment directly or indirectly. Disaster resistant constructions are of utmost need in all over the world, but they also must account for the affordability so that the solution can be accessible to everyone.

Some studies on the mechanical behaviour and seismic performance of RE have been performed in the recent years. Research groups from Peru and Mexico have been contributing with experimental research on adobe construction. The USA and Australia have been focused, since 1980, on the study of stabilized RE. Moreover, in these countries there are documents regulating earth construction. In 1980-90, India stepped forward with CSEB technology. The seismic performance of RE is almost absent from scientific research, which represents a serious gap in knowledge regarding the performance characterization of earth construction. The current work is in line with the context and ongoing research in Portugal, where the Department of Civil Engineering from University of Minho is taking an important participation.

1.3 Objectives

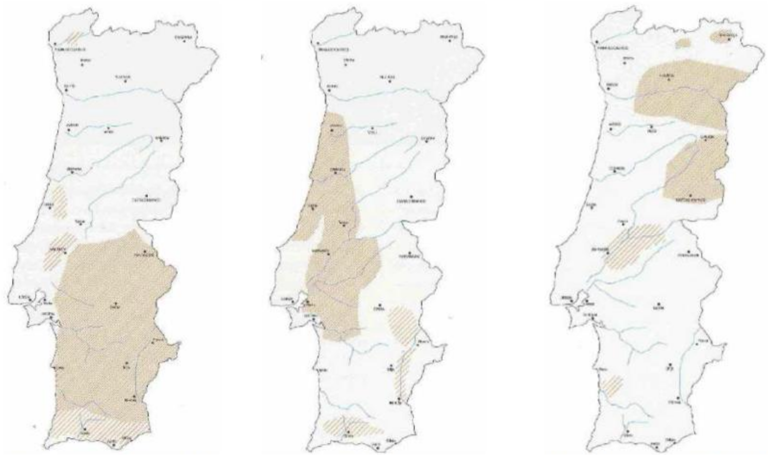
Earth constructions are found spread all around the World, where many of them were erected on zones with high seismic hazard (Figure 3). Earth constructions, such as RE, are very vulnerable to earthquakes due to their low strength (compressive and tensile), brittle behaviour, high dead-weight and poor connections between structural elements. Even in a moderate intensity seismic action, the walls tend to fail (in-plane/out-of-plane mechanisms). The seismic performance and strengthening of these structures is a challenging topic, where knowledge is still scarce.



(a) (b)

Figure 3: World map of (a) earth construction distribution and (b) of the regions with important seismic hazard (De Sensi, 2003)

Portugal is a country threatened by the occurrence of earthquakes with high intensity, where southern region has the highest seismic vulnerability, namely in the regions of Alentejo and Algarve. In these regions, RE constructions are found frequently as shown in Figure 4. These are typically classified, according to their use, in military and civil constructions. The first ones are mainly constituted by, still existing, millenary fortifications built during the Arab occupation, such as the Paderne Castle. The second ones are mainly constituted by dwellings built before 1950s, where a significant part of the population still lives in. In this last case, exterior walls are made of RE, while the interior ones can be made of the same material, adobe masonry or wattle-and-daub. Furthermore, many of these constructions have survived some high intensity earthquakes. However, the high risk of the loss of lives and loss of this important built heritage recalls the urgency in studying the seismic performance of RE constructions, as well as strengthening solutions.



(a) (b) (c)

Figure 4: Distribution of earth construction in Portugal;(a) Rammed earth; (b) Adobe and (c) Wattle and daub *(Rocha, 2005)*

The risks associated with earthquakes can be overcome with planning and strategies for seismic retrofitting of RE constructions. Research on seismic retrofitting of adobe have been done in Peru, namely with reinforced coatings using 'geomeshes'. The system increases the bearing capacity and energy dissipation capacity of the structure under seismic loading. The aim of the current research is to apply a similar reinforced coating to RE and assess its effectiveness. Though, very little information is available in the literature. Therefore, this thesis deals with the investigation of compatible materials, specifically with respect to their mechanical behaviour. This work can be a step up in the further development of numerical tools. Hence, the main objective of this dissertation is to contribute for the development of the knowledge on the strengthening of RE walls by means of reinforced coatings. The proposed objective will be fulfilled by means of an experimental program.

1.4 Methodology and outline

The dissertation work aims at assessing the performance of RE wall with reinforced coatings by comparing the results from experimental tests using two different mortars. The methodology adopted for the development of the research work is briefly discussed below.

First, a literature review was performed on earth construction, in order to allow understanding the context of the topic. This review was focused on the history of earthen construction, significance and prominence of RE technique across the globe along with the seismic risk associated to earthen heritage; which is being discussed in Chapter 1.

Later, in Chapter 2, the seismic behaviour of RE is described with respect to vernacular strengthening and intervention approaches with some basic principles of earthquake resistant houses. Further discussed are the recent international research done on seismic strengthening of masonry and adobe with reinforced coatings and their results. Lastly, case studies from Peru are discussed with respect to the use of reinforced coatings for seismic strengthening of adobe vernacular dwellings.

In Chapter 3, the global issue of RE conservation is discussed with respect to the problems related with endangered historic sites listed by UNESCO. The significance of international standards and principles for heritage conservation, formed by international organisations are also discussed. Furthermore, it addresses the compatibility of the proposed strengthening method in heritage context and future challenges for its acceptance for historic RE retrofitting.

The execution of the experimental work is presented in the last two chapters explaining the laboratory experiments. Chapter 4 deals with the experimental program carried out and presents the selection, preparation and characterization of rammed earth, mortars and reinforcing meshes.

Mechanical properties and results obtained from laboratory tests are presented in Chapter 5. The material strength with corresponding modulus of elasticity is presented for rammed earth, mortars, and meshes. Mortar and rammed earth substrate interface is also assessed. Evaluation of the laboratory tests with conclusions is presented in the final Chapter 6. Future works and recommendations are also discussed later in the chapter. The thesis work presented here is not exhaustive and is being taken forward for further studies and analysis for the same project.

2. STRENGTHENING OF RE CONSTRUCTIONS

2.1 Introduction

Over the ages RE constructions, from simple dwelling to complex structures with historical value, have been showing poor seismic behaviour around the world. Adequate knowledge on the subject is still absent, which threatens the life of inhabitants and the preservation of this heritage. This ignorance and inexperience has also led to inadequate seismic retrofit procedures. Hence, the economical, technical, and functional stability requirements is the prime need for the preservation of the heritage in RE. RE is a malleable material and can be used for curves and arches but because of its vulnerability to weather conditions and seismic actions it is not considered as good building material. Earth as a material, cannot resist the effects of moisture. Increasing the water content in RE reduces its strength and stiffness (Jaquin, et al., 2013). The unstabilised earth walls get their strength from the bonding effect of dried clay. The strength is lost if it becomes wet and consequently causes erosion or failure (Anon., 2016). The strength of RE is also reduced with erosion due to wind and driving rain.

Seismic activities cause structural damage and sometimes complete failure to unstabilised RE. Strengthening can be done by improving its seismic behaviour as well as other mechanical properties. Shrinkage, low compressive strength, cracking, durability are the major issues and many solutions have been introduced to increase its performance as a building material. Unstabilized RE consists of clay (10-20%), sand (50-60%) and gravel. It should be noted that high percentage of clay may cause shrinkage and cracking (AEI, 2016). There are various methods to stabilize RE like hydraulic binders, additives like cement or lime in addition to soil, sand and gravel. The stabilisation process increases the resistance of the material against destructive weather conditions by improving the strength and cohesion, decreasing the movements (shrinkage and swelling) of the wet soil making the soil waterproof or at least less permeable to moisture (Vora, et al., 2014). Traditionally, lime or animal blood were used to stabilize the mixture, while lime, cement or asphalt emulsions are used today. The density of soil is from 1000 to 1500 kg/m^3 but when compressed as RE the density increases from 1700 to 2200 kg/m^3 (Minke, 2006). With recent lightweight materials, unstabilized RE can achieve densities less than 1700 kg/m^3 (Schroeder, 2015).

Looking at the seismic behaviour of historic earthen structures, some massive earthen structures in Peru have been able to survive earthquakes because of their massiveness and regular configuration. The Chan-Chan city (1200AD) built with adobe walls, survived many severe earthquakes during the past 600 years. Some walls are up to 9m tall and 3m wide at the base and many slender walls are still standing without any support, a citadel shown in Figure 5. While, Bam earthquake (2003) in Iran destroyed the historic earthen citadel of Arg-e Bam built in adobe (500 BC) including several adobe houses (Blondet & Aguilar, 2007).
The architectural design of the citadel and surroundings includes upper thin walls standing over thick base walls, irregular plan configurations, and high wall densities. It seems that slender walls have collapsed, impacting adjacent walls and constructions, causing total destruction of the site, in spite of its massiveness. (Blondet & Aguilar, 2007)

(a) (b)

Figure 5: Ancient earthen structures (a) citadels of Chan-Chan and (b) Arg-e Bam *(Blondet & Aguilar, 2007)*

Similarly in Al-Hoceima, Morocco (2004), Kashmir,Pakistan (2005), Pisco, Peru (2007) and in Bhutan (2009-2011) several earthen structures were severely damaged. Nepal earthquake 2015 marked a sad day in the history for its severity and devastation. Many UNESCO world heritage sites collapsed causing heavy casualties, where constructions were made with mud bricks and timber. This difference in the performances surely raises the questions about the structures' design, materials and size as an assurance for earthquake survival. In many developed countries earth is still being used, as it is readily available and economic. Many constructions are built by the residents themselves without any technical knowledge or quality control (Blondet & Aguilar, 2007). Several researches and activities have come up in the last decade to find seismic retrofitting and strengthening solutions for historic RE as well as modern. Though little is known about the properties of historic RE but the experiments and results with the modern RE would definitely be close to the historic one as the properties are not very far. This chapter discusses about some vernacular construction methods to reinforced earthen structures and presents some current researches carried out on the seismic stability of adobe structures.

2.2 Earth construction in seismic zones

Through ages and development of the mankind, humans have learnt to live in perfect harmony with nature and learnt to cope up with the natural disasters. From the art of making dwellings, developing weapons, learning cooking, scientific inventions and the research still continues. Homo sapiens, considered to be the most intelligent living species on the earth, knows how to develop while adapting with the environment and creating the comfort and safety for their lives. Experiencing the seismic behaviour and damage patterns in earthen buildings, there have been developed vernacular strengthening techniques for earthen structures, which depend upon the locally available materials and resources. The general construction principles for seismic resistant earthen architecture are discussed with respect to the seismic behaviour and damage patterns of the adobe and RE construction techniques with some examples.

The known earthen constructions techniques can be explained as the following: The adobe is a mixture of clay, sand and straw also called mud brick or sun dried brick, which is hand shaped in timber moulds. The *Tapial*, as called in Latin America, P*isé* in France or rammed earth in the US, is a technique where a homogeneous mixture of earth and water is poured in a formwork in thin layers and compacted to increase the density. Traditionally, compaction is done by hand and in modern times done mechanically with pneumatic rammers. The *Quincha* is a technique where an earth mixture is used to fill a wooden frame work.

2.2.1 Seismic behaviour of adobe

Severe seismic damage and loss in adobe buildings was recorded in past earthquakes. Out of 0.37 million, 0.13 million (approximately 37%) buildings in adobe were damaged in Chile earthquake (2010). 90% of the adobe construction was destroyed in Curicó and the most affected region was Maule. In Aveiro region (Portugal) 25% of the existing architectural heritage is made in adobe. In some cases, inadequate intervention and unplanned rehabilitation with new materials resulted in mixed construction typologies using reinforced concrete beams, columns or slabs which are not designed to resist seismic actions and are prone to earthquake damage (Tavares, 2012).

(a) (b)

Figure 6: Adobe houses with seismic damage (a) Vertical cracks at corner of front wall and (b) Diagonal shear cracks *(Blondet & Aguilar, 2007)*

The compressive strength of adobe is much higher than its tensile strength, therefore significant cracking starts in the regions subjected to tension. Seismic forces perpendicular to the walls produce out-of-plane bending, and cracking starts at the lateral corners of the walls (Figure 6), where the tensile stresses are higher. Large vertical cracks are produced and separate the walls from each other. In an earthquake, the front walls usually collapse first with overturning, lateral seismic forces generate diagonal shear cracks within the plane of the walls (Figure 7) which follows stepped patterns along the mortar joints. These cracks are often seen at the corners of doors and windows due to the stress concentration (Blondet & Aguilar, 2007).

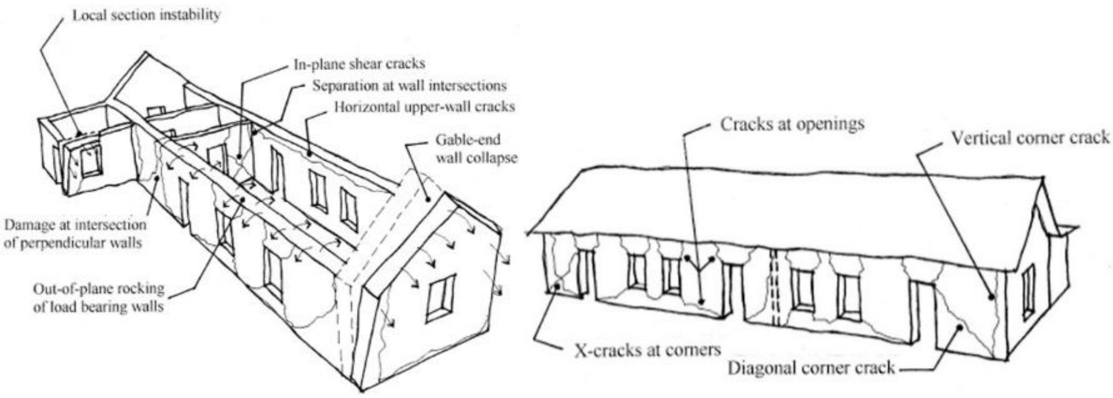


Figure 7: Typical damage pattern in earth constructions due to seismic action (Webster and Tolles, 2000) extracted *(Tavares, 2012)*

In history, with the understanding of the seismic activities, early Peruvian cultures wisely developed reinforced construction techniques with adobe, mud mortar, and wattle and daub (*quincha*). These construction types can be seen along the coast of Peru in regions like Huaca del Sol y de la Luna (100–800 AD), Chan-Chan (850–1476 AD), and Tambo Colorado (1476–1534 AD). But, with strong earthquakes over the years construction techniques were changed. The Spaniards and Spanish viceroyalty started using *quincha*, adobe, and RE (known as *tapial*) around Peru, influenced by traditional techniques by the Incas and earlier Peruvian cultures. In Lima, an earthquake prone area, a mixed construction method saved the heritage from earthquakes for more than 300 years. The first floor had thicker adobe walls and second floor was with flexible wooden-frame and earth walls (Cancino, et al., 2009).

Buttresses were used to provide stability against earthquake forces, by resisting to out-of-plane movements and preventing overturning of massive adobe walls. *Quincha* (means fence, wall, enclosure) system consists of wooden panels with cane reeds covered in mud plaster, which creates an earthquake-resistant framework. It was used throughout in Central and South America in all Spanish and Portuguese colonies. It was also used for vaults and domes construction. Later in 1908, the state government banned the use of *adobe* and *quincha* for the construction due to its poor performance and destruction. In late 20th century earthquake norms were made for regulating seismically resistant of new earthen construction. The 21st century earthquakes acted like a catalyst in the studies and research of seismic resistant structures in Peru. (Cancino, et al., 2009). With the advantages of being cheap and easily manufactured material, the adobe also poses the weakness of having low seismic resistance.

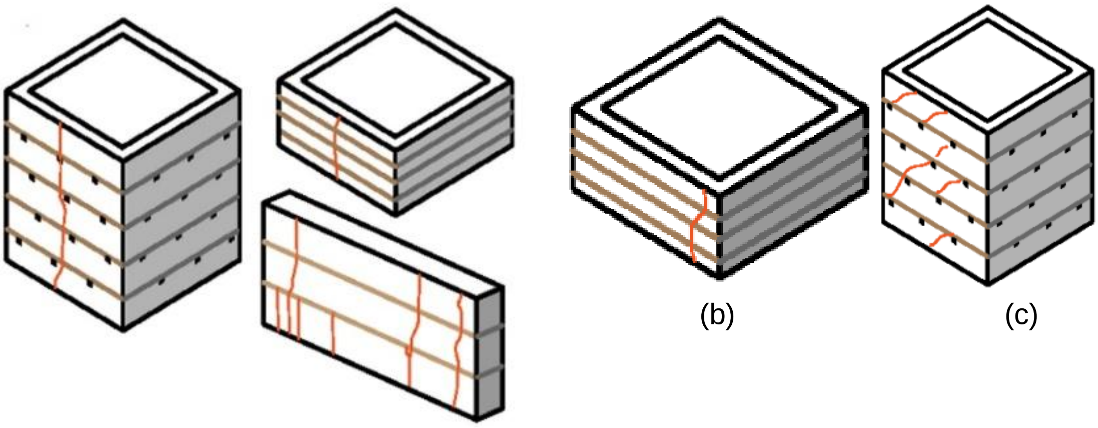
Following are some points to be considered to make adobe construction possible in earthquakes prone area. The ideal mixture is in proportion of 1:3 or 1:5 in volume as clay: sand and straw (sand 55-75%, Silt 0-28%, clay 15-18%). It could be with horsehair, rush fragments, dung, etc. and without stones, sullage, or vegetable residues. Dark and agricultural earth is to be avoided since it contains an excessive amount of organic substances. Rush (juncus) matting/brandering is used both in adobe and RE, laying the reinforcement vertically and horizontally in the walls. Vertical rushes are fixed in the foundations. It is advisable to keep

40 cm of spacing between vertical rushes and to keep horizontal rushes at every 4 courses of adobe. Experiments carried out at Pontifical Catholic University of Peru (PUCP) in Lima proved that strength and ductility in RE increases up to 40% with this brandering system when compared to adobe. Shear strength and lateral collapse displacements of 16 tons and 60 mm were found respectively in RE while 12 tons and 34 mm were the results in adobe (Jurina & Righetti, n.d.).

2.2.2 Seismic behaviour of RE

RE structures are vulnerable to seismic damage due to their low mechanical properties and high dead-loads. Poor connections in the material cause overturning, detachment of lifts and oblique cracks, even in low seismic forces (Figure 8). RE construction are very dense, brittle and is assumed to have low tensile and zero shear strength (Silva, 2014). As the compressive strength is much higher than tensile strength, RE cracks in the areas subjected to tension in earthquake motions (Blondet & Aguilar, 2007). Due to post-peak and brittle behaviour of earth, the wall loses its tensile strength completely after cracking, but it can still carry load if it is stable (Miccoli, 2014). The layered construction in RE is to be done alternately with inner and outer edges in perpendicular walls in order to integrate the walls but this is often compromised for speedy construction. Hence, this vulnerable corner can easily separate, causing corner failures due to severe stress.

Joints can be opened very easily in any structural movement, which is a common problem in later medieval period buildings, where brick quoins were used. Separation in the vertical joints of independent RE blocks may occur with structural movement, and this separation can appear as cracking in a homogeneous material. Vertical joints between two RE blocks cannot carry any tensile stress, hence the blocks separate. In load bearing transverse beam, wall plates are used to spread the load over a larger area to prevent localised shear failure of the wall beneath. If the beams are insufficiently stiff, they tend to bow under loading, allowing out-of-plane failure to occur. Furthermore, increasing load at the wall face can lead to spalling of the surface material (Jaquin, et al., 2013). Later additions in RE constructions is in general a complex problem, as integration of old and new element is very difficult to achieve (Bhutan, 2011). Minor damage and separated walls can be repaired or rebuilt. Tilted walls can be retrofitted with horizontal tie bands or reconstructed. Better seismic performance can be achieved by using adequate strengthening.



(b) (c)

(a)

Figure 8: Typical earthquake-damage pattern in rammed earth buildings: (a) vertical cracking, starts at the base and sometimes runs throughout the height; (b) Vertical cracking at corners; (c) In-plane shear cracking *(Ziegert, 2010)*

2.2.3 RE in seismic areas

The typical damages observed in RE constructions in the western Bhutan after the 2011 Sikkim-Bhutan earthquake (Figure 9-10) were vertical cracks, separation of walls at the corner, tilting of high walls, diagonal opening cracks and cracks at the connection of timber beams and wall. It should be noted that some of the damaged houses had two storeys and 80-100cm thick walls. (Bhutan, 2011)

(a) (b) (c)

Figure 9: Typical damages of RE constructions from Bhutan, after the Sikkim-Bhutan earthquake: (a) corner cracks; (b) separation of old and new walls; (c) diagonal cracks at the openings

Another type of damage noticed was displacement of *rabsey,* (Figure 10 (a)), a full height window at upper floors which is anchored in the walls preventing out of plane movement. Some places were not anchored, were just resting with the weight (Bhutan, 2011).

(a) (b) (c)

Figure 10: Typical damages of RE constructions (a) Separation of corner walls; (b) vertical wall cracks and (c) corner failure

In Alentejo, southern Portugal, the traditional RE house generally presents a simple and rectangular plan and has only one floor. The thickness of the walls is usually 50cm, increasing only in the case of taller buildings. The wall's footing is in stone masonry, with 30 to 50cm height and with the same thickness of the walls. To improve the mechanical behaviour, the soil can be stabilized with the addition of lime, cement or both (Parreira, n.d.).

Many earthquake resistant designs have been used to reinforce and retrofit and improve the seismic performance of earth constructions. Research from Latin American countries, in the last 20 years, found several parameters influencing earth construction- soil particle size distribution, humidity content, compaction level, use of natural additives, joint treatment etc. Presence of clay in soils is fundamental to have strong walls, since clay provides the dry strength. The addition of 0.25 to 0.5% of straw (5cm length) may help improving the control of micro-cracking in the walls, but it does not prevent the formation of vertical drying cracks. The RE walls can also be reinforced with high tension materials, such as canes or other timber elements placed as a mesh at the surfaces of the wall, whose objective is to improve the in-plane and out-of-plane behaviour (Vargas, n.d.). Good seismic design should have adequate research on material properties and also follow basic design concepts. Minke (2001) presents principles on construction of earthquake resistant houses made of earth, which are here also discussed.

The impact of earthquake depends not only on the magnitude but also on the depth and distance from the epicentre, geology and topography of the local of construction. Horizontal forces create more impact on the buildings than the vertical forces. During an earthquake, out-of-plane inertial forces are generated in the walls, which can be damaged or cause total collapse if the structure is not stabilised orthogonally, with buttress or ring beams.

Furthermore, slender walls can also collapse due to buckling. In-plane inertial forces are also generated, but the associated collapse mechanisms are not as dangerous, since the thrust produced just causes diagonal cracks in poor construction. So in designing, the horizontal force is to be calculated as proportional to the mass of the structure and consider displacements increase with the increased height.

The main aim in earthquake resistant houses is to resist horizontal movements with ductile behaviour and good connections to prevent collapse. The quality of earthquake resistant structure is expressed with the formula *'structural quality = resistance x ductility'*, meaning that the higher are both parameters the higher is the structural quality. However, low resistance structures are expected to be more flexible and vice versa (Grohmann, 1998). For example, in Mendoza and Argentina thick inflexible historic RE walls have high resistance to earthquake while modern slender adobe or bricks have collapsed in moderate seismic actions. There are certain possibilities within the construction, either build rigid massive RE walls with interconnected walls and roofs so that no deformation occurs or use large adobes or a flexible timber framework filled with earth, like the wattle-and-daub technique (Figure 11). In the latter case roof should be connected to the columns separated from walls to have independent movements and flexible walls should dissipate the kinetic energy by absorbing the vibrations with deflections.

Figure 11: Wattle-and-daub structure that survived after a heavy earthquake in Guatemala *(Minke, 2001)*

2.3 Principles for earthquake resistant houses

Placement - In earthquake prone areas, houses should not stand on a slope. The structure should be placed over a platform with adequate distance from the slope and marshy ground (Figure 12). For earthen structures to perform well in earthquake, the ideal thickness of the wall is 30 cm and the height should be upto 8 times the thickness of the wall. Higher walls should be supported with buttresses or thickness must be increased. Soil should have adequate amount of clay, coarse, and fine gravel for stability to prevent shrinkage.

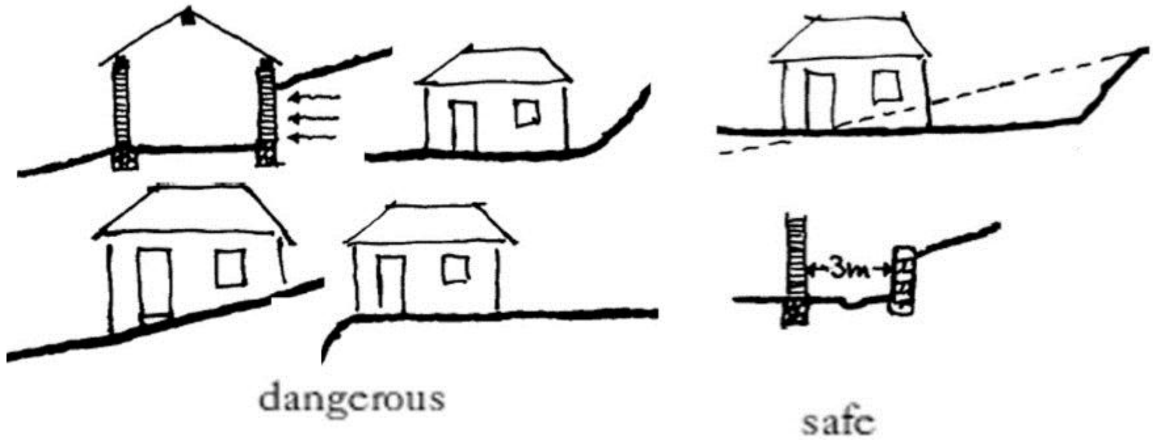


Figure 12: Dangerous and optimal placement of house on a slope; modified *(Minke & Schmidt, 2015)*

House shape form - The stability against earthquakes is effected by the shape of the plan, which should be as symmetric, regular and as compact as possible to have a uniform performance. Mass and stiffness should be uniformly distributed. The best plan consists of a circular shape, while L-shape is not very stable (Figure 13). Long shapes should be compacted and divided into parts with flexible connections.

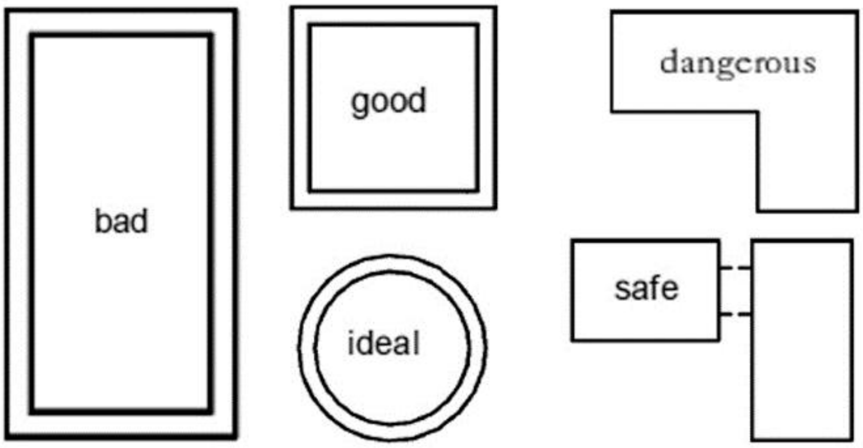


Figure 13: Seismic performance of different plan shapes used for earth construction *(Minke & Schmidt, 2015)*

An experimental research, at the University of Kassel, was done to assess the seismic behaviour of different plan shapes, where house models with RE walls were tested stroking the model with certain weight. Results are shown in the Figure 14 and 15. The similar technique with convex walls were used in Afghanistan but openings reduced the stability of the structure as stated by Minke (2001).

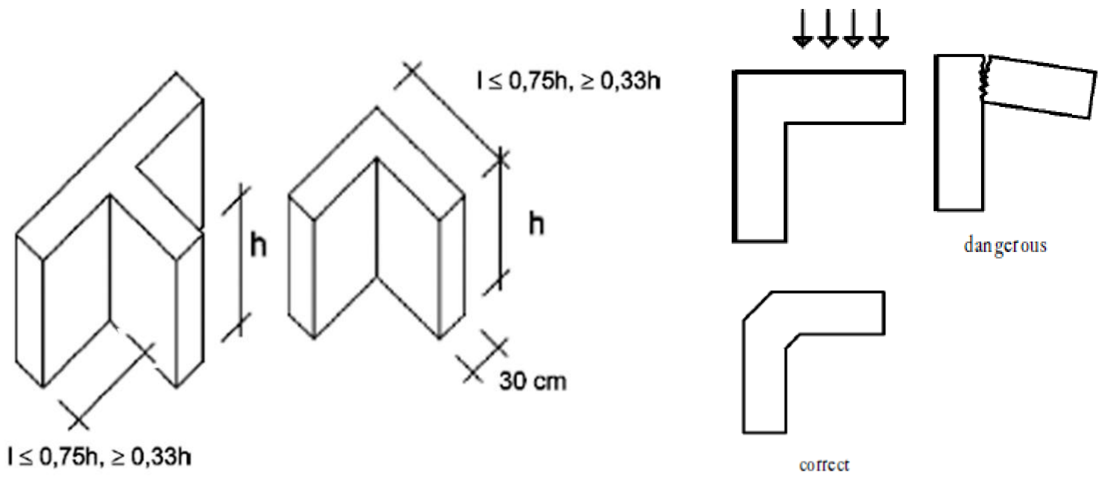
(a) (b)

Figure 14: RE model with square plan developed a large crack after the 2nd stroke, (a) one part separated after 3rd strokes and (b) collapse after 4th stroke *(Minke, 2001)*

(a) (b)

Figure 15: Circular RE models (a) first crack appeared only after 3rd stroke and (b) after 6th stroke a small part was separated *(Minke, 2001)*

In traditional RE, earthquake resistance is dictated by its stiffness and mass. RE constructions are found to be from 60 to 100 cm thick and are not too high. This process of making massive RE walls is no longer used as it is very labour intensive. Modern solutions to stabilize RE walls have been used recently. Elements of shape L, T, U, X, Y or Z have shown better stability against lateral forces due to their angles. In 30cm thick walls, free ends should not be longer than 3/4 and not shorter than 1/3 of the height. The perpendicular forces are transferred through the angle connection to the parallel walls and creates a stress concentration at the inner corner. Therefore, this section should be flexible, designed and connected well (with ties) in order to transfer the forces (Figure 16). The thickness of adobe, brick or RE walls should be at least 1/8 of its height.

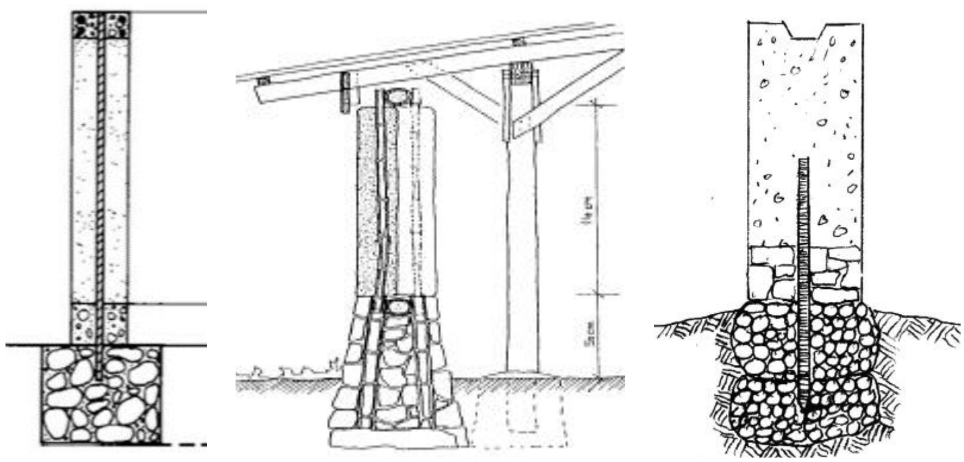


(a) (b)

Figure 16: Recommended proportions for earth walls (a) for the free ends and (b) corner extension for the connection *(Minke, 2001)*

Another method for strengthening RE walls against seismic action is by means of internal reinforcements with vertical rods embedded in the walls. Bamboo, wood or cane rods can be used for this purpose. These vertical elements should be embedded inside the walls and fixed to the foundation and the ring beam (Figure 17). Bond between foundation-plinth and plinth-wall should be good, this can be done by integrating a wooden or bamboo rod of 2.5 to 5 cm at every 40 to 50 cm (Minke, 2001).

To absorb horizontal shocks from an earthquake a floating foundation can also be done with two or three layers of plastic bags filled with pebbles. The foundation should be 10 cm wider than the plinth on each side and should be at least 40 cm deep. Horizontal reinforcing elements are not used normally, since the bond with the earthen material is poor, whereby the shear forces are not transmitted properly. It is also difficult to ram the earth below these elements because of its elastic behaviour (Minke, 2001).

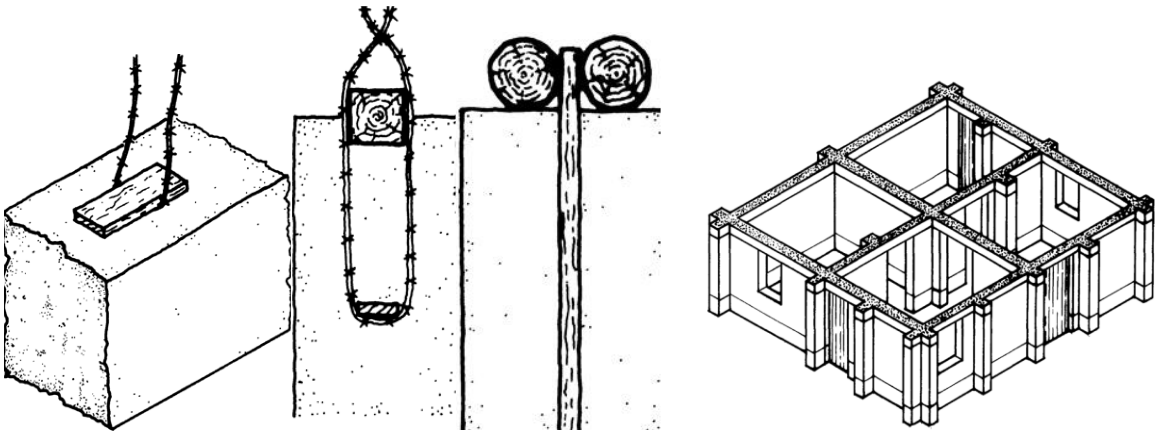


(a) (b) (c)

Figure 17: Internal reinforcement with vertical rods *(a)* foundation of external walls should be at least 40cm deep and made with stones*; (b)* separation of roof and wall system with ring

beam on top and bottom (c) *floating foundation with plastic bags filled with pebbles (Minke, 2001)*

Surveys after earthquakes found some typical design faults in South America which led to collapse of rural houses. These faults include lack of a ring beams, inadequate lintel thickness and shape of windows. Lintels should be avoided and high windows reaching up till the ring beam can be used. Connection between the ring beam and the wall should be strong to prevent buckling. The ring beam is expected to hold the wall and can be made of reinforced concrete, wood or bamboo (Figure 18). The connection should be sufficiently stiff at the corner. In case of adobe and post-beam framework, there must be a good connection between the posts and the adobe, as adobe will fall with horizontal vibrations of the earthquake. External ring beam is also possible with supporting it on pillars with strong interconnection at the corners. The roof must also be connected to the ring beam**.** The openings for windows and doors should be no more than 1 m wide. Mortar joints should not be thicker than 1.27cm between the bricks. RE constructions in seismic areas must give priority to shear strength and ductility provided by compatible materials such as cane and wood.



(a) (b) (c)

*Figure 18:*Possibilities of fixing wooden ring beams (a) wooden beams in RE wall; (b) vertical post fixed to a double ring beam in RE wall and (c) adobe walls reinforced by buttresses and ring beams on the top of the walls *(Minke & Schmidt, 2015)*

2.4 Reinforced coatings

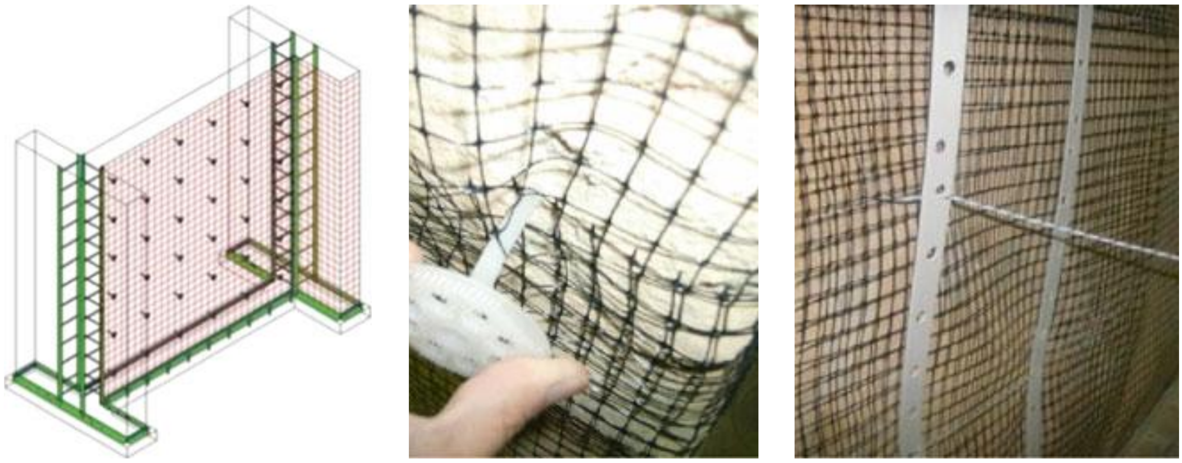
In the field of seismic retrofitting of adobe masonry structures, reinforced coatings have proved to improve greatly the structural performance. Several laboratory experiments simulating earthquakes vibrations on full scale adobe models were done at Catholic University of Peru (PCUP) in the last decades. The studies evaluated the feasibility of strengthening adobe building using ‘geomeshes’ (plastic or metallic). The reinforcement walls showed improvement in ductility and withstood a maximum lateral drift of 5.18 %, double than that of the unreinforced model. Similar experimental researches were carried out in Mexico on retrofitting with synthetic meshes (Figueiredo, et al., 2012). This technique fits within the concept of a recent strengthening composite system called externally bonded reinforcement (EBR). The EBR used in historical masonry comprises fibers embedded in mortar matrices of mineral binders, whereby this technique is known as fibre reinforced cementitious matrix (FRCM) or as textile reinforced mortar (TRM).

The use of FRCM helped in solving durability and compatibility issues in masonry strengthened with FRPs. Being reversible, mortar based matrices have many other advantages like heat resistance, vapour permeability, can be applied at low temperatures and also on wet surfaces. For historical masonry constructions lime-based mortars are preferred in case as they are more sustainable and compatible with the substrate (Felice, et al., 2014). The embedded fabrics typically form a grid with multifilament carbon, glass or steel yarns. Because of current sustainability reasons, natural fibers (flax, hemp and jute) have also been used as they are recyclable and have low specific weight (Ghiassi, et al., 2015).

The challenge in the use of these systems is that, there is not enough information about their structural performance and durability. These systems are widely used for seismic retrofitting of structures and the performance of strengthened masonry depends on the ultimate tensile strength (depends on fibre) and the substrate-reinforcement shear bond performance (which relies on the substrate, the matrix, and on fibre-matrix interaction). FRCM is also applicable where tensile failure of the textile is expected, like for confining columns/pillars and nodes or reinforcing extrados of arches/vaults. The EBR is used where bond failure is expected under shear stress like reinforcement of masonry walls (in-plane and out of- plane loads) and beams strengthening for bending and shear. The reinforcement is effective as long as the stresses are transferred from the structure to the textile. Some experimental results showed that the mortar can still provide effective load transfer between substrate and textile even after cracking (Ascione, et al., 2015).

Furthermore, the secant modulus of elasticity is generally close to that of the dry textile. If failure occurs without a proper debonding, either by sliding within the mortar (mode D) or by telescopic rupture of the textile, the maximum stress reached in shear bond tests is close to that of tensile tests on composite specimens. In these cases, the low exploitation ratio of the strength of the dry textile indicates that the mechanical properties of the fabric may not be fully exploited due to a poor textile-to-matrix bond. (Ascione, et al., 2015)

A recent research, developed in the Department of Civil Engineering of University of Aveiro (Portugal) investigated experimentally the behaviour of adobe masonry walls strengthened with a low cost technique based on a coating mortar reinforced with a low density plastic mesh (Figure 19). A real scale model was tested under cyclic horizontal loads before and after repair/strengthening. The test of the unreinforced model result in some damages easily repairable with injection of a hydraulic lime grout. In addition, the tested wall was strengthened with the reinforced coating. The strengthening solution was able to enhance the structural performance with improved stiffness and energy dissipation. Ductility and shear capacity also increased. No fragile ruptures were observed in the masonry after retrofitting which is a very common earthquake damage. The load capacity and maximum drift increased by 23.43 and 220 %, respectively (Figueiredo, et al., 2012).



(a) (b) (c)

Figure 19: Laboratory models (a) general scheme of the strengthening system (b) fixing with plastic plugs and (c) PVC beads and profiles *(Figueiredo, et al., 2012)*

Another study was presented at 9th international masonry conference at Guimaraes in 2014 about strengthening of masonry with Fibre Reinforced Geopolymer (FRGP). Basalt and ultrahigh strength steel fabrics were used to form FRGP. Reinforced geopolymeric matrix was made with metakaolin, activator and additives. The additives used were fine granulated sand, wollastonite and calcium carbonate at grain size of 0.1-0.6 mm, 0.05-0.45 mm and 0.05-0.60 mm, respectively. Two types of basalt and steel fabrics (Figure 20) were used (Garbin, et al., 2014).

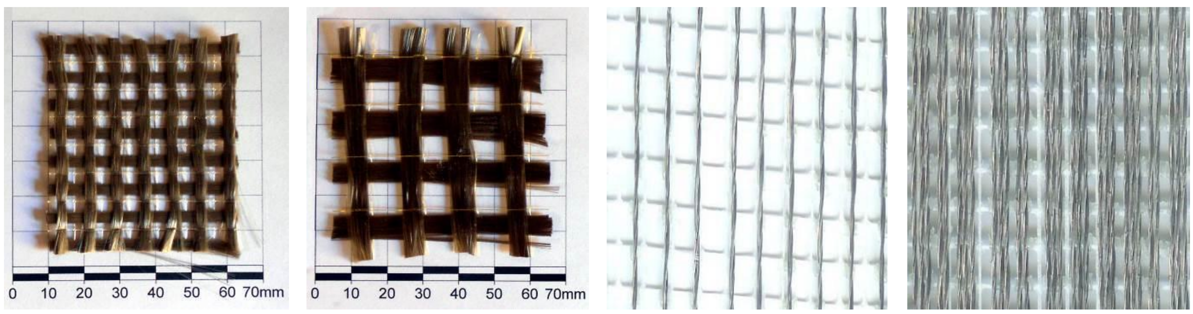


Figure 20: Basalt nets and high strength steel fabrics *(Garbin, et al., 2014)*

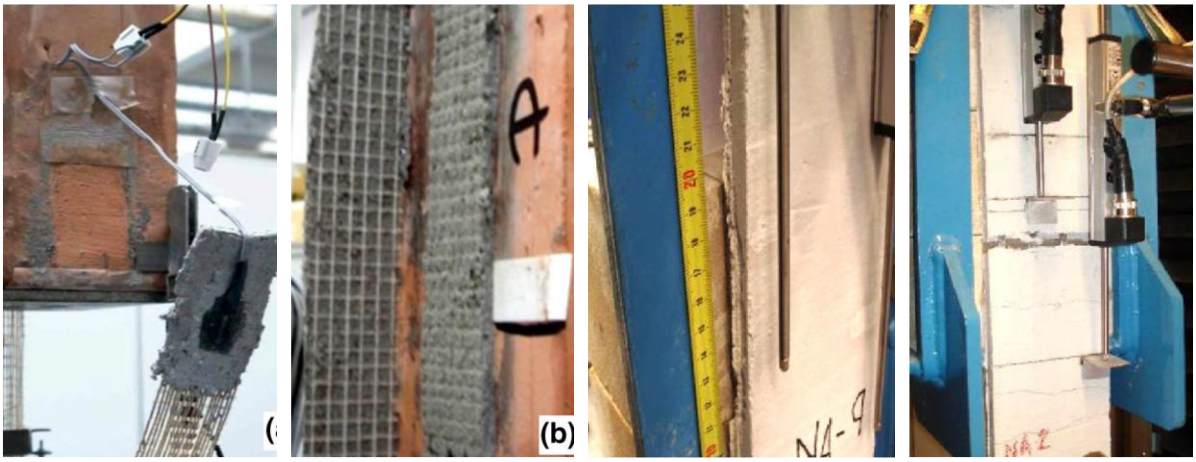
Mechanical tests, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were used to find physical and chemical properties of the reinforced/unreinforced geopolymeric mesh. Results found that geopolymeric meshes provide more heat-resistance than organic polymeric matrices and has potential to reduce CO_2 emission from 20 to 80%. Mechanical properties tested were similar in strength and stiffness. Direct pull-off test was performed in reinforced masonry with basalt net and steel (Figure 21). Further studies were carried out on FRGP, where the specimens showed good heat resistance (Garbin, et al., 2014).

(a) (b) (c)

Figure 21: Pull off test failures obtained for: (a) masonry reinforcement with basalt net 1; (b) basalt net 2 and (c) with steel fabrics *(Garbin, et al., 2014)*

In Textile Reinforced Concrete (TRC), matrices typically comprise high performance finely grained cement concrete and reinforcement textiles used are glass, carbon or aramid fibre. But to strengthen masonry, lime-based mortars are preferred to fulfil compatibility and reversibility requirements with steel cords, basalt and natural fibres as reinforcement. Fabric should provide sufficient interlocking with the matrices comprising fibrous textiles embedded in inorganic matrices. Another related research was carried out in 2014 with steel, carbon and basalt textiles used for Externally Bonded Reinforcement (EBR) of masonry, which were embedded in inorganic matrices. Following, the three composite systems were tested at three different laboratories - Steel Reinforced Grouts (SRG), Carbon Textile Reinforced Mortars (CTRM) and Basalt Textile Reinforced Mortars (BTRM) (Felice, et al., 2014). The matrices were based on cement, as well as, on lime based mortars.

The mechanical tests (tensile, bond, etc.) aimed at investigating the structural behaviour of such system following with standardizing the consistent test procedures. All three composite systems were characterised through direct unidirectional tensile tests. Three different stages (uncracked, crack-development and cracked) were shown by stress–strain relationships. Mortar matrix contributes in the first two stages, the stiffness and the ultimate tensile strength of the composites are close the textiles strength in the cracked stage. Results showed that the mechanical properties of mortar matrix and textile, textile layout, and substrate affects the tensile behaviour and the bond performance. The number of textile layers embedded in the mortar does not influence the ultimate tensile stress or Young’s modulus of BTRM. Weak textile-to-matrix bond cause stress concentration in CTRM which induces premature rupture due to non-uniform load distribution. On the contrary SRG showed non-linear behavior before failure. (Felice, et al., 2014)



(a) (b) (c) (d)

Figure 22: Failure modes in SRG specimens (a) debonding at the substrate-matrix interface in specimens with anchorage; (b) at the textile-matrix interface in specimens; (c) failure modes in BTRM specimens: debonding at the substrate-matrix interface in specimens (d) and slipping of the fibre rovings from the matrix in specimens *(Felice, et al., 2014)*

Bond tests for SRG, CTRM and BTRM showed three main failure modes (Figure 22) - mode 1: substrate-matrix interface debonding, mode 2: textile-matrix interface debonding and mode 3: fibre rovings slipping from the matrix. Mortar matrices of higher strength with stiffer textiles gave higher bond performances. Short anchorage lengths with SRG reinforcements led to failure according to mode 1, but long anchorage lengths of CTRM and BTRM showed failure to occur according to mode 2 and 3, as textile and matrix were interlocked. In Fibre-to-mortar, chemical bond and interlocking can prevent the sliding of the textile within the matrix. These matrix-to-textile bond behaviour and structural behaviour with meshes is still being studied within various researches. (Felice, et al., 2014)

The use of more sustainable materials for FRCM was also studied by Ghiassi et al. (2015). In this case the system was composed by natural fibers combined with matrixes based on lime-pozzolana and geopolymeric mortars. The tensile strength of the mortar increased with fiber reinforcement. Tensile cracks appeared in mortar first, eventually causing failure due to tensile rupture of the fibers. The pull-out tests showed that the effective bond length in the specimens with lime-based mortar is between 50 mm and 100 mm, although this value is less than 50 mm in case of geopolymeric-based mortar. The maximum pull-out force in the specimens was 1.26 kN for specimens with 100 mm bonded length embedded in lime-based mortar. (Ghiassi, et al., 2015)

2.5 Case studies on seismic strengthening solutions

Some solutions studied by the University of Kassel on RE and Catholic University of Peru (PUCP) on adobe have been used for the construction of earthquake resistant houses, after being observed good responses from full-scale shaking table tests. Some of these cases are presented below.

2.5.1 Internal reinforcement with bamboo grid

Reinforced RE low cost structures were built in 1978 after researches in University of Kassel. T-shape RE elements were reinforced with 4 vertical bamboo rods. The vertical rib stabilizes the element against horizontal forces as it acts like a buttress. The bamboo rods were fixed to the horizontal bamboo ring beam at the bottom with stretched vertical rods from the plinth (Figure 23). Rupture joints were made in the wall as vertical gaps (1-2cm) which can crack in earthquake allowing independent movements to absorb kinetic energy. The roof rests on vertical posts 50cm inside the walls to have independent movement. In earthquake prone zones, like Guatemala and Chile, roof structures houses were designed to rest on posts, separated from the walls. In Chile (1998) U and L shape wall elements were reinforced with vertical rods of colligue (similar to bamboo) as stated in Minke (2001).

(a) (b)

Figure 23:(a) 40cm high T shaped elements with 80cm length 30cm width and 14cm thick with bamboo reinforcement; (b) opening for windows *(Minke, 2001)*

(a) (b) (c)

Figure 24: Preparation of experimental models in laboratory (a) internal cane mesh reinforcement with horizontal placement; (b) external wire mesh reinforcement and (c) failure of the experimental model *(Blondet & Aguilar, 2007)*

2.5.2 External reinforcement with wire mesh

Adobe houses constructed in Peru (Figure 25) with wire mesh bands nailed on the walls and plastered with cement mortar could stand under moderate earthquakes. The models in experiments (Figure 24 (c)) showed increased strength but had brittle failure. Material cost is a big limitation for this system in Peru.

(a) (b)

Figure 25: Reinforced model after seismic test reinforced house after the 2001 earthquake Adobe buildings with external wire mesh reinforcement *(Blondet & Aguilar, 2007)*

2.5.3 External reinforcement with polymer mesh

A recent study at Catholic University of Peru (PUCP) was done to evaluate the response of polymer mesh in retrofitting historical earthen buildings avoiding brittle failure. Different amounts and types of polymer mesh were tested on five different full-scale adobe housing models with similar dimensions (Figure 26). Two types of polymer meshes were selected, namely an industrial geogrid and a cheaper plastic mesh.

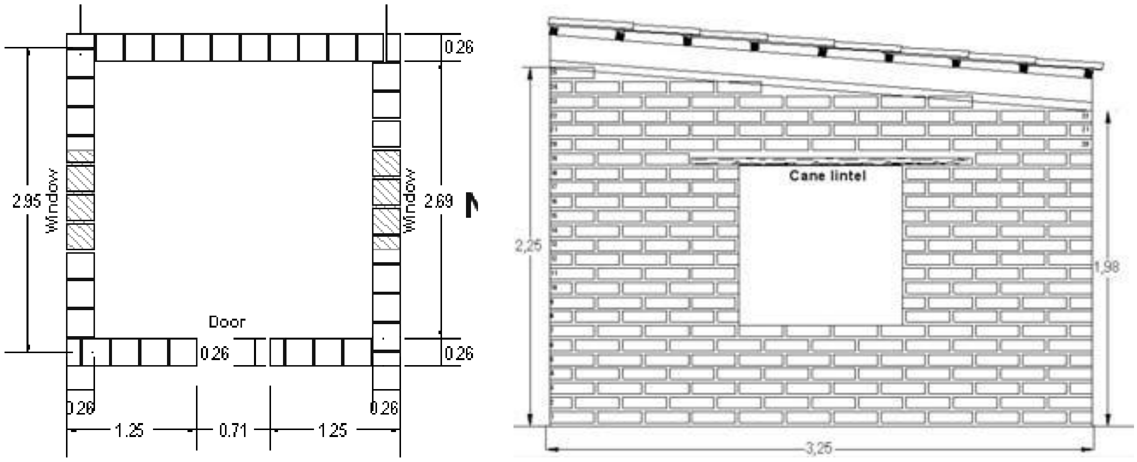


Figure 26: Drawings of the adobe models with 0.26m thick walls 3.21m long four walls *(Blondet, et al., 2006)*

These meshes should be tightly connected and tied on both sides of the walls with mud stucco plaster. The plaster increases the shear strength and the stiffness of the walls along with mesh protection from UV rays. Results showed that amount of damage on the walls increased with polymer mesh of reduced quality. For economic reasons, it is ok not to cover the full wall with mesh, placing the mesh in critical locations can prevent total collapse (Figure 27 (b)). The mesh starts working after cracking of the walls. However, further research is required to develop simple reinforcement systems and defining the ideal amount and placement of the mesh (Blondet, et al., 2006)

(a) (b)

Figure 27: Construction of the real scale house models in the laboratory (a) unreinforced model and (b) external geogrid mesh reinforcement with 75% *(Blondet, et al., 2006)*

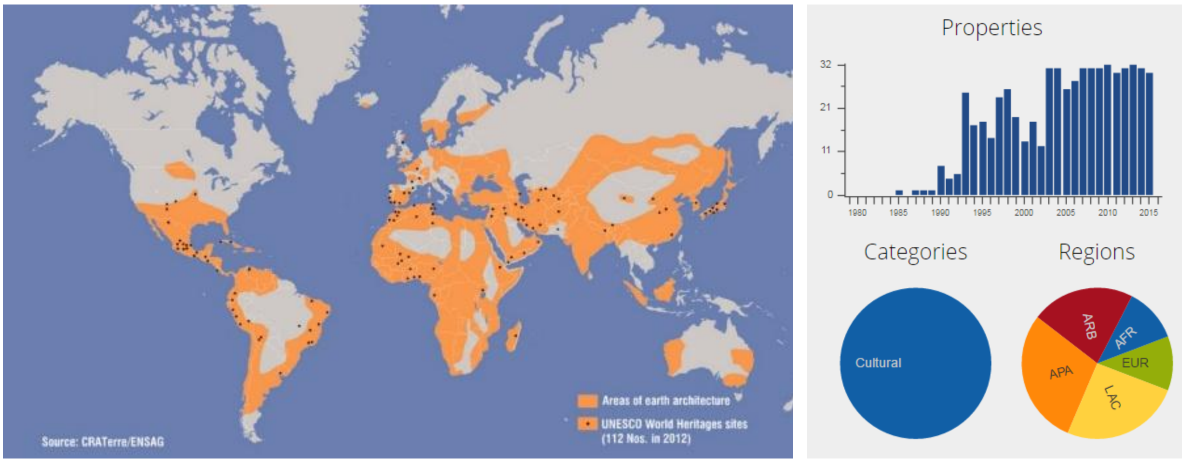
(a) (b)

Figure 28: Real scale adobe model (a) with plastic mesh reinforcement and (b) laboratory experiment *(Blondet, et al., 2006)*

3. CONSIDERATIONS ON THE USE OF FRCM IN RE

3.1 Introduction

In the modern scenario with contemporary construction, the increasing threat to the built heritage, the traditional art and architectural technology has been fading drastically. The preservation and conservation of earthen heritage is not only important from the perspective of keeping the technology known but also to keep the record of what is inherited from our rich past to be able to contribute to the future researches and keeping the knowledge alive. Today 40 % of the world population lives in earthen dwellings. 17 % of the world cultural heritage sites is built with earth (Statistics from UNCHS). About one fourth of the sites inscribed on the World Heritage List in danger are earthen sites (AEI, 2016).



(a) (b)

Figure 29: State of UNESCO World Heritage sites (a*)* earth construction areas all around the world with UNESCO listed sites *(AEI, 2016)* and (b) statistics of endangered earthen sites over last 30 years *(UNESCO, n.d.)*

The threats to earthen heritage identified by UNESCO (Figure 29) include management issues, deliberate destruction of heritage, illegal activities, impacts of tourism, natural disasters including earthquakes, floods, storms, wildfires, volcanic eruptions and other climate change impacts, etc. There are 21 sites listed as at risk due to seismic activity in countries like Azerbaijan, Ecuador, El Salvador, Ethiopia, Guatemala Iran (Islamic Republic of), Japan, Mexico, Nepal and Uzbekistan (UNESCO, n.d.). Apart from these UNESCO world heritages listed sites there are several heritage structures all around the world which are damaged and need conservation strategies, urgent interventions against natural disasters, such as earthquakes, or a comprehensive management plan.

In the late 20th century, preservation of earthen architecture has grown enormously, demonstrated by the increase in number of international conferences, training initiatives, and the formation of national and international committees dedicated to the subject of earthen architecture conservation. For instance, the very first conference of the Terra series was held in Iran in 1972 and this series still continues until the present. With the increased necessity and inclination in the subject, architects, conservation practitioners, structural engineers and researchers have integrated for the cause, since safeguarding the traditional construction techniques is a prerequisite (Jaquin, 2011). Each earth construction technique requires different approaches for conservation and strengthening interventions. RE conservation and strengthening works have attracted many multidisciplinary practioners as it poses high complexity compared to wattle-and-daub, adobe or cob. The current works and the scientific committees involved, are discussed in the chapter.

3.2 International scientific committees

There are many scientific committees and organisations all around the world taking care of the conservation of earthen building also providing funds for the preservation work of protected structures. Due to the insufficient funding, emphasis is particularly given to the endangered built heritage, while other heritage and vernacular buildings are still struggling to survive. In 1983, the Peruvian discussion about this topic led to some recommendations and establishment of networks and intensive training in earthquake-resistant structures. ICCROM and CRATerre/EAG planned to carry out training courses within the Gaia Project in 1987, Italy (Correia & Fernandes, 2006)

The first Pan-American course on the Conservation and Management of Earthen Architectural and Archaeological Heritage was held in November 1997 (PAT96), where collaborated the International Centre for Earth Construction, School of Architecture of Grenoble (CRATerre-EAG), the Getty Conservation Institute (GCI), and the International Centre for the Study of the Preservation and the Restoration of Cultural Property (ICCROM). This event established a joint program in the study and conservation of earthen architecture. These aforementioned organizations and some more like UNESCO, ICOMOS, ISCEAH, Earth Conservation Committee and some Japanese and German foundations work independently or collectively on the principles of conservation and restoration of historic structures according to Venice Charter (1964). With many scientific events and development of these institutions, have been created frameworks to promote the studies, research and work for conservation of earthen architectural heritage worldwide (Getty, 2016).

ISCEAH (International Committee on Earthen Architectural Heritage) operates under the principles and ethics of ICOMOS aiming at developing better practices and methods for the protection and conservation of earthen heritage. It involves and encourages the participation of people who play important roles in contributing to the earthen architectural, archaeological and cultural landscape heritage. in accordance with principles many master masons and earth crafts persons get to participate within the Committee at several levels.

The objectives of the scientific program of ISCEAH are focused on the following broad themes: conserving and studying the architectural heritage in use or not in use; studying the earthen archaeological environment; researching the contribution of earthen architectural heritage to cultural landscapes and its relation to the intangible heritage and also the impact on new earthen constructions and researching historic/vernacular a-seismic techniques and using them along with the current research in retrofitting of the existing structures (ISCEAH, 2016).

As part of an EU-funded project, a map of earthen heritage in the European Union was published in 2011 (Figure 30), showing the different earth building techniques. Various inventories were done in these regions. World Monument Fund (WMF) also has a list of threatened architectural monuments, which aimed at publishing vulnerable conditions and at finding sponsors for urgent stabilization work (Anon., n.d.). The NIKER project in Europe (New Integrated Knowledge based approaches to the integrated protection of cultural heritage from Earthquake-induced Risk) also aimed at developing integrated solutions to safeguard the tangible and intangible heritage. Some of the partners were also concentrated on the studies regarding seismic behaviour of RE structures.

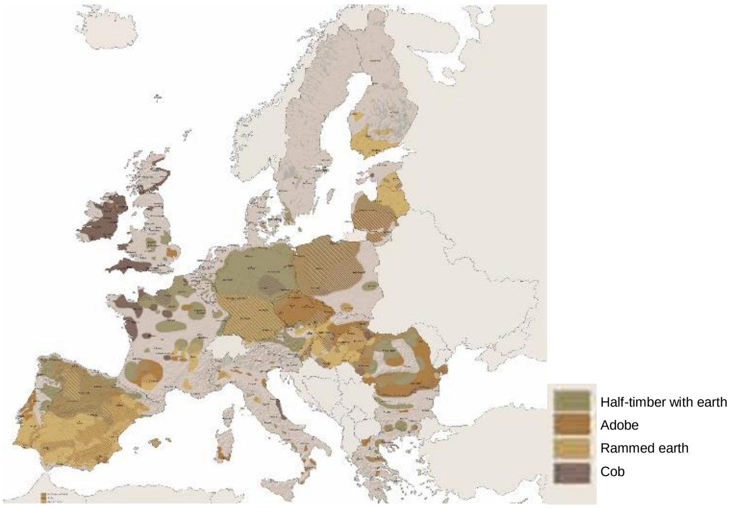


Figure 30: Map of Earthen heritage at Europe in 2011 *(Incognita, 2016)*

Currently, the fourth phase (2007-2017) project World Heritage Programme on Earthen Architecture (WHEAP) is working towards improving the state of conservation and management of earthen sites worldwide with the development of policies, spreading awareness in local communities through training workshops, exhibitions, conferences and technical publications to bring the subject on global platform, creating a network to exchange the information and experience. (UNESCO, n.d.). The first international conference on RE construction was organised by the University of Western Australia in February 2015 which discussed the recent researches and current issues experienced by different countries. Priority research topics discussed were thermal assessment and insulated rammed earth walls. The issues raised were about the lack or absence of principles, standards and protocols for the rammed constructions (Ciancio, et al., 2015)

Apart from the international bodies working on the conservation principles, many countries have developed standards for investigation procedures and seismic retrofitting codes for earthen constructions. There are many non-engineered traditional constructions being built following 'rules of thumb' and 'guidelines' regardless of applicable codes in many countries.

'*The lack of a code is acting as a barrier to rammed earth construction*' (Sethna, 2008). *'We can't offer mud rammed structures to clients since there is no code.'* (Langenbach, 2010)

These statements emphasise the issues with modern RE construction, being evident the current despair regarding RE construction in the modern engineering curriculum and construction fraternity (Langenbach, 2010). These challenges, namely the absence of construction codes and seismic retrofitting principles, leave each professional with a responsibility to develop methodologies and to overcome the global crisis in earthen construction.

3.3 General principles for conservation

Heritage structures poses various challenges in diagnosis and restoration due to their construction techniques and use material. In this case many times it is difficult to apply modern building codes and standards. ICOMOS charter presents principles for the analysis, conservation and structural restoration of architectural heritage. Some of the conservation principles are summarised here (ICOMOS, 2003). The recommendations include the principles, which presents the basic concepts of conservation and the guidelines which are the rules and methodology followed for the conservation or structural restoration.

3.3.1 General criteria

In order to achieve an ingenious method in conservation, reinforcement and restoration of architectural heritage, an interdisciplinary approach should be taken towards the building conservation. This requires effective confluence of art, history, architecture and engineering. With this consortium a systematic approach or methodology should be outlined which can predict the service life of the building and ensure its functionality and strength.

The heritage value and authenticity of historic buildings is not only based on its appearance, but also in the architectural style, integrity of its components, usage, and building technology of its time.

3.3.2 Researches and diagnosis

The primary research comprises study and investigation of historic remains, data collection and research of the historical layer, literature study on the area, the site, architectural features, methodology of construction and materials used with photographic research. The process should indicate the chronological development of the structure clearly

Condition assessment to analyse the deterioration and distress in the building with mapping current state of the building through visual inspections supported by drawings labelled with the various level of damage and deterioration. Research and investigations are carried out with the object of identifying the values and risks to the various parts of the structure. A detailed risk and value based assessment framework can provide comprehensive guidelines for conservation of the specified historic building.

Data collected with the primary historic research, architectural documentation and condition mapping can be used for the structural and risk assessment. The assessment should indicate the different types of deterioration and probable causes to evaluate the safety level and the health of the structure. Studies, knowledge and diagnosis of the historic buildings can guide in planning out the possible repair, strengthening and intervention techniques in the project depending upon the heritage value of the structure.

3.3.3 Remedial measures

Interventions should address the root causes and actions should guarantee safety and durability without harming the heritage value of the structure. New/modern materials used for restoration should be compatible with the historic material and durable avoiding adverse effects. Minimum level of intervention should be planned adopting reversibility meaning the intervention should be flexible to be replaced with more suitable measures when new research is developed.

The integrity and authenticity of the structure and its surroundings should not be hampered with the intervention. There should be evidences of restoration work which can be recognised in the future. Imperfections from the history and later additions should be kept intact as they hold the historic value. Control measures and careful planning should be taken during execution with structural monitoring during and after the intervention. Data should be kept for future references.

3.4 Compatibility concerns of FRCM

In the application of FRCM as a strengthening solution for RE construction, the use of low cost meshes and modern mortars are very debatable topics. Questions regarding non compatibility of materials being used for historic preservation can arise. The use of cement mortar can be harmful as it is impervious and going to block the breathing of the RE wall. Measures will have to be taken to keep the wall away from water seepage inside and moisture intake as cement coating is not going to let it escape. Secondly are the objections about keeping the integrity and authenticity of the structure. In the case of unplastered RE, stabilised mortars coatings on the façade may change the appearance of the building. In the case of plastered RE, it is not going to have much impact if a material similar in properties and appearance is used.

Thirdly, it is questionable if the proposed system is effective and functional. The bond interface between the materials applied in different time periods may not be effective. Over the time historic RE acquires different properties than new earthen materials. Questions about the performances of both are raised, as both should have similar properties and perform together to withstand the vibration induced by an earthquake. If the historic RE and modern materials are not having similar movement behaviour, the system might not be effective. To understand this problem, the research needs to be addressed to the bond interaction between the coatings and the historic RE walls.

Very limited literature is available on the repair and conservation of rammed earth structures, as it is a very recent field of study. RE being monolithic earth construction technique is difficult and requires deep knowledge for conservation works. RE is more difficult to repair than mud brick, as Feilden states (2003). It is difficult to bond the old and new material, due to shrinkage issues. Furthermore, the materials and mixtures used are affected by inconsistent variations in terms of quality (Correia & Fernandes, 2006). Environmental conditions and state of the structures can also accelerate the deterioration if not maintained. In the present context for the retrofitting proposal, the conservation could be difficult, since most of the buildings are habitable spaces. The work should always be planned thoroughly in these situations.

3.5 Materials for FRCM in RE

The FRCM composite mix requires two materials- meshes and mortar matrices. The selection of both materials for reinforcement of RE should be on the basis of guidelines and principles of ICOMOS. It should be compatible with the original material and should not cause any adverse effect. For RE the earth mortars and lime mortars have been widely used for the repair and conservation works of RE. Hence it will be the best suited for FRCM as these mortars being porous in nature conforms with the material and structural properties of RE.

Regarding the meshes, there is no mention for the seismic retrofitting of RE with FRCM (fibre reinforced cementitious matrix), reference can be drawn from other earthen structures. Steel meshes were used in Hacicnda de los Quintos, Spain, in order to reinforce the load bearing wall which had high vertical loads. The reinforcement increased the compressive strength and was done in both side of the wall. The meshes were stitched together with bars through the thickness of the wall. But this has no information about the seismic performance of the structure (Mileto, et al., 2012).

Many examples and researches of mesh reinforcement can be found in masonry constructions. This kind of retrofitting holds the masonry components into a single unit and prevents the collapse. The possible materials could be steel cage, polymer, polypropylene band (PP-band mesh), bamboo meshes and plastic carrier bags. The possible materials which could be used are steel, industrial geo-grid and bamboo are difficult in application as they lack in flexibility. But soft polymer, PP-band and plastic carrier bag can be deformed easily and make the application easy (Navaratnarajah, 2015).

RE has high water absorption capacity, hence meshes should be corrosion resistant. Workmanship with some materials can be a challenge in the application of FRCM strengthening technique for seismic stability. The selection of the particular mesh type for FRCM should consider availability of the material and cost effectiveness along with the structural properties and performance. It should be flexible to provide easy installation. Mesh surface should be unpolished or rough to provide a good grip with mortars. The mesh thickness should be appropriate to be able to apply the plaster without difficulty. (Navaratnarajah, 2015).

4. CHARACTERISATION OF THE RAW MATERIALS

4.1 Introduction

The selection of materials used in the experimental program was done keeping in mind the criteria for material compatibility in repairing historic buildings. For reinforced coatings in RE two materials are needed i.e. mortars and meshes. As for RE structures, the compatibility of course is a major issue, so recommended material for strengthening and repair works in earth structure is earth-based mortars. Regardless of the increasing interest and need for earth-based repair materials, there has been no standards for these mortars. Only German standard DIN 18947 (DIN, 2013) was established recently regarding the assessment of mechanical and physical properties of earth mortars. With its low embodied energy earth mortars and plasters lower the ozone concentrations since clay acts as a passive removal material (PRM). It is also used for indoor plastering as it contributes to sustainability and it can be produced without addition of any chemical stabilizer (Lima & Faria, n.d.).

Different types of earth mortars can be used for conservation works – specifically designed mortars and premixed mortars available in the market and produced according to industrialized processes. Other possibility is to reuse mortar salvaged from demolished structures and sites, cleaned and prepared to get required consistency. As previously discussed externally bonded reinforcement can be done with modern or traditional mortar as far as it does not compromise with the compatibility of the material. Following the protocols and the advantages, the intention was to use a traditional earth mortar for the current experimental work but because of the time constrains and material availability a commercial earth mortar was procured from local manufacturer, called M2. The other mortar taken was a modern cement mortar called M1, comprising natural cement, hydraulic lime and sand, which were also procured from local manufacturers. Cement mortars are widely used for repair works in earth constructions without following any compatibility concerns, this work intends to show some comparative results in terms of compatibility with earth structures.

Despite of the existence of a few standards available for earth mortars, there is lack in principles and information for reinforcing meshes. Considering this fact meshes were selected according to their easy availability and economy. Some varieties of meshes were bought from the local market including plastic and metallic meshes. This chapter presents the characterisation of material for both the mortars and meshes which were tested with different standard procedures. Particle size distribution or granulometry was done finding the fractions of the material content of earth mortar and sand in cement mortar. The workability of the mortars in fresh state was identified with flow table test and used for establishing the Water/Solids ratio (W/S) for casting the specimens.

4.2 Characterisation of rammed earth

The RE earth wallet used in the experimental program was compacted using the corrected soil resulting from past experimental research at University of Minho. There are many standards and guidelines defining soil specifications depending on the source. Not all soils are suitable for producing RE. Every standard gives importance to different properties of soil due to its inhomogeneous behaviour. The following properties and test results are extracted from the previous works at UMinho. Various soils were tested for mechanical properties and finally the corrected/stabilised soil complying with the standards was named as S6 and used for RE specimens. Test results for granolumetry, compressive strength, Young modulus, plasticity and proctor compaction test are presented here for the selected soil S6.

4.2.1 Granulometry

The soil S6 was characterized using dry sieving method for the fractions coarser than 0.075 mm and sedimentation to define the fine fractions less than 0.075 mm using the LNEC Specifications E196 *(LNEC, 1966)*. The PSD curve obtained for the soil S6 granulometry is similar to that of RE recommended in the German standards (Figure 31). The soil S6 was corrected with two types of the soil S4 and S5. The PSD results are presented in Table 2. The comparative results of PSD curve of S4, S5 and S6 are shown in the Figure 32.

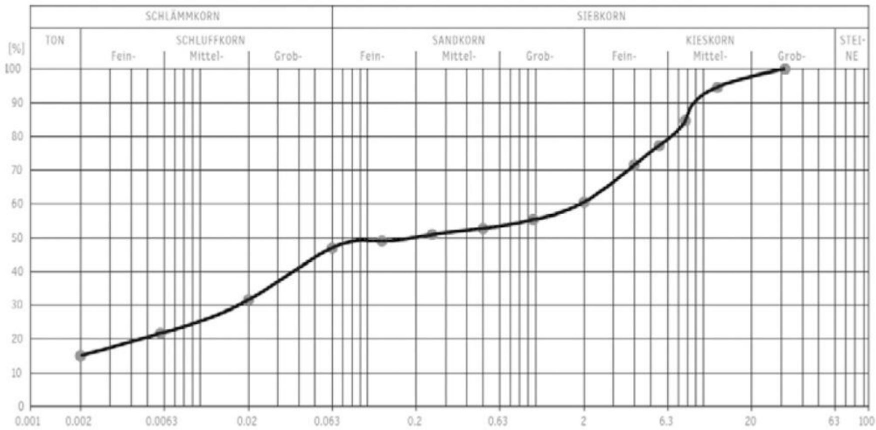


Figure 31: Optimal PSD curve for RE recommended by the German Code *(Röhlen & Ziegert, 2014)*

Table 2: PSD of soil S6 compared with the German recommendations for rammed earth (Silva, 2013)

Soil type	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Cobble (%)
Soil S6	14	16	32	37	1
German Code	15	30	15	40	0

Clay < 0.002 mm; 0.002 mm ≤ silt < 0.063 mm; 0.063 mm ≤ sand < 2.0 mm

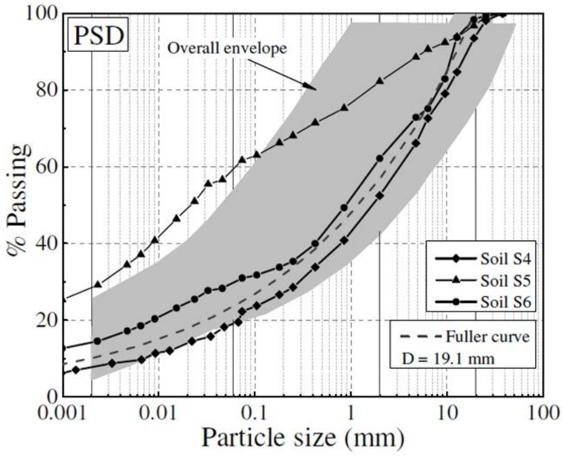


Figure 32: PSD curve of the soil S6 (corrected with soil S5 and S4 types) *(Silva, 2013)*

4.2.2 Plasticity

The ability of a soil to deform while resisting an increasing load in presence of moisture, is called Plasticity. Soil plasticity is indicated with the Plasticity Index '*PI*', which is the range of water contents where the soil exhibits plastic properties. PI is derived from Atterberg limits (Liquid Limit '*LL*'; Plastic Limit '*PL*' and Shrinkage limit '*SL*') with the formula *PI = LL – PL*. Soil changes its behaviour from semi-solid to plastic and from plastic to liquid at *PL* and *LL*, respectively. In the *PI* range of moisture soil remains plastic; soils with a high *PI* are considered to be clay, and low *PI* values are typical of silty and sandy soils. The soils where the *PL* cannot be determined or is equal to the *LL* are considered non-plastic. Therefore, higher plasticity index is indicative of higher clay content and its value is directly correlated with properties such as the shrinkage of material after drying (Gomes, et al., 2014).

For the selected soil S6, the test was conducted according to ISO 17892 (ISO, 2004) and the liquid limit and plastic limit were determined in laboratory using the Casagrande shell method and thread-rolling test respectively. Table 3 and the graph (Figure 33) show the results and low index of plasticity. Hence the consistency is outside the recommended parameters due to a low content of clays. Considering these values, the soil S6 is classified as a Sandy Low Plasticity Clay saCll (ISO, 2013).

Table 3: Atterberg limits of soil S6 (Silva, 2013) and recommended values

	Liquid Limit W_L (%)	Plastic Limit W_P (%)	I_P (%)	Classification (ISO)
Soil S6	23	16	7	saCll
Recommended (Houben & Guillaud, 1989)	30-35	12-22	18-13	-

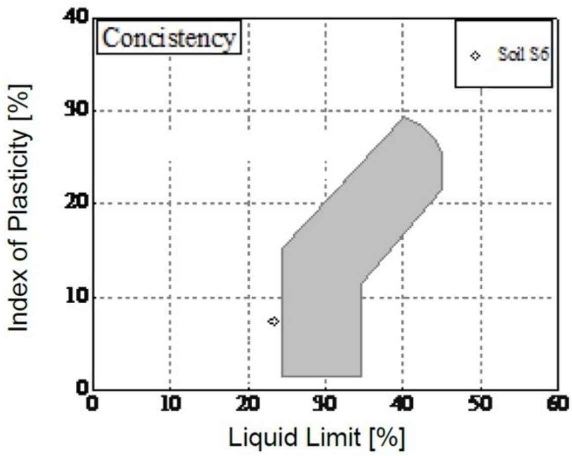


Figure 33: Consistency of soil compared with recommended ranges of values *(Silva, 2013)*

4.2.3 Proctor compaction test

The Proctor test is a laboratory test method for determining the optimal moisture content at which a given soil will achieve its maximum dry density. It consists of compacting soil at known moisture content into a cylindrical mould of standard dimensions in certain amount of layers, each receiving a compaction by a hammer at a specified height. This process is repeated for various moisture contents and the dry densities are determined for each. The dry density, depends on the soil type, the moisture content during the compaction process, and the energy of compaction.

The test was performed according to standard DIN 18127 (DIN, 2012). Both Proctor and drop tests gave similar results for the water content in soil S6 and shown in Table 4 and compared with the values recommended by Houben & Guillaud (1989). The graphical relationship of the dry density with moisture content is used to establish the compaction curve (Figure 34). The peak point of the compaction curve gives the maximum dry density (ρ_{max}) and its corresponding moisture content is called the optimal water content (OWC) for a given compaction energy (Dominguez, 2015).

Table 4: Compaction properties of soil S6 (Silva, 2013) and recommended values.

	Density ρ_{max} (g/cm^3)	Optimal water content OWC (%)	Drop Test Water Content DTWC (%)
Soil S6	2.10	10.1	9.7
Recommended values (Houben & Guillaud, 1989)	1.8-2	5-15	-

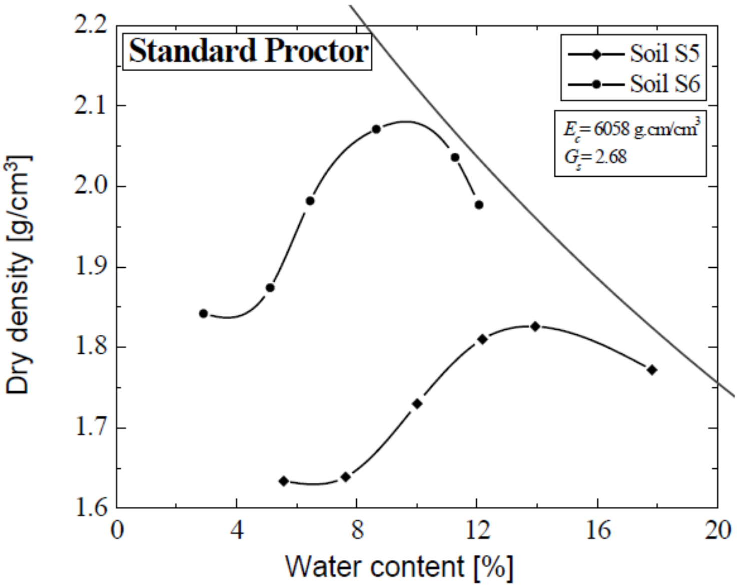


Figure 34: Compaction curve of soils S6 *(Silva, 2013)*

4.3 Characterisation of mortars

4.3.1 Granulometry

1. Characterization of cement mortar M1

The first mortar chosen was cement mortar which consisted of cement: hydraulic lime: sand in the proportions 1:0.47:9.67 (in weight), respectively (Figure 35). This composition resulted from the conversion of the typical composition of 1:1:6 (in volume) used for plastering works in current constructions. All three components were obtained from a local supplier.

Figure 35: Cement, hydraulic lime and sand used to manufacture mortar M1.

The cement and hydraulic lime were manufactured by CIMPOR, where the cement corresponds to a CEM II/B-L 32.5 N and the hydraulic lime to a HL 5. The sand was provided by Soargila company and its particle size distribution was characterized according to LNEC specification E196 (LNEC, 1966). Figure 36 illustrates the testing procedure used for the dry sieving of the sand.

(a) (b) (c)

Figure 36: Dry sieving of sand (a) total mass of the sand taken for sieving; (b) vibration for 10 minutes and (c) particles size distribution of the sand in M1

Table 5 present the results of dry sieving test of the sand and the resultant PSD curve is shown in Figure 37.

Table 5: PSD of mortar M1 obtained from dry sieving.

Sieves		Measured quantity (g)	Percentage (%)
No.	mm		
20	0.85	0.29	0.1
40	0.425	55.25	25.3
60	0.250	142.02	65
80	0.18	15.87	7.3
140	0.106	2.73	1.2
200	0.075	0.24	0.1
Rest		2.1	1

Clay < 0.002 mm; 0.002 mm ≤ silt < 0.063 mm; 0.063 mm ≤ sand < 2.0 mm

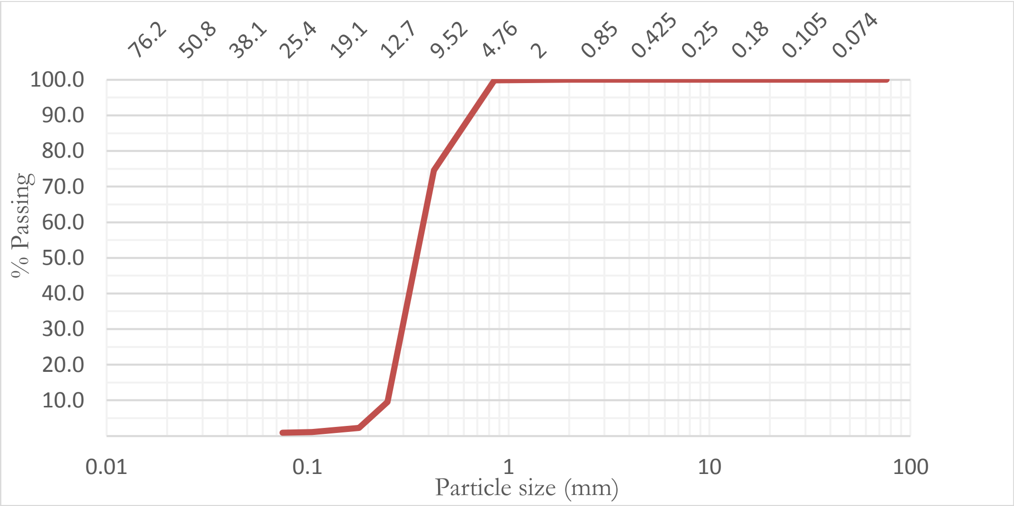


Figure 37: PSD curve of the sand for M1

2. Characterisation of earth mortar M2

A commercial earth mortar was taken as mortar M2, which was provided by a local manufacturer in Portugal. The mortar is ready to mix and can be mixed manually or using a mixer as given in the technical sheet. It consists of a clay-sand (0-2mm) mix with oat straw with length shorter than 10mm. Furthermore, it does not include any additional binder in its composition. The density specified by the manufacturer for the harden mortar is approximately 1800 kg/m^3. The product is typically provided in big bags of 1000kg. The manufacturer specifies to add approximately 20% of water to prepare the mixture. The recommendations given from the company are in accordance with the experience of earth material in plastering the buildings.

The PSD of the material was done following the methods indicated in LNEC Specifications E196. The method follows wet sieving of the coarse fraction (sand) and sedimentation of the fine fraction (silt and clay). The recommended particle size passing through sieve No. 10 (2mm) should be around 115 gm and 65gm for sandy soils and silty/clay soils respectively. Hence, a sample of mass 60.2 g was taken. Wet sieving involves washing the material through the 2 mm sieve, passed material is mixed with a dispersing agent to disaggregate the particles. The suspension is washed through a 0.075 mm sieve (ASTM sieve No. 200) after one hour and the retained material is oven dried and then dry-sieved. Whereas the distribution of particle sizes <0.075 is determined by a sedimentation process. Figure 38 shows the fraction separated by dry sieving and Table 6 shows percentage of the separated fractions through different sieve sizes.

(a) (b)

Figure 38: Dry sieving of earth mortar M2 (a) total mass taken and (b) fractions divided with different size sieves.

Table 6: PSD measurement for Earth mortar M2 particles with dry sieving

Sieves		Measured quantity (g)	Percentage %
No.	mm		
20	0.85	4.4	7.3
40	0.425	14.1	23.4
60	0.250	17.4	28.9
80	0.18	5.6	9.3
140	0.106	5.1	5.5
200	0.075	1.1	1.2

[2] Clay < 0.002 mm; 0.002 mm ≤ silt < 0.063 mm; 0.063 mm ≤ sand < 2.0 mm

Sedimentation consists of measuring of density of the suspension at different intervals, using a hydrometer and checking the temperature variations. Figure 39 shows the different steps involved in the procedure of sedimentation.

(a) (b) (c) (d)

Figure 39: Granulometry with sedimentation procedure; (a) heating; (b) sieving; (c) measurement of the suspension density and (d) measurement of temperature after 48 hours.

Table 7 shows the measurements of density and temperature and the resultant PSD curve is presented in Figure 40. The results show the presence of clay, silt and sand is 10%, 10% and 80%, respectively. The graph can be compared with the ones of RE soil and sand, hence it can be concluded that it is similar to PSD graph of sand (Figure 37). The earth mortar M2 has less clay content and has coarser particles of varying sizes as it also appears visually and with the texture.

Table 7: PSD measurement for earth mortar M2, obtained from the sedimentation test.

t (min)	T (ºC)	L (*)	Z (cm) **	D=K*SQRT(Z/t) (mm)	Total passed %
0.5	24.6	1.008	15.3	0.0554	16.59
1	24.6	1.008	15.56	0.03918	16.59
2	24.6	1.007	15.56	0.02794	13.93
5	24.6	1.007	15.56	0.01767	13.93
15	24.6	1.007	15.56	0.0102	13.77
30	23.8	1.065	15.69	0.00724	12.17
60	23.4	1.006	15.82	0.00514	10.62
250	22.5	1.006	15.82	0.00252	10.14
1440	21.5	1.005	16.08	0.00106	6.94
2880	21	1.005	16.08	0.00075	6.67

*Reading in the hydrometer ** Position of the centre of gravity of the hydrometer

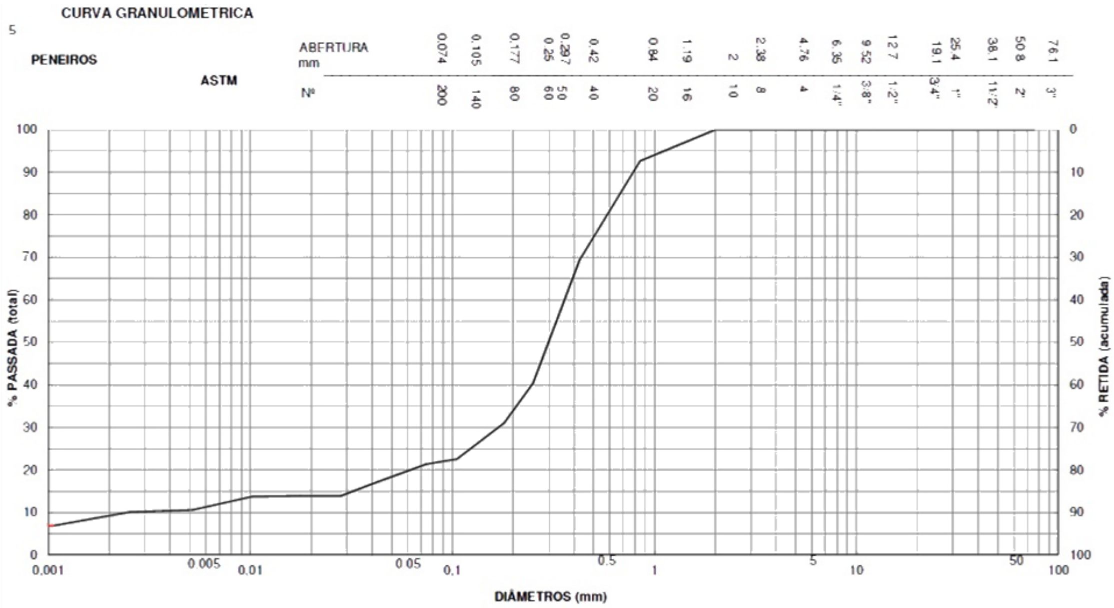


Figure 40: PSD curve of the earth mortar M2.

4.3.2 Bulk density

The bulk density of the raw materials composing the mortar M1 is parameter required to convert its composition in volume into weight. On the construction site, workers typically use compositions in volume, since they are more easily prepared, by not requiring using a scale. The European Standard NP EN 1097-3 (EN1097-3, 2002) is a procedure to determine the loose bulk density and voids of dry materials. The dry mass of aggregates filling a specified container is determined by weighing and the corresponding loose bulk density is calculated. The percentage of voids is calculated from the loose bulk density and the particle density.

(a) (b)

Figure 41: Mass of the material weighed in 1000ml container for (a) sand and (b) cement

A clean container is taken followed by weighing it. The container is filled with the material with a shovel to overflowing (Figure 41). The excess material is removed and the surface is flattened with a ruler. The full container is weighed. The procedure is repeated with 3 samples.

Table 8: Calculation of bulk density of sand for cement mortar M1 using EN 1097-3.

Sand	Mass of empty container m_1 (gm)	Mass of container with specimen m_2 (gm)	Mass of specimen $M = m_2 - m_1$ (gm)	Container capacity V (cm³)	Apparent density $\rho = \frac{M}{V}$
	1173.2	2709.4	1536.2	1000	1.536
	1173.3	2714.2	1540.9		1.541
	1173.2	2711.5	1538.3		1.538
Average					1.538
CoV (%)					0.15%

Table 9: Calculation of bulk density of lime for cement mortar M1 using EN 1097-3.

Lime	Mass of empty container m_1 (gm)	Mass of container with specimen m_2 (gm)	Mass of specimen $M = m_2 - m_1$ (gm)	Container capacity V (cm³)	Apparent density $\rho = \frac{M}{V}$
	1173.4	1924.7	751.3	1000	0.751
	1173.3	1925.1	751.8		0.752
	1173.2	1925.6	752.4		0.752
Average					0.752
CoV (%)					0.07%

Table 10: Calculation of bulk density of cement for cement mortar M1 using EN 1097-3.

Cement	Mass of empty container m_1 (gm)	Mass of container with specimen m_2 (gm)	Mass of specimen $M = m_2 - m_1$ (gm)	Container capacity V (cm³)	Apparent density $\rho = \frac{M}{V}$
	1173.3	2130.7	957.4	1000	0.9574
	1173.3	2129.3	956		0.956
	1173.3	2132.6	959.3		0.9593
Average					0.958
CoV (%)					0.17%

Table 8, Table 10 and Table 12 show the calculation for bulk/apparent densities for the raw materials comprising cement mortar M1 and earth mortar M2 respectively. Bulk /apparent densities obtained for sand, lime and cement obtained are 1.54 g/cm^3, 0.75 g/cm^3 and 0.96 g/cm^3 respectively. The values can be compared to typical values, namely 1.45-1.65 g/cm^3, 0.561 g/cm^3 and 1.506 g/cm^3 respectively. (Powderhandling, n.d.). Table 11 shows the calculation for the composition of materials in cement mortar M1 in weight from the composition in volume.

Table 11: Calculation for the proportion of materials in cement mortar M1

	Cement	Hydraulic Lime	Sand
Composition in volume	1	1	6
Composition in weight	1	0.79	9.64
Binder-Aggregate ratio	1	5.40	

Table 12: Calculation of bulk density of earth mortar/M2 using EN 1097-3

Earth mortar/M2	Mass of empty container m_1 (gm)	Mass of container with specimen m_2 (gm)	Mass of specimen $M = m_2 - m_1$ (gm)	Container capacity V (cm^3)	Apparent density $\rho = \frac{M}{V}$
	1173.3	2623.5	1450.2	1000	1.4502
	1173.2	2628.2	1455		1.455
	1173.2	2634.8	1461.6		1.4616
Average					1.455
CoV (%)					0.39

4.3.3 Flow consistency and workability

With the bulk density procedure, the volumetric proportions and the composition of mortar M1 in weight was formulated. To attain required performance characteristics, flow table test was performed in fresh state of mortars according to EN 1015-3. It determines flow consistency, which is a measure of the fluidity/wetness of the fresh mortar. It gives a measure of the deformability of the fresh mortar when subjected to stress. (EN:1015-3, 1999).

Preparation of mortars mixtures was done as given in the standard EN 1015-3 with some alterations as earth mortars are not included. A material mass of 1500 g was taken and mixed with different water ratios for 5 samples. The mixture was prepared in a mechanical mixer with a stainless steel vat of 3l capacity. The calculated water content and material was put in the clean apparatus and gently stirred by hand for 1 minute using a palette knife to homogenize the material. The mixing was done at a constant slow speed with paddle mixer driven by an electric motor for 90 seconds, pause of 90 seconds (removing the adhering mortar from the vat with a spatula and adding to the mixture) and again mixing for 60 seconds.

(a) (b) (c)

Figure 42: Flow table test for cement mortar M1 (a) fresh mortar placed in the mould; (b) and (c) difference in diameters of spread mortar with different water content

The fresh mortar was placed in the lubricated mould on the disc of the flow table. The mortar was introduced in two layers with tampering each layer by a piston for 10 strokes. Excess mortar was removed flattening the surface with a palette knife. The disc was jolted for 15 times, at a rate of one per second and the mould was removed. The measurement of the diameter of the spread mortar was taken in two directions using callipers. The results were noted in mm. The flow value is measured by the mean of these diameter readings. Figures 42 and 43 show the different steps in the flow table test for both the mortars.

(a) (b) (c)

Figure 43: Flow table tests of mortar M2 (a) mixture with given moisture content of 20%, showing water excess; (b) mould before and (c) after jolting spread

The procedure was repeated 5 times increasing/decreasing water content to get the desired flow i.e. between 160mm-176mm is considered as great and between 152 -177 is good (Gomes, et al., 2013). The obtained flow value/workability was plotted with the increasing water content. Table 13 shows the various values obtained for different water ratios in cement mortar M1 and the corresponding graph is shown in Figure 44. Similarly, Table 14 and Figure 45 present the workability results for the earth mortar M2.

Table 13: Calculation of flow consistency/workability for cement mortar M1

Cement: Lime: Sand (1:0.79:9.64)					
W/S	Water content (ml)	Weight of sample (g)	Diameter readings (mm)		Flow value/ Workability (mm)
0.16	240	1500	157	157	157
0.163	244.5	1500	160	159	159.5
0.166	249	1500	170	170	170
0.167	250.5	1500	166	161	163.5
0.17	255	1500	180	172	176

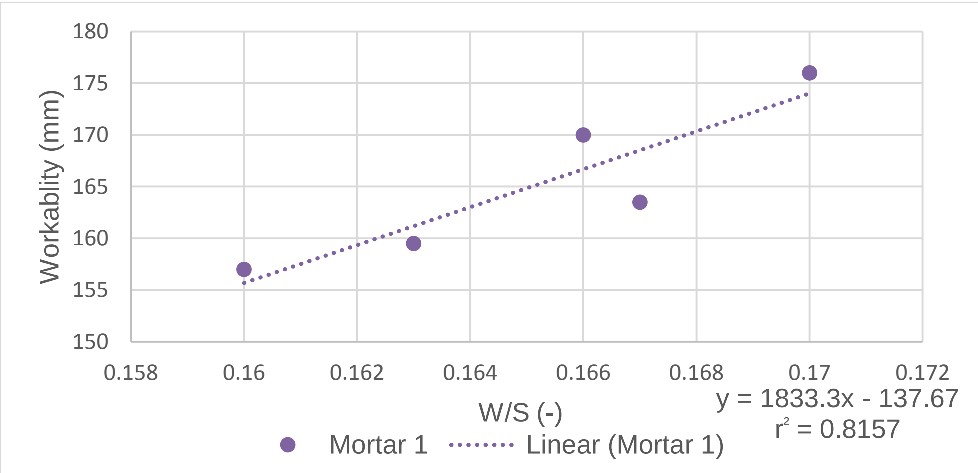


Figure 44: Variation of the workability with the W/S for cement mortar M1

Table 14: Calculation of flow consistency/workability for earth mortar M2

W/S	Water content (ml)	Weight of sample (gm)	Diameter readings (mm)		Flow value/ Workability (mm)
0.15	225	1500	158	154	156
0.16	240	1500	165	172	168.5
0.163	244.5	1500	170	171	170.5
0.165	247.5	1500	180	172	176
0.17	255	1500	181	184	182.5

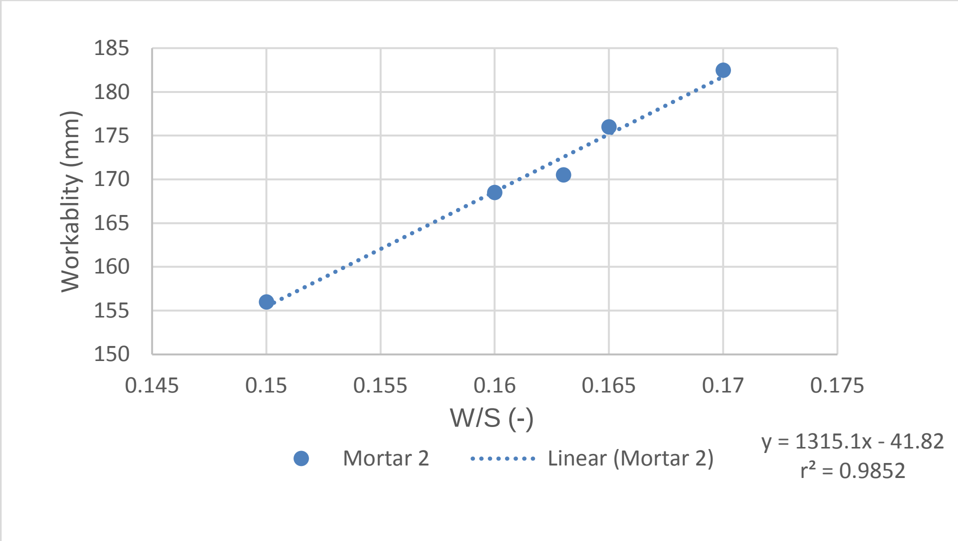
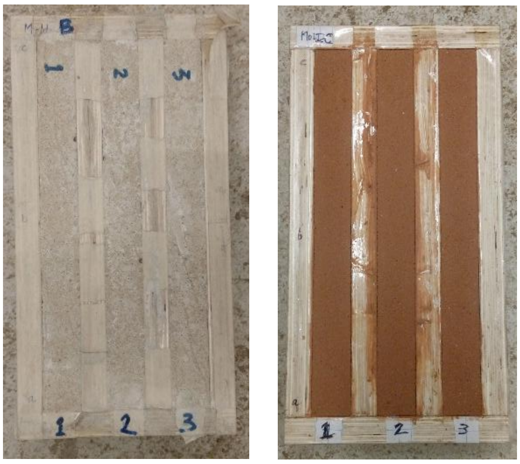


Figure 45: Variation of the workability with the W/S for earth mortar M2.

There is a linear correlation between the measured flow values with increasing water content (W/S). The coefficient of correlation 'r^2' value generated with the equation is related to the fitting of the trendline in the graph and ranged between 0-1. Values higher than 0.8 are preferable as it gives the best fitting of the trendline and experiments can be crosschecked. The optimum value for mortar flow selected for further tests specimens was 170mm for both M1 and M2 and water content was calculated with the help of the respective fitted curve.

4.3.4 Linear shrinkage

The material shrinkage limit (SL) is defined as the boundary between the semi-solid and solid states. It is the reduction in volume that a material experiences with evaporation of moisture. The dark colour of the mixture turns a lighter as it cures. For earth materials, shrinkage is commonly evaluated by the Alcock´s test/linear shrinkage or shrinkage box test and is mostly due to the presence of clay in the soil (Gomes, et al., 2014). For both mortars M1 and M2, the specimens were casted in a wooden mould of size 30*30*300mm and were kept under specific environmental conditions in climatic chamber with 20ºC temperature and 57.5% RH for drying. There was no shrinkage observed in mortar M1 and 0.5 mm separation observed in earth mortar M2, but in both cases the specimens could not be demoulded after complete drying (Figure 46). This could be attributed to less clay content in earth mortar i.e. only 10% as per PSD results. The average percentage of shrinkage in earth mortar M2 was calculated as 0.33%, which complies with the maximum limit of 2% (Gomes, et al., 2013).



(a) (b)

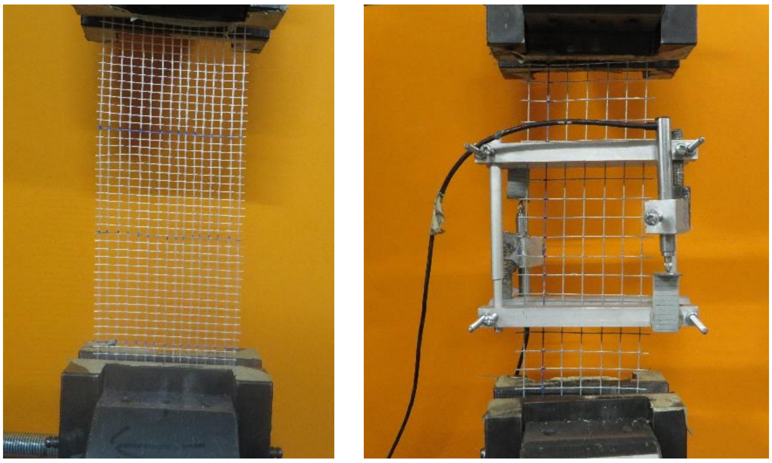
Figure 46: Moulds of mortar specimens: (a) for cement mortar M1 showing no shrinkage and (b) for earth mortar M2 showing 0.33% linear shrinkage.

4.4 Characterisation of meshes

Four different varieties of reinforcing meshes were bought from local market keeping in mind that their cost should be as cheap as possible. The meshes were tested in the laboratory for the mechanical properties in tension. Following, the selected mesh types are discussed briefly.

Fibreglass mesh - This type of mesh is widely used for repair of buildings and also for seismic retrofitting. Glass fibre mesh coatings are applied to material surfaces with appropriate resins. This application increases the tensile strength of the structure and stiffens the element against bending. It is frequently used as a repair layer for cracks/joints in drywall finishes. It has good protection against corrosives. Figure 47 (a) shows the one of the specimens use for testing the selected mesh. It should be noted that this mesh has different properties in both main directions, since the threads of each have different thickness. Moreover, this mesh corresponds to a low quality grass fibre, different from those typically used in repairs with epoxy resins.

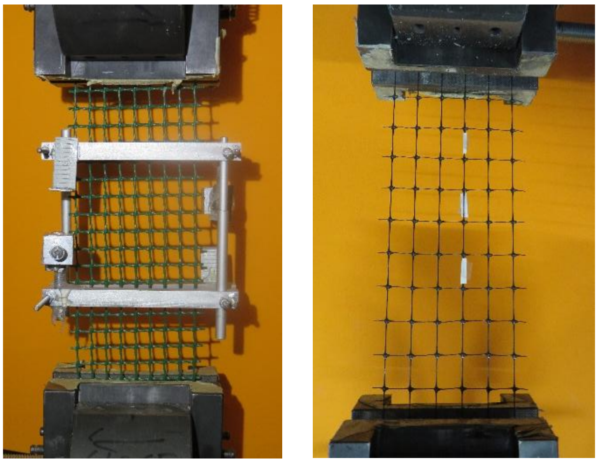
Metallic mesh - Some research works were already done on the strengthening of earth constructions with metallic meshes. As discussed previously metal meshes have performed well in seismic retrofitting of adobe structures in Peru. Clearly the use of reinforcement is successful in improving seismic performance of adobe buildings, but it could be challenging as it is expensive and prone to corrosion (Navaratnarajah, 2015). A specimen of the selected metallic mesh is shown in Figure 47 (b).



(a) (b)

Figure 47: Set up of the meshes in the testing machine (a) glass fibre mesh and (b) metallic mesh

High density and low density plastic meshes - For the current work two types of plastic meshes were selected- high and low density meshes. These meshes are comparatively lighter in weight than metallic and glass fibres meshes. The plastic meshes, over the metallic ones, present as main advantage not to be susceptible of corrosion. Figure 48 shows the mechanical test setup for both the plastic meshes tested within the experimental program.



(a) (b)

Figure 48: Set up of the meshes in the testing machine (a) high density plastic mesh and (b) low density plastic mesh

The meshes can be compared on the basis of their prices, given in Table 15. The low density plastic mesh is the cheapest, while the metallic one is the most expensive, in about four times. It should be noted that the glass fibre mesh presents the second cheapest price, which is comparable to that of the low density mesh. The high density plastic mesh presents an expensive price, in line with the metallic mesh.

The glass fibre mesh is the densest of all in terms of threads per meter i.e. 180 threads per meter in both horizontal and vertical directions (directions defined as x and y). And low density plastic mesh has the lowest number of threads per meter which is 60, also in both horizontal and vertical directions.

Table 15: Comparison of meshes on the basis of prices and density of threads

Mesh Type	Price/m^2 (€/m^2)	Threads/m	
		x (horizontal)	y (vertical)
Glass fibre	0.90	180	180
Metallic	1.90	80	80
High density plastic	2.73	90	90
Low density plastic	0.63	60	60

5. MECHANICAL CHARACTERIZATION

5.1 Introduction

The following chapter presents the main mechanical properties of the mortars and meshes, which were tested within the experimental program. Flexure and compression tests were done in hardened beam specimens while uniaxial compression test in cylindrical specimens provided Young's modulus for both the mortars. As the mechanical strength depends on various factors, including water content of the mixture. Hence, the tests results are presented with the moisture content in the corresponding specimens which was measured after the tests to conclude. The two mortars M1 and M2 were also tested for the bond strength with RE substrate. The testing procedures and respective results are discussed in the following sections.

5.2 Characterization of RE

Uniaxial compression tests were performed on six cylindrical RE specimens of soil S6. Figure 49 shows the stress-strain curves of the all the specimens CURE 1 – CURE 6. Table 16 summarises the results in terms of density (ρ_d), compaction water content (W), compressive strength (f_c), Young modulus (E_o) and equilibrium water content (W_{eq}).

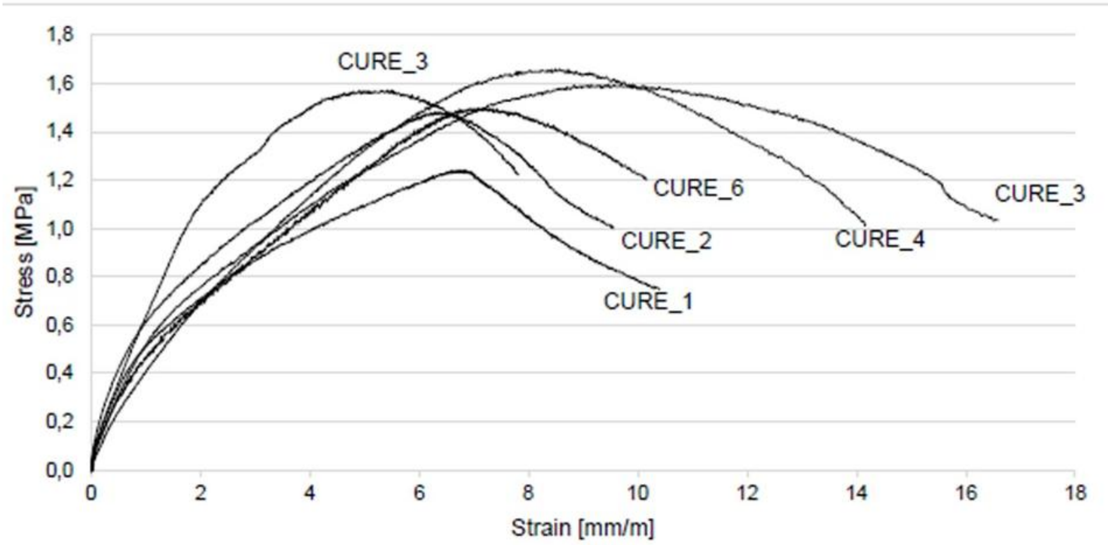


Figure 49: Stress-strain curves of the RE cylindrical specimens manufactured with soil S6 *(Dominguez, 2015)*

The average compressive strength was of about 1.5 N/mm^2 obtained for an average equilibrium water content of about 0.6 %. The Young's modulus (*E_0*) was computed between 5% and 30% of the compressive strength of all the specimens and the average value obtained was 536 N/mm^2.

Table 16: Results of the RE cylindrical specimens for soil S6 tested under compression *(Dominguez, 2015)*

Specimen	W (%)	ρ_d (g/cm^3)	f_c (N/mm^2)	E_o (N/mm2)	W_{eq} (%)
CURE_1	8.3	2.05	1.24	595	0.7
CURE_2	7.5	2.06	1.48	712	0.6
CURE_3	7.1	2.07	1.57	606	0.7
CURE_4	7.0	2.08	1.66	358	0.6
CURE_5	7.3	2.07	1.59	495	0.6
CURE_6	8.1	2.05	1.49	428	0.4
Average	7.6	2.07	1.5	536	0.6
CoV (%)	7.1	0.5	8.8	22.6	14.1

5.3 Characterization of mortars

5.3.1 Testing of beam specimens

CEN EN 1015-11 (EN:1015-11, 1999) standards was used to prepare the specimens to determine the flexural and compressive strength of hardened mortar. The fresh mortar of consistency 170mm (selected from workability experiment) was used to prepare the mixture for both M1 and M2 mortars. The specimens were casted using a wooden mould of size 40x40x160mm (cross section x length). CEN EN 1015-11 specifies the procedure and curing conditions for cement and lime but not for earth-based mortars. Hence, for earth mortars curing conditions were adjusted.

(a) (b)

Figure 50: Cement mortar M1 in (a) fresh state and (b) hardened state after demoulding

Figure 50 shows the different stages of cement mortar M1 specimens preparation. The mould with fresh mortar was kept sealed with a plastic film for 7 days in the mould to protect from atmospheric drying. After 7 days, the film was removed and specimens were demoulded and kept in climatic chamber with 20 ± 2 °C and 50 ± 5% RH for the next 14 days. Whereas for earth mortar M2 the mould (Figure 51 (a)) with fresh mortar specimens was directly moved to the climatic chamber for drying in a controlled atmosphere. For both mortars, the total curing period was 21 days from the day of casting. In this period the beams were tested for weight at specific intervals to calculate moisture content. When the specimens hardened and reached the age of 21 days (Figure 52) they were tested for mechanical properties.

(a) (b)

Figure 51: Earth mortar/M2 in (a) fresh state and (b) hardened state before demoulding

The Three-point bending tests were performed according to standard EN 1015-11 (1999). Demoulded prism specimens were weighed and measured for cross section. Prisms were placed in the machine on the supporting rollers and the load was applied without shock and increased continuously with the rate of 0.005 N/mm/s until the failure. Figure 50 shows the placement of the mortar specimen on the machine and the failed beam divided in two pieces. The calculations and results for flexural strength are presented in Table 17 and Table 18 for cement mortar M1 and earth mortar M2, respectively.

(a) (b) (c)

Figure 52: Destructive testing for flexural strength in mortar specimens (a) placement of the prism on the testing machine; failure of (b) cement mortar M1 and (c) earth mortar M2

Table 17: Calculation for flexural strength for cement mortar M1

Specimen no	Distance between the axes of the support l (mm)	Width of specimen b (mm)	Depth of the specimen d (mm)	Maximum load F (N)	Flexural strength (MPa) $f=1.5\times\frac{Fl}{bd^2}$	Density ρ_d (g/cm^3)	Moisture content (%)
FM1B1	100	39.77	38.045	666.85	1.74	1.81	1.14
FM1B2	100	40.50	41.42	769.57	1.66	1.79	1.00
FM1B3	100	40.10	39.73	616.3	1.46	1.71	1.30
Average					1.62	1.77	1.15
CoV (%)					8.82	3.15	13.41

Table 18: Calculation for flexural strength for earth mortar M2

Specimen no	Distance between the axes of the support l (mm)	Width of specimen b (mm)	Depth of the specimen d (mm)	Maximum load F (N)	Flexural strength (MPa) $f=1.5\times\frac{Fl}{bd^2}$	Density ρ_d (g/cm^3)	Moisture content (%)
FM2B1	100	41.30	38.02	134.07	0.34	1.92	0.61
FM2B2	100	41.12	41.42	120.88	0.26	1.72	0.58
FM2B3	100	39.70	39.60	109.08	0.26	1.77	0.65
Average					0.29	1.80	0.61
CoV (%)					15.59	5.82	5.59

The compression tests were performed according to standard EN 1015-11 (1999). Both the halves of the prisms obtained from flexural tests were taken and placed in the machine and the load was applied without shock and increased continuously at the rate of 0.025 N/mm/s until the failure (Figure 53). Maximum load was recorded. Compressive strength is calculated by dividing the maximum load by the cross sectional area of the specimen in contact with the bearing plate. The strength is reported to the nearest 0.05N/mm^2 for individual results. Calculation and results for compressive strength are presented in Table 19 and Table 20 for cement mortar M1 and earth mortar M2, respectively.

(a) (b)

Figure 53: Destructive test for compressive strength on mortar specimens (a) failure of cement mortar M1 and (b) development of cracks in earth mortar M2.

Table 19: Calculation for compressive strength for cement mortar M1

Specimen no	Width of specimen b (mm)	Depth of the specimen d (mm)	Maximum load F (N)		Compressive strength (MPa) $\rho = \frac{F_{\max}}{area *}$	Density ρ_d (g/cm^3)	Moisture content (%)
CM1B1	40.00	38.05	A	2721.56	1.79	1.81	1.14
			B	2840.18	1.87		
CM1B2	40.00	41.42	A	3407.70	2.06	1.79	1.0
			B	3099.87	1.87		
CM1B3	40.00	39.73	A	3878.65	2.44	1.71	1.3
			B	3432.36	2.16		

Average		2.03	1.77	1.15
CoV (%)		12.00	3.15	13.41
$*area = bxd$				

Table 20: Calculation for compressive strength for earth mortar M2

Specimen no	Width of specimen b (mm)	Depth of the specimen d (mm)	Maximum load F (N)		Compressive strength (MPa) $\rho = \frac{F_{max}}{area *}$	Density ρ_d (g/cm^3)	Moisture content (%)
CM2B1	40.00	38.02	A	925.43	0.61	1.92	0.61
			B	1016.42	0.67		
CM2B2	40.00	41.42	A	849.18	0.51	1.72	0.58
			B	781.26	0.47		
CM2B3	40.00	39.60	A	876.19	0.55	1.77	0.65
			B	800.19	0.51		
Average					0.55	1.80	0.61
CoV (%)					13.27	5.82	5.59
$*area = bxd$							

The average flexural and compressive strengths obtained for the cement mortar M1 are 1.62 N/mm^2 and 2.03 N/mm^2, respectively. While for the earth mortar M2 the flexural strength is 0.29 N/mm^2 and compressive strength is 0.55 N/mm^2.Results show that flexural and compressive strength of mortar M1 is approximately 6 and 4 times higher than the mortar M2. Furthermore, the bulk density obtained for the cement mortar M1 specimens is 1.77 g/cm^3, while that for earth mortar M2 is 1.8 g/cm^3, which is a similar value to that provided by the manufacturer. Today with fine-grained construction soil, mineral and fine-fibres organic aggregates it is possible to produce light earth mortars with bulk density less than 1.2 g/cm^3.

5.3.2 Testing of cylindrical specimens

The assessment of the compression behaviour of the mortars was done also using cylindrical specimens to find the stress-strain curve and resultant Young's modulus. The cylindrical moulds were taped from one side in order to secure and pack the base. For earth mortar specimens, drying of mortar was difficult with only one open surface. Hence the plastic moulds were pierced with several holes of 2mm diameter all around the surface of the mould to provide air to the mortar inside. The fresh mortar mixture of flow consistency 170mm was prepared and poured in cylindrical plastic mould with 85-87mm diameter and 170mm height. The compaction was carried out in three layers inside the plastic mould using piston. The cement mortar M1 specimens were kept packed with plastic film for 7 days in normal room temperature, after 7 days demoulded and moved to climatic chamber for controlled drying for next 14 days. Earth mortar M2 specimens were kept directly in the climatic chamber with 20 ± 2 °C and 57.5 ± 5% RH, and after 7 days of drying demoulded and cured for next 14 days. Total curing period for both the mortars was 21 days.


(a)

(b)

Figure 54: Preparation of cylindrical specimens for uniaxial compression test (a) cement mortar M1 specimen kept packed with plastic film and (b) application of gypsum on the specimens for testing.

The specimens were prepared by flattening the top and bottom with gypsum to ensure uniform loading (Figure 54). The specimens were placed in the compression machine with two rings at 1/3 of the height fixed with LVDTs (displacement transducers) to measure the deformations at the middle third part of the specimens. A monotonic load was applied with a constant velocity of 0.003 mm/s until failure. The deformations and the load applied during the tests were recorded. An additional transducer was necessary to control the velocity of loading, since it is too low to be controlled directly through the loading jack.

Table 21: Results of cylindrical specimens tested under compression for cement mortar M1

Cement mortar M1	Moisture content (%)	Density ρ_d (g/cm^3)	Compressive strength f_c (MPa)	Modulus of elasticity E_o (MPa)
M1C1	1.67	1.76	1.92	4554.1
M1C2	1.28	1.74	1.77	3771.4
M1C3	1.84	1.74	2.50	6710.4
M1C4	3.03	1.69	2.27	5021.6
Average	1.95	1.73	2.11	5014.38
CoV (%)	38.64	1.76	15.61	24.78

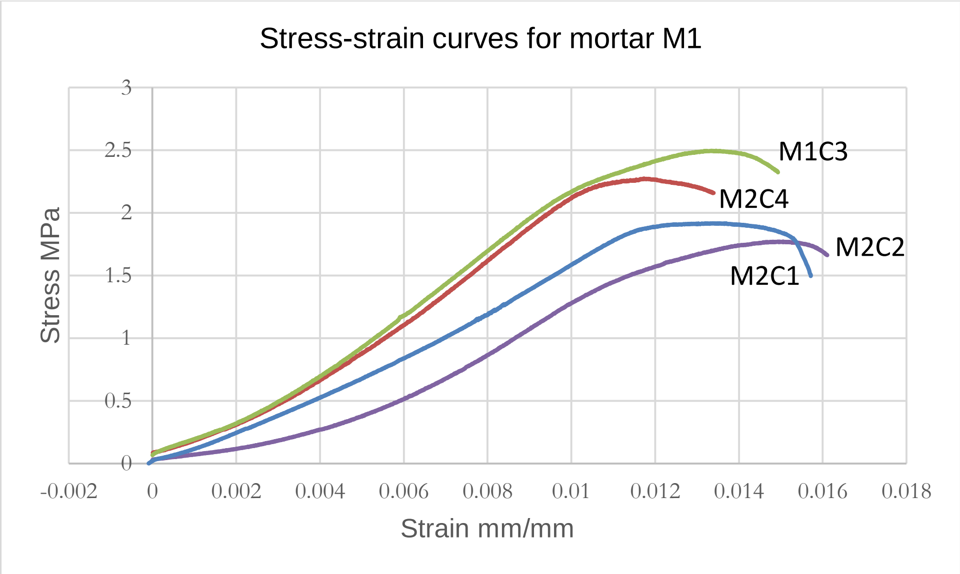


Figure 55: Stress-strain curves for four cement mortar M1 specimens i.e. M1C1-M1C4 plotted using external LVDT reading

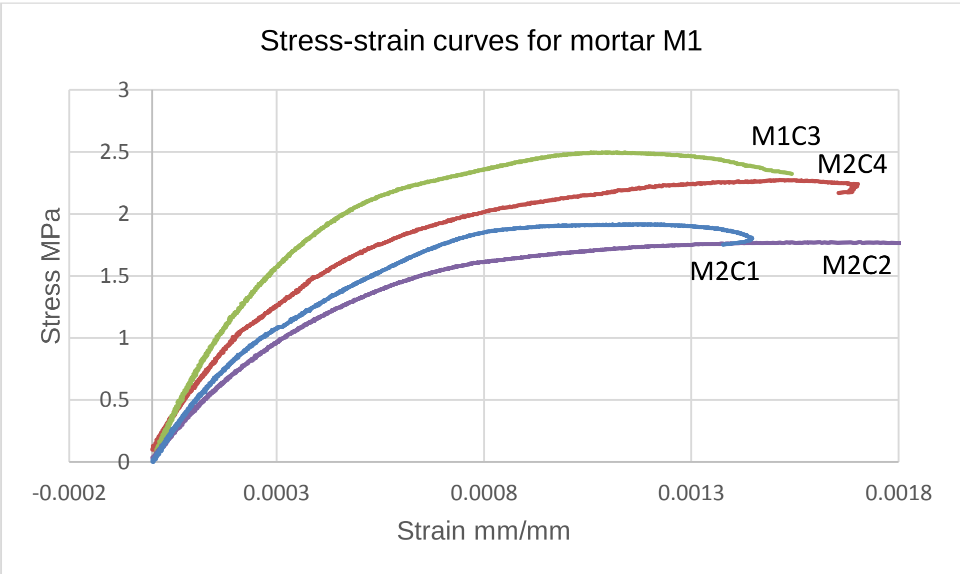


Figure 56: Stress-strain curves for four cement mortar M1 specimens i.e. M1C1-M1C4 plotted using internal LVDTs reading

From Table 21, the average compressive strength f_c obtained for four cement mortar M1 specimens was of about 2.11 MPa, with a corresponding average equilibrium water content of about 1.95%. Furthermore, the values obtained for this parameter varied between 1.77 and 2.50 MPa. Figure 55 shows the axial stress-strain curves for all four cement mortar M1 specimens, where the strains were computed with the external LVDT displacement. The difference in the axial stress-strain curve can be seen in the Figure 56 graphs, plotted with the internal LVDTs. The strains measured with both methods greatly differ, meaning that the external LVDT measures large accommodation displacements. Thus, the strain computed in this way are not reliable. On the other hand, it allows to obtain the shape of the compression behaviour after the peak, which is not possible by the internal LVDTs due the occurrence of damage in the specimens.

Table 22: Results of cylindrical specimens tested under compression for earth mortar M2

Earth mortar/M1	Moisture content (%)	Density ρ_d (g/cm^3)	Compressive strength f_c (MPa)	Modulus of elasticity E_o (MPa)
M2C1	0.61	1.71	0.56	1341.6
M2C2	0.63	1.65	0.61	1615.2
M2C3	1.03	1.67	0.61	1207.90
Average	0.76	1.68	0.59	1388.23
CoV (%)	31.83	1.62	4.92	14.96

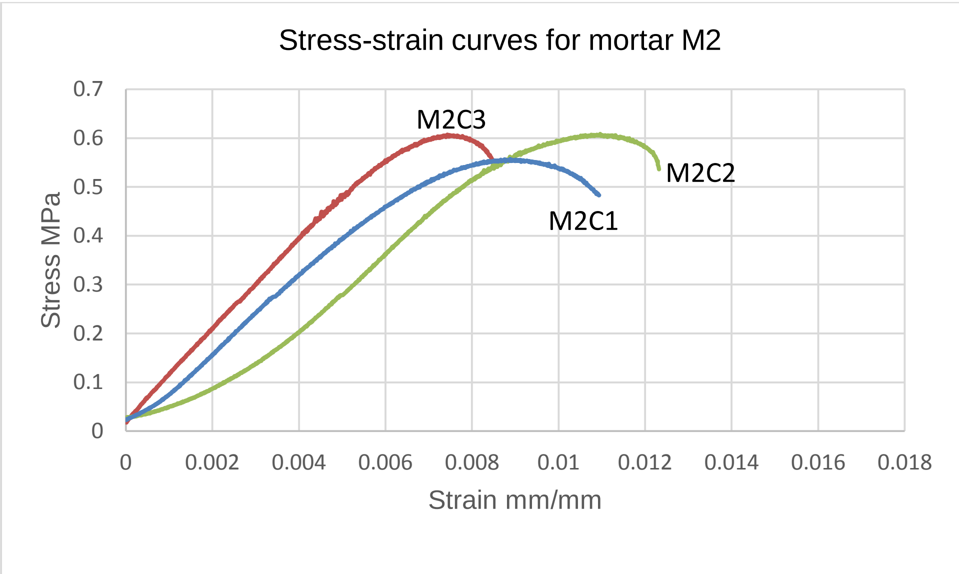


Figure 57: Stress-strain curves for three earth mortar M2 specimens i.e. M1C1-M1C3 plotted using external LVDTs reading

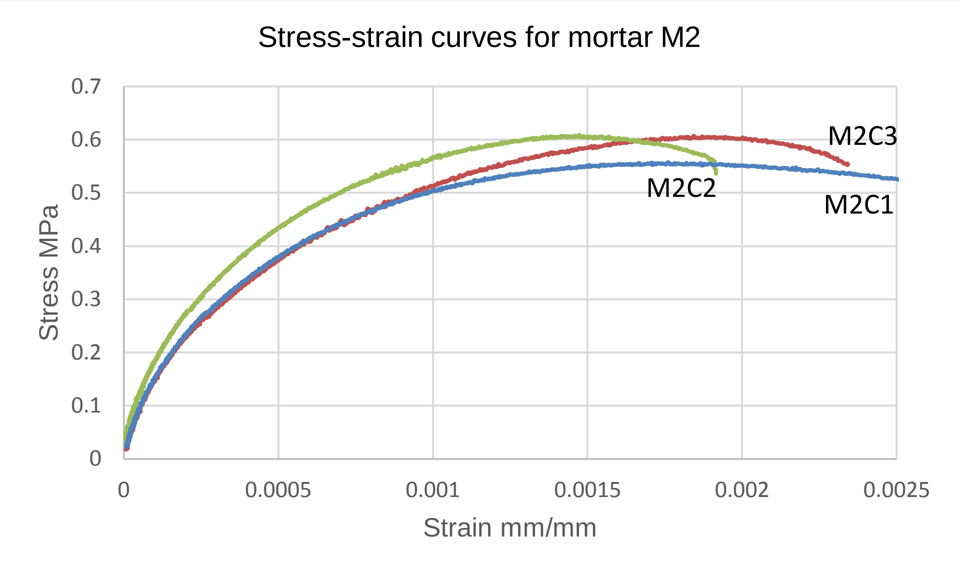


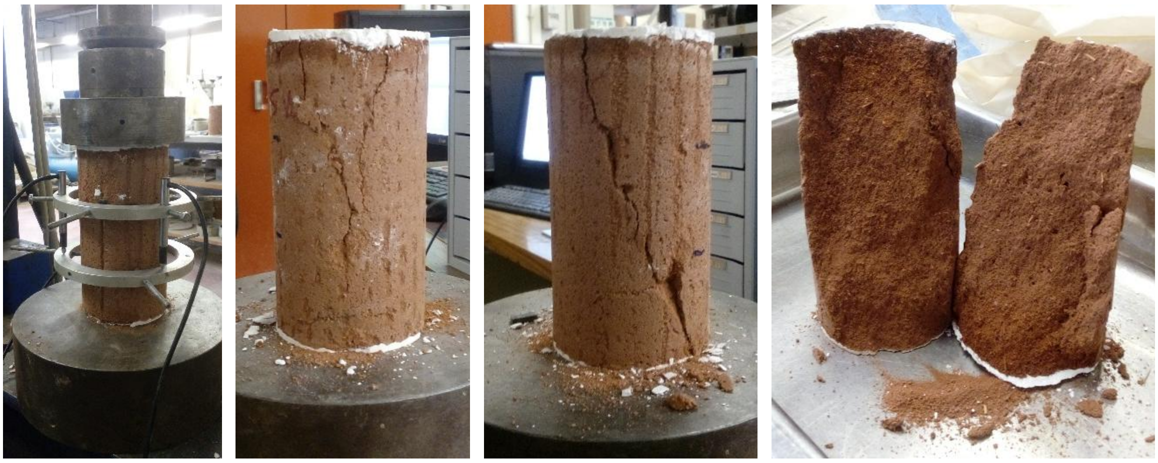
Figure 58: Stress-strain curves for three earth mortar M2 specimens i.e. M1C1-M1C3 plotted using internal LVDTs reading

For earth mortar M2 the average compressive strength f_c, obtained for three specimens, was of about 0.59 MPa with an average equilibrium water content of 0.76%. Furthermore, the values of this parameter range between 0.56 and 0.61MPa (Table 22). The axial stress-strain curves are shown in Figure 57 and 58, plotted with external LVDT and internal LVDTs displacements, respectively. The modulus of elasticity (E_o) was computed between the 5% and 30% of the f_c and the strain γ by linear fitting for both mortars. The acquired average value for the cement mortar M1 specimens is 5014.38 MPa for an average density of 1.73g/cm^3, while for earth mortar M2 the average Young's modulus (E_o) obtained is 1388.23 MPa for an average density of 1.68 g/cm^3. The young's modulus for cement mortar M1 is 4 times higher than that of the earth mortar M2. The coefficient of variation for earth mortar M2 is relatively lower than that of the cement mortar M1 specimens. From the acquired average values of Young's modulus we can conclude that modulus of elasticity of mortar M1 is approximately 10 times higher than modulus of RE (Table 16) and for earth mortar M2 it is 4 times than that of the modulus of RE.

The failure modes in the specimens were almost with a main diagonal crack that splitted the specimens in two wedges, except in one case of cement mortar M1, which developed three vertical cracks separating the specimen equally. The different failures modes of the specimens are shown in Figure 59 and 60.

(a) (b) (c) (d)

Figure 59: Uniaxial compression test for cement mortar M1 (a) Setting of the specimen in the testing machine; (b) formation of a diagonal cracks and palling of the specimen surface from top and bottom; (c) separation with main vertical/diagonal crack and (d) symmetric separation of specimen with 3 vertical cracks

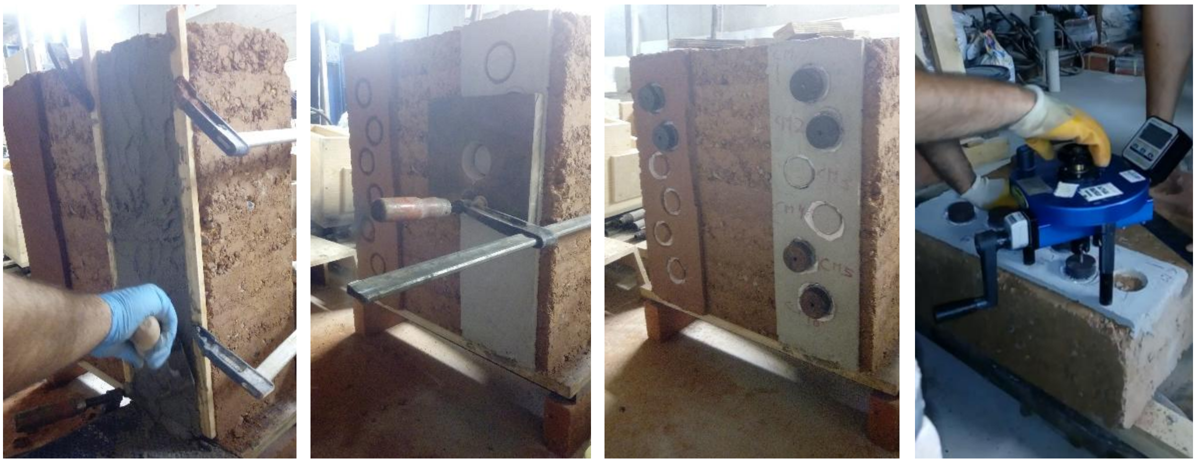


(a) (b) (c) (d)

Figure 60: Uniaxial compression test for earth mortar M2 (a) Setting of the specimen in the testing machine; (b); (c) vertical diagonal cracks and (d) separation of the specimen with diagonal crack.

5.4 Direct pull-off test

The test is useful to find mechanical properties of the materials both in situ or at the site. The test is conducted on material substrate with an overlay of mortars. It can be used to obtain the near-surface tensile strength of the substrate material, tensile strength of a repair or overlay material and the adhesion properties with bond strength between the two materials. For the current work the two mortars, cement mortar M1 and earth mortar M2 were applied in RE substrate and the test was followed according to the standard ASTM C1583 (ASTM:C1583, 2004). The RE surface was scrubbed with a nylon brush removing all the loose particles to obtain a clean surface. The surface was then sprinkled with water to have a moist surface. Thereafter, both prepared mixtures of the mortars were rendered on each side of the RE wallet (55x55x20 cm^3) surface with 10mm of thickness. After 21 days of curing the pull-off tests were conducted. The test specimen is formed by drilling a shallow core into the mortar surface and leaving the intact core of 50mm diameter attached to the RE. It is recommended in the standard that the core should be drilled 2-5mm inside the substrate. But cutting with a circular driller through large aggregates and rough surface of RE it could not be drilled in circular motion. Figure 61 shows various stages of the preparation for pull-off test specimen.



(a) (b) (c) (d)

Figure 61: Preparation of pull-off test (a) rendering of mortars; (b) drilling of holes with clamp support; (c) gluing of pull heads on test specimens with adhesive and (d) fixing of apparatus on pull heads

The drills were then dusted to remove the dirt and the diameter of the circular test specimen were measured in two directions at right angles to each other recording the average diameter. The test apparatus was assembled. The 50mm isolated test specimens are glued with metal circular pull-heads are glued using the epoxy adhesive and left to harden for 24 hours. The pull heads are fitted to an apparatus with a screw for applying a direct pull tensile force ensuring the same axis. The apparatus pulls the metal pull head until failure and maximum load applied is measured (Figure 62). The tensile bond strength is calculated with the maximum load required for failure and the area of the bond.

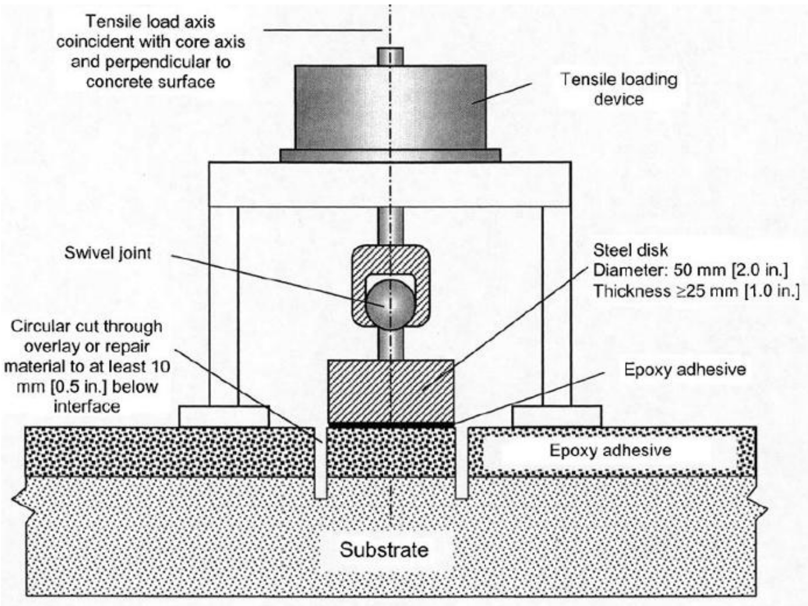


Figure 62: Schematic of the test apparatus setup with substrate *(ASTM:C1583, 2004)*

The planned tests specimens were 6 with interfaces in each mortar, but some test specimens were already damaged and readings could not be taken. Hence, few more drills were made in each mortar. Out of 8 bond specimens in cement mortar M1 and 10 in earth mortar M2, 6 were damaged in providing only 7 readings in M1 and 3 load readings in M2. The average tensile forces calculated for both the mortars was 0.06 MPa and 0.03 MPa with CoV of 47.94% and 57.74% for cement mortar M1 and earth mortar M2, respectively. The results are shown in the Table 23 and 24 for respective mortars.

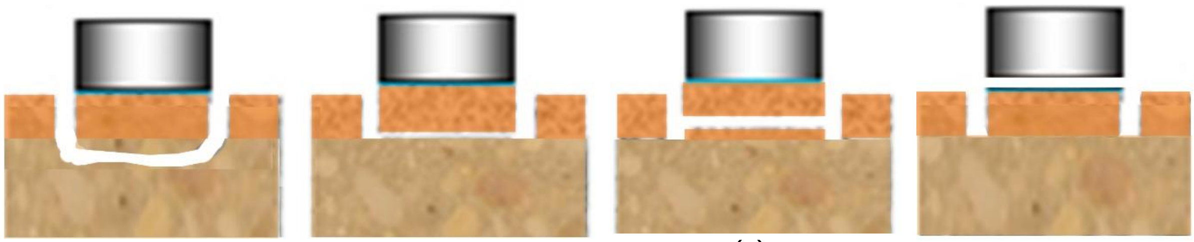
Table 23: Calculation of tensile bond force for cement mortar M1

Cement mortar M1	Diameter ϕ (mm)	Area of bond A^* (mm²)	Total applied load F (N)	tensile bond strength $T = \frac{F}{A}$ (MPa)
M1P1	47.55	1775.41	-	-
M1P2	48.10	1816.73	59.90	0.03
M1P3	48.06	1813.71	175.90	0.10
M1P4	48.28	1830.73	114.90	0.06
M1P5	47.86	1799.02	53.90	0.03
M1P6	48.32	1833.77	63.90	0.03
M1P7	49.20	1900.78	141.90	0.07
M1P8	47.25	1753.45	169.00	0.10
Average			111.34	0.06
CoV (%)			47.29	47.94

Table 24: Calculation of tensile bond force for earth mortar/M2

Earth mortar M2	Diameter ϕ (mm)	Area of bond A^* (mm^2)	Total applied load F (N)	tensile bond strength $T = \frac{F}{A}$ (MPa)
M2P1	45.54	1628.47	---	---
M2P2	45.15	1600.70	---	---
M2P3	45.92	1655.77	---	---
M2P4	45.19	1603.89	---	---
M2P5	45.02	1591.85	84.90	0.05
M2P6	45.88	1652.88	38.99	0.02
M2P7	46.50	1698.23	---	---
M2P8	45.50	1625.97	---	---
M2P9	45.95	1658.29	---	---
M2P10	46.86	1724.62	42.90	0.02
Average			55.6	0.03
CoV (%)			45.78	57.74

The pull-off test also evaluates the failure mode, according to ASTM C1583 with respect to the interface failure position shown pictorially in Figure 63. These modes are classified as Mode 1 failure in the substrate, which is a cohesive failure; Mode 2 is an adhesive failure where the bond fails with separation of mortar and substrate. In Mode 3 the failure occurs in the mortar overlay which shows weakness due to some inhomogeneity in the mortar/overlay itself. Mode 4 is a failure at epoxy and mortar overlay interface which cause detachment of the pull head from the mortar surface.



(a) (b) (c) (d)

Figure 63: Failure modes in pull off test (a) Mode 1 failure in substrate; (b) Mode 2 failure in bond; (c) Mode 3 failure in overlay and (c) Mode 4 failure at glue and overlay interface. Modified (CAE, 2016)

The bond interfaces in cement mortar M1 showed mostly Mode 1 failure except M1P1 which was damaged before the extraction. The interfaces of bond failure are shown in Table 25 for each bond specimen pull head.

Table 25: Characterization of failures for cement mortar M1.

Bond specimen	Type of failure
 M1P1 M1P2 M1P3	Mode 1/mode 2
 M1P4 M1P5 M1P6	Mode 1
 M1P7 M1P8	Mode 1

Pull off in earth mortar gave very poor results as compared to cement mortar M1. Mode 1 failure was observed in five specimens where four were already damaged before the application of the apparatus. Only three specimens M2P5, M2P6 and M2P10 could be tested for bond strength with direct pull. M2P5 gave the maximum force of 0.05MPa with more of Mode 2 failure. M2P6 and M2P10 were recorded for 0.02MPa each with Mode 1 and Mode 3 failure respectively. The different failure modes with images of the tested specimens are shown in Table 26.

Table 26: Characterization of failure modes for earth mortar M2 specimens

Test specimens			
Failure mode	M2P5 Mode 1/Mode 2	M2P6 Mode 1	M2P10 Mode 3

Looking at the surfaces of the RE substrate and the pull head failures it can be concluded that the cement mortar M1 showed a better adhesion on the RE substrate compared to the earth mortar M2. This could be attributed to the binding effect of cement mortar M1, which earth mortar M2 lacks, recalling the PSD results where clay content was only 10% in M2. Also, RE surface is very porous, the large particles of sand could not bind with the substrate, whereas the cement mortar M1 could bind well within the pores of the RE. With this behaviour, one recalls the hypothesis that cement mortar would have stabilized RE, forming a thin external layer of RE with improved properties, which results in a deeper bond failure and higher tensile bond strength.

To confirm this conjecture, the height from the mortar surface till the bond failure was measured for each sample. It was found that the height was higher in cement mortar M1 (average of 12.15 mm) than in earth mortar M2 (11.51 mm). Now this result can be explained with the good bonding of cement mortar M1 with RE which could pull the material from the substrate in large amount, whereas the earth mortar M2 with a week bond failed to do so. Figure 64 shows the tested specimens from pull-off test and different mode of failures can be seen with the amount of RE surface visible from the cores. In earth mortar M2 specimens (Figure 64 a and b) the RE surface is highlighted with yellow colour to be able to differentiate between the substrate and the mortar.

(a) (b) (c) (d)

Figure 64: Tested specimens from pull-off test (a); (b) Mode 1/cohesive and Mode 2/adhesive failures visible in earth mortar M2; (c) and (d) Mode 1/cohesive failures in cement mortar M1

5.5 Tensile tests of meshes

All the four types of meshes (glass fibre, metallic mesh, high density plastic and low density plastic) were tested for their tensile strength. Each mesh was tested in its both directions using three specimens. The meshes were cut in bands with dimensions of about 100x400 mm^2 to prepare the specimens. In order to fix the mesh to the claws of the testing setup, the edges were sandwiched between steel plates with dimensions 120x50 mm^2 with an epoxy mortar. In addition, the deformations of the metallic and high density plastic meshes were measured by means of a calliper apparatus of 100 mm of length and instrumented with two LVDTs (see Figure 65). The objective was to measure deformations directly in the mesh to compute the Elasticity modulus. However, this apparatus could not be used for other meshes, since it tends to cut them due to their low thickness of the threads. Thus, the Elasticity modulus was calculated using the axial strains computed with the displacements measured by the actuator. Furthermore, the comparison between both methods shows little difference.

The tests were performed in displacement control at rate of 0.010 mm/s for the metallic and glass fibre meshes, and of 0.050 mm/s in the other cases. Varying the rate of testing was required in order to provide to all tests a similar duration, namely about 15 min.

Figure 66 presents the tensile stress-axial strain curves for one mesh of each type tested in Y direction. The development of the curves is similar in X direction. Here, it is possible to observe that the plastic meshes present an absurd elongation, where their maximum bearing capacity is achieved after a large value of strain. After this point, the meshes are capable of maintaining their maximum bearing capacity for even higher values of strain. This failure mode is evident in Figure 67. The metallic and fibre glass meshes present a more brittle behaviour, where the threads of the mesh fail suddenly one by one (Figure 68). In this case, the maximum tensile stress is achieved for a much lower value of axial strain.

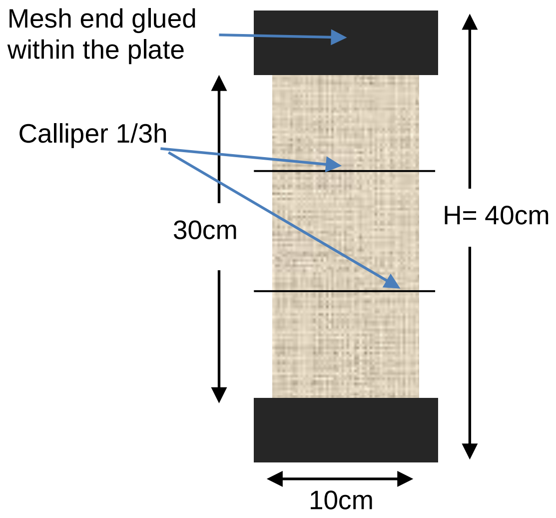


Figure 65: Schematic of tensile strength test mesh specimen

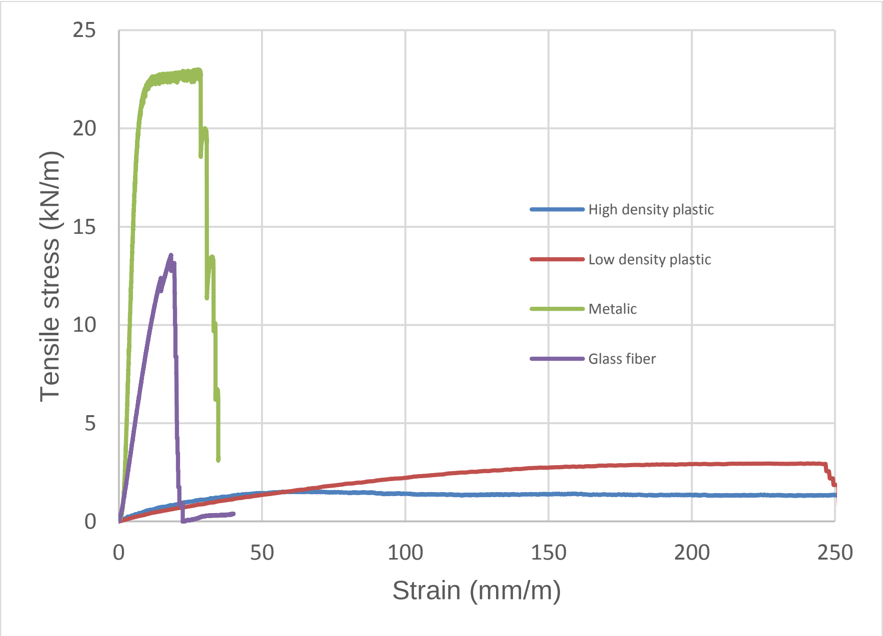
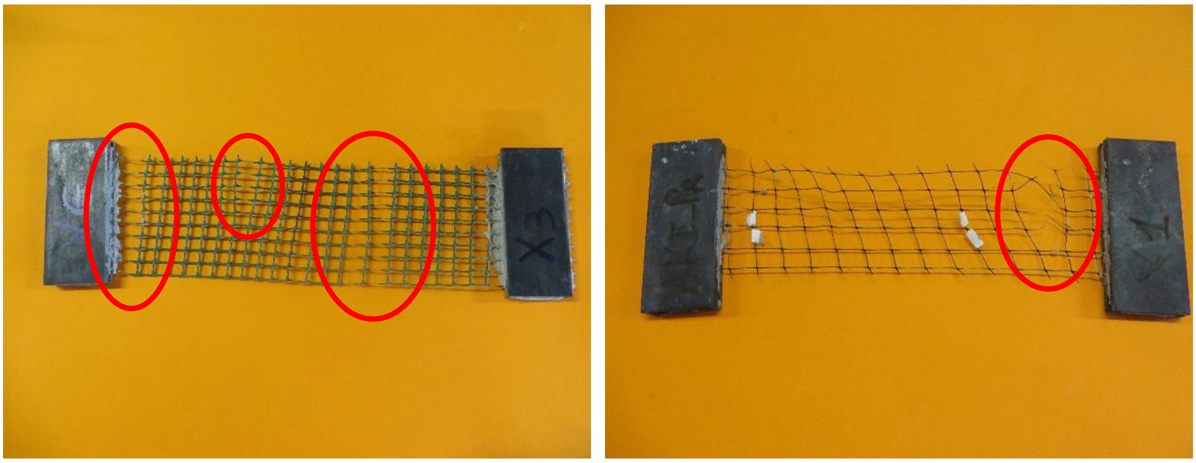
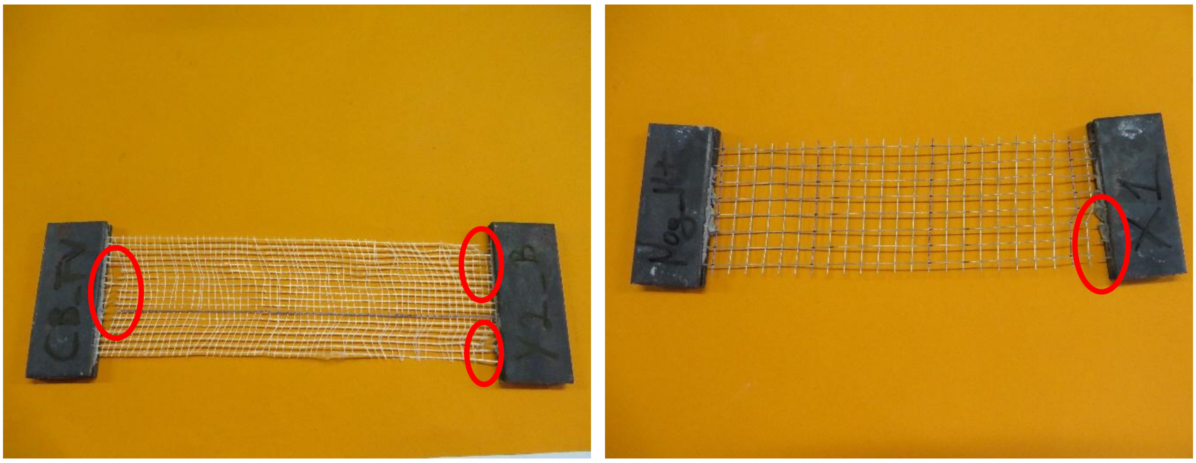


Figure 66: Tensile stress-axial strain curves for some of the tested meshes in the y direction



(a) (b)

Figure 67: Tensile failures in (a) high density plastic mesh and (b) low density plastic mesh



(a) (b)

Figure 68: Tensile failures in (a) glass fibre mesh and (b) metallic mesh

Table 27 shows the obtained average results for the tensile strength of all the four types of meshes and corresponding Young's modulus. The highest tensile strength calculated was for the metallic mesh 17.2 kN/m and 19.7 kN/m in x and y directions, respectively. Whereas the high density plastic mesh gave the lowest results of tensile strength i.e. 1.7 kN/m and 1.6 kN/m in x and y directions, respectively. One thing is noticeable though the low density plastic mesh ruptured, it gave higher strength than high density mesh. Considering the modulus of elasticity, the low density plastic is the most deformable mesh of all giving the values 27.5 kN/m and 29.3 kN/m in x and y directions, respectively. The highest values were obtained by the metallic mesh, namely 3671 kN/m and 3638 kN/m in x and y directions, respectively. Despite of having the maximum number of threads in glass fibre the Young's modulus for glass fibre if 4-7 times lesser than that of metallic mesh, but still much higher than those of the plastic meshes.

Table 27: Comparison in between the selected meshes in terms of average values

Mesh Type	Tensile strength (kN/m)		Young modulus (kN/m)	
	x direction	y direction	x direction	y direction
Glass fibre	8.6	12.3	564.1	958.4
Metallic	17.2	19.7	3671.3	3638
High density plastic	1.7	1.6	71.6	61.3
Low density plastic	3.1	2.9	27.5	29.3

5.6 Comparison of modulus of elasticity of materials

To be able to comment on the compatibility of the meshes with RE, cement mortar and earth mortar, the Elasticity modulus of all material must use the same unit. The reason for this variation is that the meshes were tested for tensile strength in two dimensional specimens giving the results in kN/m. Whereas the RE and both mortars were tested in 3-dimensional cylindrical specimens for compression giving results in N/mm^2. To do the conversion, there are two assumptions. First the modulus of elasticity obtained from tensile strength is equal to the modulus of elasticity from the compression tests. Secondly, the values from the mortars have to be multiplied by a range of expectable thicknesses of the materials, namely 10-20 mm. In this way, it is possible to make a comparison with the Elasticity modulus of the meshes. The same applies to the RE, for which an average thickness of 500 mm can be assumed.

Table 28: Comparison of young's modulus

Materials	E_o (N/mm^2)	E_o kN/m	
RE	536	268000	
Cement mortar M1	5014.38	5014.4 - 10028.8	
Earth mortar M2	1388.23	1388.2 - 2776.5	
-		x (horizontal)	y (vertical)
Glass fibre mesh	-	564.1	958.4
Metallic mesh	-	3671.3	3638.0
High density plastic mesh	-	71.6	61.3
Low density plastic mesh	-	27.5	29.3

Table 28 shows the converted results for Young's modulus in kN/m. Comparing the Young modulus of the RE with those of both mortars, it is observed that the cement mortar M1 is about one order of magnitude stiffer than the RE. On the other hand, the earth mortar M2 is just about 2 times stiffer. With respect to the meshes, it is observed that the stiffness of the plastic meshes fall much below the stiffness of both mortars. Only the metallic and glass fibre meshes fall within stiffness with identical order of magnitude.

6. CONCLUSIONS AND FUTURE WORKS

6.1 Main conclusions

Earth constructions all over the world constitute a significant part of the built heritage. Rammed earth, being one of the oldest construction techniques in the world, still does not achieve enough knowledge and conservation methodologies as compared to modern construction materials. The irony continues even with the preservation techniques and construction codes. It is indeed related to the interest and awareness of the people. Understanding of the risk, hazard, disaster management and seismic stability associated with RE structures is still far from the reach of people. Having said that, one does have some design principles and seismic strengthening techniques for RE with natural and vernacular methods. The scientific studies for seismic retrofitting of earthen structures has been an active research since last 40 years in many countries. And some positive results were obtained from laboratory experiments of full-scale adobe models with retrofitted with geo-meshes. The models showed increased structural stability against seismic events and the procedures were used in strengthening low cost houses in Peru.

The dissertation work has adopted a similar research approach for the seismic strengthening of rammed earth, namely with respect to the use of reinforced coatings. From the state of art and the conservation principles, it is recommended that the materials used for the strengthening system should be physically, mechanically and chemically compatible with RE. Mortars should be durable and ensure a long-term bond to the RE substrate. Earth mortars have higher compatibility with RE than cement based mortars, since cement-based mortars are less porous. This can cause additional problems to the RE construction by not allowing the moisture from the structure to escape. The characterisation earth mortar M2 revealed that it has very less clay and silt content (10% each) with 80% of sand in the material with straws of sizes smaller than 10 mm. The presence of sand and straw fibres reduces the shrinkage/cracking and the linear shrinkage observed only 0.33%.

The mechanical properties of cement mortar M1 seem much greater than those of earth mortar M2. The uniaxial compression test provided average compressive strengths of 2.11 MPa for cement mortar and 0.59 MPa for earth mortar M2. With respect to the compressive strength of the RE (1.5 MPa), this parameter is found to be within the strength of both mortars. Dry unconfined compressive strength of RE is normally in the range of 0.4 - 4 MPa and the modulus of elasticity values vary between 100-1000MPa. Modulus of elasticity for cement mortar M1 is almost 4 times higher than that of earth mortar M1 i.e. 5014.38 MPa and 1388.23 MPa respectively. Whereas Modulus of elasticity for RE was obtained as 536 MPa. Considering the elastic modulus of both mortars, it can be concluded that earth mortars would be more compatible with RE.

The average flexural strength of cement mortar M1 (1.62 MPa) obtained was almost 5 times higher than that of the earth mortar M2 (0.29 N/mm^2) and the average compressive strength

of cement mortar M1 (2.03 MPa) gave 4 times higher values than earth mortar M2 (0.55 N/mm^2).
Flexural and shear strength of RE is already considered very low. The dry density of cement mortar M1 calculated from beam specimen was 1.80 g/cm^3 and cylinder was 1.73, whereas earth mortar M2 beam and cylinder specimens gave 1.68 and 1.77 g/cm^3, respectively. Dry density of RE is mentioned as 1.75 g/cm^3 which is comparable to all the cases in both the mortars.

The modulus of elasticity obtained with the tensile test on meshes gave very low values except in the case of the metallic mesh. Low density plastic mesh proved to the most deformable mesh with the lowest values of the Young's modulus. Comparison of the meshes Young's modulus values with those of both mortars revealed that the stiffness of the plastic meshes fall much below the stiffness of both mortars. Only the metallic and glass fibre meshes fall within stiffness with identical order of magnitude.

Pull-off test gave many significant findings. The learnings can be concluded as; firstly, the cement mortar M1 was found to have a good adhesion with the RE substrate than earth mortar M2. The cement mortar M1 seemed to have stabilised the RE substrate as the depth from the overlay surface to the RE failure surface was slightly higher in M1 test specimens than M2 specimens. The mortar overlay should have good bonding with the RE substrate in order to perform as an integrated solution.

And secondly, because of the rough surface and large gravel present in RE the circular drilling could not be done in the substrate. This issue could be simplified and solved by cutting/slicing the mortar surface and the substrate to 2-5mm deeper in a polygonal shape, this method was used in recent research on masonry from Cardani et al. (2016) in Italy. Though this pull-out test provides limited information but is very useful in evaluating preliminary strength in reinforced conditions (Cardani, et al., 2016). The polygonal cutting will be a useful solution in the case when the mortars will be reinforced with meshes where circular drilling would be a more difficult task.

6.2 Future research

This experimental work serves as starting point of a major research project, where the strengthening of rammed earth constructions will be studied in detail. Therefore, the experience obtained from the experimental program of this work is used to identify the future needs and requirements of the project research. Some of the important points are listed below:

Selection of materials - Mortar materials selection needs a careful thought, as it is needed to have adequate amount of clay and binder/stabilizer in the mortar to increase the adhesion with the substrate. Soils/mortars with high clay content also have high dry strength. As a part of this project, other 5 types of earth mortars are also being experimented as a complementary master thesis. Lime mortar can also be an option as overlay or used as a binder in earth mortar. As general comment, it should be noted that further research is needed with respect to the adhesion capacity of mortars to earthen supports.

Reinforcing meshes - Meshes should be ductile in order dissipate energy through deformation and increase the structural capacity of the system. From the tensile test of common low cost meshes, it is possible to state that reinforced coatings are expected to have marginal contribution for the structural capacity, even if the mesh is fully exploited. On the other hand, major contribution is expected with respect to the ductility and energy dissipation, providing that good connection is established with the support. Therefore, future research should be also addressed to the study of anchoring systems.

Project feasibility - Earth is considered as the material for poor. The retrofitting methods and materials should be affordable, locally available and easily transportable. Workmanship and executions should also be kept in mind. The strengthening methods could be more complicated for implementation at the local sites than during laboratory testing. A thorough research at case studies is also recommended.

Conservation works – The conservation of built heritage is an interdisciplinary subject, hence structural retrofitting of any rammed earth building should be complying with the principles and guidelines of ICOMOS. In no case the strengthening method should cause additional problem to the existing structure. Therefore, future investigations should be addressed to the study and mitigation of compatibility and durability issues, with respect to the use of reinforced coatings in rammed earth constructions.

Disaster awareness - Even if the reinforced coating strengthening solution is fully developed, it is always a challenge to spread awareness and the prerequisite of the seismic retrofitting. The word should be spread to one and all and people should be stimulated to strengthen their own houses.

REFERENCES

AEI, 2016. *Auroville Earth Institute.* [Online]
Available at: http://www.earth-auroville.com/building_with_earth_en.php
[Accessed April 2016].

Anon., 2016. *www.culture-terra-incognita.org.* [Online]
Available at: http://www.culture-terra-incognita.org/images/pdf/map.pdf

Anon., 2016. *www.earthstructures.co.uk.* [Online]
Available at: http://www.earthstructures.co.uk/history.htm
[Accessed April 2016].

Anon., n.d. *www.lowimpact.org.* [Online]
Available at: http://www.lowimpact.org/lowimpact-topic/rammed-earth-building/
[Accessed May 2016].

Anon., n.d. *www.madehow.com.* [Online]
Available at: http://www.madehow.com/Volume-3/Rammed-Earth-Construction.html
[Accessed May 2016].

Ascione, L., Felice, G. & Santis, S., 2015. A qualification method for externally bonded Fibre Reinforced Cementitious Matrix (FRCM) strengthening systems. *Elsevier.*

ASTM:C1583, 2004. *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),* West Conshohocken: ASTM International.

Bhutan, 2011. *The Royal Government of Bhutan, United Nations and The World Bank: Joint Rapid Assessment for Recovery, Reconstruction, and Risk Reduction,* s.l.: s.n.

Blondet, M. & Aguilar, R., 2007. *Seismic Protection of Earthen Buildings.* Peru, s.n.

Blondet, M., Vargas, J., Velasquez, J. & Tarque, N., 2006. *Experimental Study of Synthetic Mesh Reinforcement of Historical Adobe Buildings.* s.l., ISBN.

CAE, 2016. *Consortium Avantech Engineering Pvt. Ltd., www.avantech.in.* [Online]
Available at: http://www.avantech.in/products/bond-test-pull-off-test.aspx

Cancino, C., Farneth, S. G. F., Neumann, P. & Webster, F., 2009. *Damage Assessment of Historic Earthen Buildings After the August 15, 2007 Pisco, Peru Earthquake,* Los Angeles: The Getty Conservation Institute.

Cardani, G. et al., 2016. On site composites-to-masonry bond evaluation in presence of rising damp and salt crystallization. *Brick and Block Masonry – Trends, Innovations and*

Challenges – Modena, da Porto & Valluzzi (Eds), Taylor & Francis Group, London(ISBN 978-1-138-02999-6).

Ciancio, D., Beckett, C., Augarde, C. & Paul, J., 2015. *First international conference on rammed earth construction.* s.l., ICE.

Ciancio, D. & Beckett, C., February 2015. *Rammed Earth Construction: Cutting-Edge Research on Traditional and Modern Rammed Earth.* s.l.:CRC Press.

Correia, M. & Fernandes, M., 2006. *International Seminar Theory and Practice in Conservation..* Lisbon, s.n.

Culture-terra, n.d. *http://www.culture-terra-incognita.org.* [Online]
Available at: http://www.culture-terra-incognita.org/images/pdf/map.pdf
[Accessed May 2016].

De Sensi, B., 2003. *Terracruda, La Diffusione Dell'architettura Di Terra (Soil, Dissemination of Earth Architecture),* s.l.: s.n.

DIN, 2013. *DIN 18947 Earth plasters - Terms and definitions, requirements, test methods,* s.l.: s.n.

DIN, 2012. *Soil, investigation and testing - Proctor-test.* 18127:2012-09 ed. Berlin: s.n.

Dominguez, O., 2015. *Preservation and repair of rammed earth constructions,* s.l.: s.n.

EN:1015-11, 1999. *Methods of test for mortar for masonry- Part 11: Determination of flexural and compressive strength of hardened mortar.* s.l.:BSI.

EN:1015-3, 1999. *Methods of test for mortar for masonry- Part 3: Determination of consistence of fresh mortar (by flow table),* s.l.: s.n.

EN1097-3, 2002. *Ensaios das propriedades mecânicas e físicas dos agregados. Parte 3: Determinação da baridade e do volume de vazios.* s.l.:ICS.

Felice, G. et al., 2014. Mortar-based systems for externally bonded strengthening of masonry. *Materials and Structures*, 12 June.

Figueiredo, A. et al., 2012. Seismic retrofitting solution of an adobe masonry wall. *Materials and Structures*, 46(203–219).

Garbin, E. et al., 2014. *Characterization of Fibre Reinforced Geopolymers as structural strengthening material for brick masonry.* Guimarães, s.n.

Getty, 2016. *www.getty.edu.* [Online]
Available at: http://www.getty.edu/conservation/our_projects/field_projects/terra/

Getty, 2016. *www.getty.edu.* [Online]
Available at: http://www.getty.edu/conservation/our_projects/field_projects/terra/

Ghiassi, B. et al., 2015. *Tensile and bond characterization of natural fibers embedded in inorganic matrices.* s.l., s.n.

Gomes, M., Gonçalves, T. & Faria, P., 2013. *The compatibility of earth-based repair mortars with rammed earth substrates.* Glasgow, Scotland, 3rd Historic Mortars Conference.

Gomes, M. I., Gonçalves, T. & Faria, P., 2014. Unstabilised rammed earth: characterization of the material collected from old constructions in south Portugal and comparison to normative requirements. *International Journal of Architectural Heritage,* Taylor & Francis, 8(2)(185-212. DOI 10.1080/15583058.2012.683133).

Gramlich, A. N., March 2013. A concise history of the use of the rammed earth building, technique including information on methods of preservation, repair and maintenance.

Grohmann, M., 1998. *Introduction al diseno sesmorresistence, in: Laboratorio de Construccion Experimental, Universidad de Kassesl (ed.),* Kassel, Germany: s.n.

Houben, H. & Guillaud, H., 1989. *Traité de construction en terre. L'encyclopédie de la construction en terre. ,* s.l.: Marseille: Edition Parenthèse..

ICOMOS, 2003. *ICOMOS Charter- Principles for the Analysis, Conservation and Structural restoration of Architectural heritage.* Zimbabwe, ICOMOS: 14th General Assembly.

Incognita, T., 2016. *Earthen architecture in europe,* s.l.: s.n.

ISCEAH, 2016. *isceah.icomos.org.* [Online]
Available at:
http://isceah.icomos.org/index.php?option=com_content&task=view&id=1&Itemid=2

ISO, 2004. *Geotechnical investigation and testing - Laboratory testing of soil Part 12: Determination of Atterberg limits..* Geneva: ISO/TS 17892-12:2004.

ISO, 2013. *Geotechnical investigation and testing - Identification and classification of soil.* 14688-1:2002 ed. Geneva: s.n.

Jaquin, P., 2011. *The earthen architecture initiative,* s.l.: Getty Conservation Institute.

Jaquin, P., Gerrard, C., Augarde, C. & Canivell, J., 2013. Damage in historic rammed earth structures: A case study at Ambel.

Jurina, L. & Righetti, M., n.d. *Traditional building in Peru,* s.l.: s.n.

Keefe, L., 2012. *Methods and Materials, Repair and Conservation.* s.l.:Routledge.

Langenbach, R., 2010. *'Earthquake Resistant Traditional Construction' is Not an Oxymoron: The Resilience of Timber and Masonry Structures in the Himalayan Region and Beyond, and its Relevance to Heritage Preservation in Bhutan.* USA, s.n.

Lima, J. & Faria, P., n.d. *Eco-efficient earthen plasters. The influence of the addition of natural fibers.* São Miguel, Azores, s.n.

LNEC, 1966. *LNEC E196 - Particle size distribution analysis.* Lisbon: Laboratório Nacional de Engenharia Civil: s.n.

Miccoli, L. e. a., 2014. Static behaviour of rammed earth: experimental testing and finite element modelling. *Materials and Structures,* Issue 11527..

Mileto, C., Vegas, F. & Cristini, V., 2012. Rammed Earth Conservation. In: s.l.:CRC Press, p. 293.

Minke, G., 2001. *Construction manual for earthquake-resistant houses built of earth,* s.l.: GATE-BASIN (Building Service and Information Network) andGTZ GmbH (Gesellschaft für Technische Zusammenarbeit)).

Minke, G., 2006. *Building with Earth:Design and Technology of a Sustainable Architecture.* Basel · Berlin · Boston: Birkhäuser.

Minke, G. & Schmidt, H., 2015. Building earthquake resistant clay houses. *Ithaka-Journal for biochar materials, ecosystems and agriculture (IJ-bea),* Issue ISSN 1663-0521, www.ithaka-journal.net/87, pp. 349 -355.

Navaratnarajah, S., 2015. Mesh type seismic retrofitting for masonry structures: Critical issues and possible strategies. *European Journal of Environmental and Civil Engineering.*

Parreira, D. J. d. S., n.d. Seismic Analysis of a Rammed Earth Building.

Powderhandling, n.d. *www.powderhandling.com.* [Online]
Available at: https://www.powderhandling.com.au/bulk-density-chart
[Accessed May 2016].

Rocha, M., 2005. *Rammed earth in traditional architecture: construction techniques. ,* Portugal, Argumentum, Lisbon, Portugal: A. C. Terra, Earth architecture.

Röhlen, U. & Ziegert, C., 2014. *Lehmbau-Praxis Planung und Ausführung,* Berlin: Beuth Verlag GmbH.

Schroeder, H., 2015. Sustainable Building with Earth. In: s.l.:Springer.

Silva, R. A. M. d., 2013. *Repair of Earth Constructions by Means of Grout Injection,* s.l.: s.n.

Silva, R. e. a., 2014. Conservation and new construction solutions in rammed earth. In: Structural rehabilitation of old buildings. *Springer,* pp. 77-109.

Silva, R. et al., n.d. *Rammed earth: feasibility of a global concept applied locally,* s.l.: s.n.

Tavares, A., 2012. *Process of Rehabilitaion and Strengthening of Earth Constructions - Seismic Concerns.* s.l.:s.n.

UNESCO, W. H. C., n.d. *http://whc.unesco.org.* [Online]
Available at: http://whc.unesco.org/en/soc/?action=list&sitescategory=1&themes=1
[Accessed May 2016].

UNESCO, W. H. C., n.d. *http://whc.unesco.org.* [Online]
Available at: http://whc.unesco.org/en/earthen-architecture/
[Accessed May 2016].

Vargas, J. P. p., n.d. *Earthquake resistant rammed-earth (Tapial) buildings,* pp. Pricipal Professor, Dept. of Civil Eng., Catho;ic University of Peru, PERU.

Vora, M., Patel, A. & Shaikh, M., 2014. Stabilization of rammed earth. *IJRET: International Journal of Research in Engineering and Technology,* 03 Issue(04).

Ziegert, C. &. P. C., 2010. Inventory of earthquake-induced failure mechanisms related to construction types, structural elements, and materials. *NIKER: New integrated knowledge based approaches to the protection of cultural heritage from earthquake-induced risk*, p. 72.