Doctoral Thesis

MECHANICAL, STRUCTURAL AND SEISMIC BEHAVIOR OF RAMMED EARTH CONSTRUCTIONS

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Programa de Doctorado en Ingeniería Civil

UNIVERSITÀ DEGLI STUDI FIRENZE

International Doctorate in Civil and Environmental Engineering

Editor: Universidad de Granada. Tesis Doctorales
Autor: Fernando Ávila Cruces
ISBN: 978-84-1117-693-4
URI: https://hdl.handle.net/10481/80013

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Dept. of Civil and Environmental Engineering

International Doctorate in Civil and Environmental Engineering, cycle XXXV

University of Florence

UNIVERSIDAD DE GRANADA

UNIVERSITÀ DEGLI STUDI FIRENZE

December 2022

Mechanical, Structural and Seismic Behavior of Rammed Earth Structures
Comportamiento Mecánico, Estructural y Sísmico de las Construcciones en Tapial
Comportamento Meccanico, Strutturale e Sismico delle Costruzioni in Terra Battuta

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A todos los que han puesto su
granito de arena en este proyecto.

Acknowledgments

I would like to thank my supervisors Prof. Rafael Gallego, Prof. Mario Fagone and Prof. Giovanna Ranocchiai for their help and advice during the development of this doctoral thesis. Prof. Gallego trusted me from the beginning to join the team at the University of Granada and carry out this research with them, and Prof. Fagone and Prof. Ranocchiai believed in this project and opened to me the doors of their department at the University of Florence.

Words cannot express my gratitude to Prof. Esther Puertas for her invaluable patience, feedback and constant support during these years. She is the main reason why I started this research, and this thesis would never have been possible without her.

I would also like to acknowledge my colleges in Granada and in Florence; they have been a great help and a source of inspiration during the course of this research. Special thanks to Dr. Ignacio Arto for his help and advice during the conduction of the tests at the University of Granada, and to Prof. Roberto Bardotti –scientific manager of the DICEA Geotechnical Laboratory– and Enzo Barlacchi and Leonardo Bucci –technical manager and assistant, respectively, of the DICEA Structures and Materials Laboratory– for their valuable help during the conduction of the tests at the University of Florence.

Lastly, I would like to thank my family for their enormous support and encouragement. These few lines are not enough to express all my gratitude, without them I would not have made it this far. I am also really thankful to my friends, those I have met during these years of doctoral studies and those who have been with me since long before, for filling these years with great moments that have given me the necessary strength to move forward and reach my goals.

Abstract

This doctoral thesis presents a thorough analysis of the mechanical, structural and seismic behavior of rammed earth structures, aimed at encouraging the use of this technique in modern construction.

Rammed earth is a traditional construction technique that has been used all over the world since antiquity, but today it is attracting renewed interest as an environmentally sustainable building solution. However, the lack of national and international standards based on the structural knowledge of this kind of constructions, makes it difficult for designers and builders to adopt this technique in new constructions. In this regard, as a first step, this thesis presents a detailed compilation of the most relevant results obtained by several researchers about the mechanical and physical properties of rammed earth, including the laboratory tests used to measure these properties and the additives and reinforcements that can be used to improve the material behavior.

An experimental testing campaign is carried out to evaluate the mechanical properties of rammed earth stabilized with one of the most relevant additives, lime, focusing on the effect of increasing lime contents and the strength development process, two factors that are essential to build constructions with this technique and that have not been thoroughly studied yet. Compression tests and nondestructive ultrasonic pulse velocity tests are performed.

For unstabilized rammed earth, the uniaxial compression tests are combined with diagonal compression test in order to assess also the shear behavior of the material, essential to understand its failure mechanisms (particularly under extreme loads such as a seism). This data is used to develop a numerical model of the material based on the concrete damage plasticity model in the FEM software Abaqus. The proposed behavioral model is evaluated by replicating with finite elements the diagonal tests carried out in laboratory.

Considering the vulnerability of rammed earth structures under the action of an earthquake and the numerous areas of earth construction with a significant seismic hazard, in the last part of this study the seismic behavior of this kind of structures is evaluated. The state of the art about this topic is presented and analyzed, including the scientific research about the structural behavior of rammed earth walls subjected to horizontal loads, potential seismic reinforcements, and requirements and recommendations indicated in the existing standards and guidelines about earth construction in seismic areas.

Resumen

Esta tesis doctoral presenta un análisis detallado del comportamiento mecánico, estructural y sísmico de las estructuras construidas con la técnica del tapial, orientado a incentivar su uso en la construcción contemporánea.

El tapial es una técnica de construcción tradicional usada en numerosos lugares del mundo desde la antigüedad, y que hoy está generando un renovado interés como solución constructiva medioambientalmente sostenible. Sin embargo, la falta de normativa nacional e internacional basada en el conocimiento estructural de este tipo de construcciones dificulta, para diseñadores y constructores, su introducción en edificios de nueva construcción. En este sentido, como un primer paso, la presente tesis muestra una revisión detallada de los resultados más relevantes obtenidos por numerosos investigadores sobre las propiedades mecánicas y físicas de la tapia, incluyendo los ensayos empleados para medir estas propiedades y los aditivos y refuerzos que pueden ser usados para mejorar el comportamiento de este material.

Se lleva a cabo una campaña de ensayos para evaluar las propiedades mecánicas de la tapia estabilizada con uno de los aditivos más relevantes, la cal, centrada en determinar el efecto del uso de contenidos crecientes de cal y en el proceso de obtención de resistencia, dos factores esenciales para emplear esta técnica en nuevas construcciones y que no han sido todavía estudiados en profundidad. Para esto, se lleva a cabo ensayos a compresión y ensayos no destructivos de velocidad de ultrasonidos.

Para la tapia sin estabilizar, los ensayos de compresión uniaxial se combinan con ensayos de compresión diagonal, con el objetivo de determinar también el comportamiento a cortante del material, fundamental para entender sus mecanismos de fallo (especialmente bajo cargas extremas, como las sísmicas). Los datos experimentales se usan para desarrollar un modelo numérico del material basado en el modelo *concrete damage plasticity* de Abaqus. El modelo propuesto se evalúa replicando en elementos finitos los ensayos de compresión diagonal realizados en laboratorio.

Teniendo en cuenta la vulnerabilidad de las estructuras de tapia frente a la acción de un terremoto y las numerosas áreas con presencia de construcción en tierra que presentan un riesgo sísmico elevado, en la última parte de este estudio se evalúa el comportamiento sísmico de este tipo de estructuras. Se presenta y analiza el estado del arte sobre esta materia, incluyendo la investigación científica relativa al comportamiento estructural de muros de tapia sometidos a acciones horizontales, posibles refuerzos sísmicos, y requisitos y recomendaciones indicados en las normativas y guías existentes sobre construcción con tierra en regiones con alta sismicidad.

Riassunto

Questa tesi di dottorato presenta un'analisi in dettaglio del comportamento meccanico, strutturale e sismico delle strutture in terra battuta (pisé), con l'obiettivo di potenziare il suo uso nell'edilizia contemporanea.

Il pisé è una tecnica di costruzione tradizionale usata in diversi luoghi di tutto il mondo dai tempi antichi, e oggi sta suscitando un rinnovato interesse come soluzione costruttiva ecosostenibile. Tuttavia, la mancanza di normative nazionali e internazionali basate sulla conoscenza strutturale di questo tipo di costruzione, rende difficile per progettisti e costruttori l'introduzione di questa tecnica in nuove costruzioni. In questo senso, come primo passo, la presente tesi mostra un rapporto dettagliato dei risultati più rilevanti ottenuti da numerosi ricercatori sulle proprietà meccaniche e fisiche della terra battuta, comprese le prove di laboratorio usate per determinare queste proprietà e gli additivi e i rinforzi che possono essere utilizzati per migliorare il comportamento di questo materiale.

Viene effettuata una campagna di test per valutare le proprietà meccaniche della terra battuta stabilizzata con uno degli additivi più rilevanti, la calce, per determinare l'effetto dell'uso di contenuti crescenti di calce e il processo di evoluzione della resistenza, due fattori fondamentali per l'utilizzo di questa tecnica nelle nuove costruzioni e che non sono stati ancora studiati in profondità. A tal fine, si effettuano test di compressione e test non distruttivi di velocità di propagazione degli impulsi di ultrasuoni.

Per il pisé senza additivi, le prove a compressione uniassiale si combinano con prove di compressione diagonale, al fine di determinare anche il comportamento a taglio del materiale, fondamentale per capire i suoi meccanismi di rottura (particolarmente in situazioni estreme, come l'azione sismica). I dati sperimentali sono usati per sviluppare un modello numerico del materiale basato sul modello *concrete damage plasticity* di Abaqus. Il modello proposto viene valutato replicando in elementi finiti la prova di compressione diagonale sviluppata in laboratorio.

Tenendo conto della vulnerabilità delle strutture in terra battuta sotto l'azione di un terremoto e delle numerose aree con presenza di costruzione in terra che presentano un elevato rischio sismico, nell'ultima parte di questo studio si valuta il comportamento sismico di questo tipo di strutture. Si presenta e analizza lo stato dell'arte su questa materia, compresa la ricerca scientifica esistente relativa al comportamento strutturale dei muri di pisé sottoposti ad azioni orizzontali, i potenziali rinforzi sismici, e requisiti e raccomandazioni indicati dalle norme e linee guida sulla costruzione in terra in regioni con alta sismicità.

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Chapter 1
Introduction

1.1. Motivation

Earth has always been one of the most widely used building materials, from the beginnings of mankind to the present day. Proof of this is that approximately 17 % of the buildings on UNESCO World Heritage List are made of earth, and that around one third of the world's population lives in earthen dwellings. The reasons for this success are the great availability of the material at a very limited cost, its workability and versatility, and its good mechanical and insulating properties.

As a result, numerous techniques have been developed over the centuries using earth as the main material, among which rammed earth stands out for its long historical tradition in several countries all over the world. Rammed earth building technique consists in compacting soil in layers between temporary formwork, that are removed once the desired height of the wall is reached. The source material for rammed earth is soil graded from clay to fine gravel, combined with a certain amount of water and, sometimes, other additives.

The knowledge about rammed earth as a construction technique has traditionally been transmitted orally from one generation to the next one, with few structural notions, most of them based only on geometric relations between the dimensions of the elements. Thus, despite the extensive worldwide presence of rammed earth constructions, most of the existing standards regarding this technique are based on these geometric relationships and traditional knowledge and building experience, without delving into the understanding of the mechanical and structural behavior of the material. Likewise, there are few standards related to the laboratory testing procedures for rammed earth, so researchers and builders have to use methodologies initially designed for other construction materials.

This situation contrasts with the growing interest developed over the last years in the introduction of this technique in modern construction. As sustainability becomes an increasingly important aspect in the building sector, techniques and processes capable of reducing environmental impacts through the minimization of industrial processes and the use of locally available are receiving a new boost. This concept of sustainable construction is also framed within the UN Sustainable Development Goals, particularly with goals number 9 “Build resilient infrastructure, promote sustainable industrialization and foster innovation” and 12 “Ensure sustainable consumption and production patterns". In this sense, rammed earth has acceptable mechanical properties and good thermal and acoustic insulating capacity, with almost zero environmental impact, characteristics that seem to augur a promising future.

This contrast between the enormous worldwide presence of rammed earth and the growing importance of its use in new construction structures, and the little attention it has received so far from the regulatory system, highlights the need to develop a methodology for the study of the behavior of rammed earth structures, which allows the understanding of the structural behavior of existing rammed earth constructions and the introduction of this technique in modern construction.

1.2. Aim and scope

The aim of this doctoral thesis is to deepen the knowledge about rammed earth mechanical, structural and seismic behavior, focusing on the introduction of this technique in modern construction.

To reach this general goal, the following research lines are developed within the framework of the present thesis:

1. Evaluation of the state of the art or rammed earth construction, including scientific research and published standards.
2. Characterization of the mechanical properties of rammed earth by means of destructive and nondestructive laboratory tests.
3. Analysis of the potential improvements of rammed earth mechanical behavior by additivation, focusing on lime-stabilized rammed earth.
4. Development of a numerical behavioral model, based on the experimental data, that accurately replicates the behavior of the rammed earth material.

1.3. Organization of the document and methodology

The content of this document is divided into eight chapters, including the present introduction and a last chapter with final conclusions. Each chapter describes and details one of aspect of the investigations carried out during the research of the present doctoral thesis; indicating, if applicable, the methodology followed, a discussion of the results and the conclusions drawn.

The first two chapters introduce de research and analyze the origins of earth construction, the existing techniques and the current regulations and standards about this kind of structures. Chapters 3 and 4 focus on the mechanical and physical properties of rammed earth, evaluating the characterization techniques and the potential improvements via stabilization and reinforcement. Chapters 5 and 6 include the experimental tests carried out in the universities of Granada and Florence in order to assess several aspects of the mechanical behavior of unstabilized and lime-stabilized rammed earth; using this information to develop, at the end of the sixth chapter, a numerical finite element model for rammed earth. Finally, the last chapter before the general conclusions focuses on the seismic behavior of rammed earth constructions.

A brief description of the content of each chapter is presented below.

Chapter 2. Background: earth as a building material

From the very beginning, the human being has used earth as a construction material. Its availability at little or no cost, its versatility and its mechanical and insulating properties have turned it into an excellent constructive solution throughout history. Different cultures all over the world have developed several building techniques using earth as the main material, adapting them to the local conditions and the improvement of the building methods. This chapter presents a review of the use of earth as a construction material over time, describing the main building techniques that use this material as it basis. In a second part of the chapter, an analysis of the principal standards about earth construction is included, focusing on rammed earth building technique.

Chapter 3. Mechanical and physical properties of unstabilized rammed earth

The aim of this third chapter is to critically review the existing literature about unstabilized rammed earth characterization, considering the tests and experiments carried out by several authors and compiling and analyzing the results obtained and their variability; with the final purpose of identifying relevant values and possible relationships between them.

The first section of this paper analyses the requirements that soils must meet in order to be considered acceptable for unstabilized rammed earth construction. The second part deals in detail with the test results of the main mechanical properties. The third section evaluates the thermal, acoustic and humidity insulating properties of the material. The fourth section focuses on the durability of rammed earth and the impact of aggressive environments; and the last section analyzes the environmental benefits and economic impact that have been measured in diverse studies for unstabilized rammed earth constructions, comparing the results with other common construction materials.

Chapter 4. Stabilization and reinforcement of rammed earth

When rammed earth technique is to be applied in new constructions, its mechanical performance is frequently not good enough to reach the values defined by the building standards. To improve these mechanical properties –and also some other aspects such as the thermal and acoustic behavior– diverse additives can be added to the soil and water mixture, leading to the so-called stabilized rammed earth.

Considering the above, this chapter analyzes the state of the art of stabilized rammed, aiming to present the different options for rammed earth stabilization, from the point of view of the property that needs to be improved, in order to make it easier for researchers and builders to choose the best alternative and to understand the consequences (mechanical, environmental and economical) derived from the stabilization.

The chapter is divided into five parts, including the mains aspects to be considered when choosing a construction technique or material. The first one presents the main stabilizers that have been commonly used in rammed earth construction, their characteristics and the characteristics of the soil to be used for stabilization. The second and third parts regard the mechanical behavior and insulating properties of stabilized rammed earth, focusing on how each kind of stabilizer is used to enhance each parameter. Then the durability is analyzed, as one of the greatest concerns about rammed earth structures. Finally, the last sections evaluates the environmental and economic impact of this building technique, focusing on how the use of stabilizers could affect some of the main benefits of traditional unstabilized rammed earth construction.

Chapter 5. Lime-stabilized rammed earth: lime content and strength development. Experimental campaign

Analyzing the existing buildings made of rammed earth, it is possible to observe that one of the additives with longest tradition for rammed earth stabilization is lime, existing several examples of historic constructions made of lime-stabilized rammed earth and a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils. However, and despite its historical use, today lime has been superseded by cement as the most common stabilizer for rammed earth, and as a consequence there is a lack of scientific research specifically analyzing the effects of lime stabilization in the mechanical properties of rammed earth.

Against this background, the study described in this chapter presents an analysis of the effect of lime stabilization in the mechanical behavior of rammed earth, evaluating the compressive strength and stiffness of the material with diverse lime contents and analyzing its strength development process. In addition, this chapter includes an evaluation of nondestructive ultrasonic pulse velocity testing technique as a tool to assess the mechanical properties of RE without damaging the sample.

Chapter 6. Constitutive models for rammed earth. Experimental campaign and numerical analysis

Several studies have been developed over the last years regarding the mechanical characterization of rammed earth, with some authors proposing different constitutive models to represent the mechanical behavior and failure mechanisms of the material. The existing research, however, has been mainly focused on the compressive behavior and has been developed mostly for stabilized rammed earth, in the pursuit of finding the material with the best mechanical performance.

The study presented in this chapter aims to develop a numerical model of unstabilized rammed earth that accurately reproduces its behavior both under compression and shear. As complex behavioral models need a significant amount of input data, in the first part of the study shown in this chapter, unconfined compression tests and diagonal compression tests were carried out to define the compressive and shear behavior of this material. In a second part of the study, an elastoplastic behavioral model for the material is developed, using the mechanical properties obtained experimentally and some other parameters retrieved from literature (evaluating their influence on the model through a sensitivity analysis). The accuracy of the model is evaluated replicating the experimental diagonal test with a finite element model and analyzing its behavior.

Chapter 7. Seismic behavior of rammed earth structures

Rammed earth constructions have some characteristics –high mass, low tensile and shear strength– that make them potentially vulnerable to seismic events. However, according to several post-seismic investigations, rammed earth constructions show acceptable seismic behaviors, proving that a proper design and execution can provide rammed earth structures a satisfactory seismic performance. The seismic design of this kind of structures is particularly interesting considering that many of the areas where earthen constructions are usually built are areas with a significant seismic hazard.

In this chapter, the seismic behavior of rammed earth constructions is evaluated, analyzing the structural response of rammed earth walls subjected to in-plane and out-of-plane loads and the most common failure modes under the action of an earthquake. Reinforcement solutions to improve the seismic performance of rammed earth are also evaluated, together with general recommendations for the construction of rammed earth buildings in areas with seismic hazard.

Chapter 8. Overall results and conclusions and future work

This last chapter includes general conclusions drawn as a result of the whole research carried out during the development of the present doctoral thesis. The main results of the research are evaluated and potential future work derived from this investigation is proposed.

The overall conclusions of the thesis are presented in English, Spanish and Italian.

Chapter 2
Background: earth as a building material

2.1. Introduction

From the very beginning, the human being has used earth as a construction material. Its availability at little or no cost, its versatility and its mechanical and insulating properties have turned it into an excellent constructive solution throughout history [1, 2]. Different cultures all over the world have developed several building techniques using earth as the main material, adapting them to the local conditions and the improvement of the building methods. Numerous examples of the use of earth construction by several civilizations have survived to the present day.

The progress of societies from ancient times to the present day has led to the development of regulations and standards to ensure the structural safety of constructions, and earth building techniques have been no exception. Several earth construction standard have been developed in diverse countries, but many of them are based on the traditional geometrical relationship and building recommendations. The advances in the use of modern construction materials (i.e. reinforced concrete and steel) have focused on them the scientific research for decades, leaving the technological development of earth construction techniques in the background.

The current chapter presents a review of the use of earth as a construction material over time, by different cultures and in diverse geographical zones of the planet; describing the main construction techniques that use this material as it basis. In a second part of the chapter, an analysis of the principal standards about earth construction is included, focusing on the technique of rammed earth.

2.2. Historical context

Considering the great availability of earth in almost any location and the ease with which it can be used in construction with little labor, it is not surprising that it has been one of the most widely used building materials throughout history. In fact, as it can be observed in Figure 2.1, earth construction is worldwide extended (particularly in warm and arid climate zones),existing several heritage buildings made with these techniques, many of which are included in the UNESCO World Heritage List [3, 4].

In this section, the historical presence of earth constructions in the world is analyzed, highlighting the most remarkable buildings in each continent, taking into account their historical and architectural relevance.

Figure 2.1: Areas of the world with tradition of earth construction and UNESCO World Heritage Sites. Adapted from [5].

2.2.1. Asia

The first examples of earth architecture that are still preserved today are located in Near and Middle East. Some of the oldest examples have been found in the Turkestan Region (Kazakhstan), where some archaeological sites dating from 8000 BCE to 6000 BCE already show houses made with adobe [6]. Somewhat later are the rammed earth foundations found in the locations of the ancient civilization of Assyria, dating from ca. 5000 BCE [1], or the ancient Persian cities of Tepe Yahya (3400 BCE) [7] and Chogha Zanbil (13th century BCE) (Figure 2.2a), in the current territory of Iran, also constructed with the technique of adobe.

In the Far East, particularly China, we can also find several examples of the use of earth as a construction material. It is worth to highlight, due to their historical and architectural relevance [3], the Mausoleum of the First Qin Emperor, from the 2nd century BCE, o some sections of the Great Wall of China (3rd century BCE – 17th century CE), wich are built with rammed earth or adobe and then covered with stone [1].

Somewhat more recent, but also noteworthy within Chinese earthen architecture, are the cylindrical rammed earth constructions called *tulou* in Fujian, which began to be built in the 15th century; or the Ancient City of Ping Yao (14th – 20th century) with its incredible earthen wall (Figure 2.2b) [3]. To these great constructions we must also add the long tradition existing in this country in the use of earth for the construction of private houses, which still lasts today.

(a)

(b)

Figure 2.2: Historic earth constructions in Asia: **(a)** Chogha Zanbil ziggurat, Iran (©G. Gerster, AGE Fotostock) and **(b)** rammed earth wall of the Ancient City of Ping Yaoa, China (©T. Joffroy, CRA-terre).

2.2.2. Africa

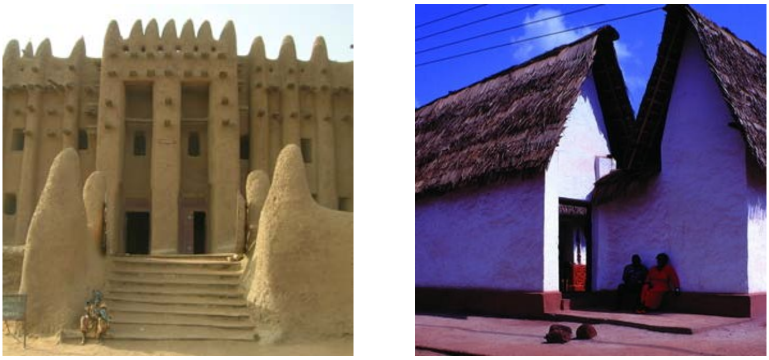
In addition to the described zones in the Middle East, it is also in the northeast of Africa where some of the oldest examples of large earthen constructions are preserved. In Upper and Middle Egypt, earth blocks constructions have been estimated to be more than 4000 years old, some of which, such as the fortification of the Medinet Habu or the Temple of Ramses II at Gourna, are still preserved today.

In addition, adobe house building has been used in the desert areas of Egypt and the rest of North Africa for at least 10 thousands years [8]. The reason for the widespread use of earthen construction on the African continent is mainly due to its good thermal performance, helping keeping the interior cool during the day and warm at night [9], and its low cost and great potential for reuse of materials [10, 11].

In Sub-Saharan Africa, there are numerous examples of earth construction techniques, hundreds of years old, that are still used today thanks to the oral transmission of knowledge. It is possible to highlight the Old Town of Djenné (Mali, Figure 2.3a), which began to be built in the 3rd century BCE; the Fortified Historic Town of Harar Jugol (Ethiopia, 13th century) [12]; or the traditional architecture of Asante (Ghana, see Figure 2.3b), Sukur (Nigeria) or Koutammakou (Togo).

2.2.3. Europe

In Europe, the use of earth for construction has historically been very present. Some studies [1] affirm that in the area corresponding to present-day Germany, earth was already used in the Bronze Age as an infill in timber-



(a) (b)

Figure 2.3: Earth construction in Africa: **(a)** Old Town of Djenné, Mali (©F. Bandarin, UNESCO) and **(b)** traditional earth house in Asante, Ghana (©T. Joffroy, CRA-terre).

framed houses and in wattle-and-daub walls. In the same country there is also one of the oldest examples of mud blocks construction, the Heuneburg Fort, dating from the 6th century BCE [1].

During the Middle Ages, earth was used in construction in Central Europe mainly in the so-called mixed techniques, as a filler for timber framing and for roof insulation. Later, between the 15th and 19th centuries, the use of rammed earth had a great expansion for the construction of buildings in Central Europe, especially in France (Figure 2.4a) and Germany, some of which are still inhabited today [1].

Since the 19th century and up to the present day, the enormous development of construction technologies and modern building materials, such as concrete or steel, progressively replaced masonry –and particularly raw earth masonry– on the European continent. In spite of this, data such as the fact that currently 15 % of rural buildings in France are made of rammed earth, or that the United Kingdom is the main consumer of adobe among industrialized countries [13], make clear the relevance, even today, of raw earth in European construction.

In the case of Spain, there are references of earth constructions around the first century BCE, included in the *Naturalis Historia* of the Roman writer Pliny the Elder, who described the presence in Hispanic territory of forts and watchtowers built with earth. Today there are few examples in the country of earth constructions of the entity of those described by Pliny, but the use of these techniques in housing is still very present, especially in the southern half of the Iberian Peninsula [7].

In Spain, among the diverse earthen construction techniques, rammed earth has reached a special development. So much so that UNESCO recognizes as World Heritage Sites up to four examples of rammed earth architecture in this country [3]: the Alhambra in Granada (Figure 2.4b), built mostly in rammed earth between the 13th and 16th centuries; the Royal Alcázars of Seville, which include several walls built with this technique during the same historical period; the historic center of Cordoba, preserving numerous buildings made with earth; and the *Desmochada Tower* of Caceres, part of the Almohad enclosure of the city, also made in rammed earth between the 13th and the 16th century.

(a)

(b)

Figure 2.4: Earth construction in Europe: **(a)** wattle and daub house in the medieval town of Provins, France (©E. Westerveld) and **(b)** the Alhambra of Granada, Spain (©P. Schinz).

2.2.4. America

The case of America, especially Central and South America, is particular because of its historical circumstances. Already in pre-Columbian America there was an important tradition of earth construction, with its own techniques and methods, but these techniques were later deeply combined with those brought by the Spaniards who arrived in the Americas since 1942 [1, 7].

Several examples of pre-Hispanic earthen architecture can be found in the continent [3, 14], been possible to highlight, due its antiquity, the Sacred City of Caral-Supe (Peru), erected between 3000 and 1800 BCE and where the smaller buildings are built with a wooden structure and earthen covering of infilling. Other examples are the burial chambers of the Tierradentro National Archaeological Park (Colombia), built between the 6th and 10th centuries; or the North Platform of the Monte Albán Archaeological Zone (Mexico, 1st century CE), built with a mixture of stones and earth (Figure 2.5a).

Even more numerous are the examples of the mixture of cultures and combined earth construction techniques visible in many historic urban centers in Latin America. Among the many that could be cited, the following stand out as part of the UNESCO Inventory of earthen architecture [3]: the cities of Potosí (Bolivia), Quito (Chile) and Antigua Guatemala (Guatemala) and the old towns of Cartagena de Indias (Colombia, Figure 2.5b), Valparaiso (Chile) or Puebla (Mexico), where there are several constructions made mainly of adobe or with mixed techniques. In the Old Havana (Cuba), on the other hand, there are some of the best examples of rammed earth construction in the American continent.

(a) (b)

Figure 2.5: Earth construction in Latin America: **(a)** Monte Albán Archaeological Zone, Mexico (©H. Guillaud, CRA-terre) and **(b)** Old Town of Cartagena de Indias, Colombia (©Einer Rivera)

In North America, the United States also preserve some examples of pre-Columbian earthen architecture. It is worth to mention, as a part of the UNESCO World Heritage, the constructions in the Chaco Canyon (9th – 13th century), the walls and dome-shaped roof in the Mesa Verde National Park (since 9th century) made with earth mortar, or the adobe houses of the Pueblo de Taos (11th – 15th century).

2.2.5. Current situation

Today, earthen construction, which allows the use of local materials and minimizes industrial processes, is gaining new momentum due to two fundamental characteristics it possesses:

- Low cost, which makes it an ideal solution for countries and regions with low resources.
- Low environmental impact, in line with the necessary evolution of construction towards an environmentally sustainable model.

These two factors position earthen construction as an important ally in achieving the Sustainable Development Goals set by the United Nations [15], and a strong alternative of common construction materials to enhance the environmental sustainability in the building activity. In fact, earth construction, in general, and rammed earth construction, in particular, are becoming more and more relevant in the building sector, with several examples of modern constructions made with these techniques in the last few years (Figure 2.6).

(a)

(b)

Figure 2.6: Examples of modern rammed earth construction: **(a)** "*Casa de Tapia*" in Ayerbe, Huesca, Spain (©X. d'Arquer, dobleSTUDIO) and **(b)** "Torcasso Residence", New Mexico, USA (©R. Reck).

The following data also offers a revealing perspective on the relevance of earthen construction for humanity:

- Between one-third and one-half of the world's population lives in earthen houses [10, 16, 17].
- Around half of the world's population knows how to build earthen houses [13].
- Circa 17 % of the constructions UNESCO World Heritage List are made with earth [3].
- Approximately a quarter of the constructions declared as "in danger" within the UNESCO World Heritage are made with earth [3].

2.3. Raw earth building techniques

As it has been explained above, different civilizations have given throughout history diverse answers to the problem of how to use earth for construction, developing numerous building techniques with this material as a basis.

Although there exists diverse classifications, several authors [14, 18] group raw earth construction techniques into three fundamental typologies:

1. Block construction.
2. Continuous or monolithic construction.
3. Mixed techniques.

Another relevant classification [19, 20] attends to the moisture content of the material, both during manufacturing and construction. Thus, we can define wet manufacturing techniques, where the manufacturing moisture is between the plastic limit and the liquid limit; and dry manufacturing techniques, with a water content at manufacture close to the optimum moisture content (OMC) of the soil. In both cases, the manufactured material can be placed on site directly or after prior drying.

Combining the two criteria, we can establish the general classification for the main raw earth construction techniques shown in Table 2.1.

Table 2.1
Classification of raw earth building techniques.

	Wet manufacture		**Dry manufacture**	
	Wet construction	**Dry construction**	**Wet construction**	**Dry construction**
Blocks		Adobe		Compressed earth blocks
Monolithic	Cob		Rammed earth	
Mixed techniques	Wattle and daub			

2.3.1. Block construction

Block construction includes all those techniques that use earth blocks that are manufactured before being placed on site. The most representative of these techniques, and one of the most common earth construction techniques in the world, is **adobe** (Figure 2.7a). The construction with adobe consists of the manufacture of blocks of clayey earth with a significant amount of water, by hand or by means of a mold, which are then dried and placed one on top of the other until the construction element in question is finished.

The adobe construction technique has the following advantages [18]:

- Easy to manufacture and store before positioning on site.
- Good thermal and acoustic insulation properties.
- Low-skilled labor required.
- Allows the construction of a wide variety of elements (walls, arches, vaults, domes...).

As main drawbacks we can cite [18, 21]:

- It requires large amounts of water in its manufacture.
- It requires soil with high clay content, which is not easily found everywhere.

- In the traditional procedure, it is difficult to guarantee the homogeneity of the dimensions of the blocks.
- The resulting material absorbs a large amount of water due to its high porosity (no significant compaction), not recommended in very rainy climates.
- Poor seismic behavior, especially for vaults and domes.
- Considerable thickness of the walls, which reduces the useful space of the building.

We can also find in this group the so-called **"superadobe"** or bagged earth, in which the blocks are tubular fabric bags (made of polypropylene or jute) filled with earth, placed one on top of the other and then compacted [14]. To these techniques, we must add the **compressed earth blocks (CEB)** (Figure 2.7b), very similar to adobe in the building technique but with a different manufacturing process that includes manual or mechanical compaction.

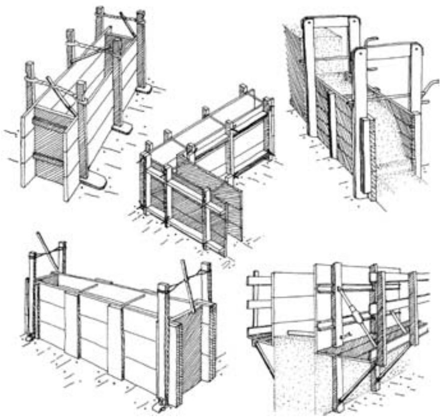
(a) (b)

Figure 2.7: Earth block construction: **(a)** adobe building in Sa'dah, Yemen (©B. Gagnon, Wikimedia Commons) and **(b)** Primary School Tanouan Ibi, Mali, made of CEB (©Levs Architecten).

2.3.2. Monolithic construction

Monolithic construction techniques refer to those in which the earth bearing element is continuous. Among these techniques, **rammed earth** clearly stands out. This technique requires the placement of temporary formwork on both sides of the element; the earth mixture –with a certain moisture content– is poured in the formwork and compacted in layers of about 7.5 cm to 15 cm [9, 20, 22, 23]. After the execution of the wall, which is usually between 30 cm and 50 cm thick [24–26], it must be left to cure/dry for a period of time to acquire its full strength.

Traditionally, wooden formwork has been used (Figure 2.8a) and compaction was performed with manual rammers also generally made of wood (Figure 2.8b), but nowadays it is common to find metal formwork, like the ones used for concrete, and the use of pneumatic rammers that facilitate the task and offer a more uniform result (Figure 2.9).



(a)

(b)

Figure 2.8: Traditional rammed earth building technique: **(a)** wooden formwork and **(b)** manual ramming process [1].

Rammed earth construction allows the use of a greater variety of soils as raw material, making it frequently possible to use material found in the vicinity of the construction site. Since its origins, it has been common to mix the soil used in rammed earth construction with other materials earth (fibers or stabilizers) with the aim of improving its mechanical behavior and durability. Rammed earth buildings are frequently covered with lime or cement plaster and painted to improve the durability, as it is the case of the rammed earth dwellings in the city of Lyon (France), shown in Figure 2.10a.

Rammed earth construction technique has the following advantages [14, 18, 21]:

- Easy to manufacture on-site, without the need for storage areas.
- It allows the use of a wide variety of soils, being possible to choose the one closest to the construction site.
- Lower water content in manufacture than adobe, suffering less shrinkage and creep.
- Good thermal and acoustic insulation properties, as a strongly compressed material.
- Low-skilled labor required.
- Longer useful life than other earth techniques, e.g. adobe.
- It can be built in both dry and humid climates.
- Better seismic performance than adobe constructions [27].

(a) (b)

Figure 2.9: Modern rammed earth building technique: **(a)** construction site (©Aerecura Rammed Earth Builders) and **(b)** compaction with pneumatic rammer (©Rammed Earth Consulting).

As main disadvantages we can cite [18]:

- Suitable almost only for the construction of walls.
- Significant thickness of the walls, reducing the useful space of the building.
- Certain difficulty for its conservation and rehabilitation.

(a) (b)

Figure 2.10: Monolithic earth constructions: **(a)** rammed earth dwellings in Lyon, France [24] and **(b)** cob house in Worcester, UK [13]

Another kind of of earthen monolithic construction, of greater simplicity and whose origin is of the most ancient, is the so-called **cob** (Figure 2.10b). The procedure consists of the formation of walls by manually stacking a mixture of mud and straw. Each "layer" has a thickness of about 50 cm and it is necessary to wait for it to dry completely before placing the following [21].

2.3.3. Mixed techniques

We define as "mixed techniques" all those techniques that combine a load-bearing structure, traditionally wood or bamboo, with an earthen structure that may or may not have a load-bearing function.

On the one hand we have the most traditional typologies, which have a light structure of wood or bamboo covered by a mixture of clayey soil –often with vegetable fibers– usually known as **wattle and daub** [14, 21] (Figure 2.11a). On the other hand, there are techniques in which the load-bearing structure –made of wood or today also of steel or concrete– has a greater entity (Figure 2.11b), and the earth is used only to cover gaps and provide thermal and acoustic insulation (e.g. a conventional beams-and-pillars building structures combined with earth walls that separate the parts of the house and provide insulation and transversal rigidity).

(a) (b)

Figure 2.11: Mixed earth building techniques: **(a)** wattle and daub house under construction in Turkey (©Atulya K. Bingham, The Mud House) and **(b)** wood and earth mixed technique houses in Stratford-upon-Avon, UK.

With regard to the mixed techniques, especially those with a light wooden structure, the following advantages can be listed [18]:

- The use of various materials allows for greater adaptability to local conditions.
- Better seismic behavior than other earthen structures, due to the greater flexibility of the assembly.
- Good thermal and acoustic insulation properties (compared to other conventional construction techniques).
- The use of larger (stronger) load-bearing structures allows for a wide variety of construction solutions and designs.

The main disadvantages are [18]:

- Greater constructive complexity and level of training of the workers.
- In solutions with wooden structure, worse fire performance.
- In solutions with wooden structure, more susceptible to attack by fungi and insects.
- When the load-bearing structure becomes more complex, the construction technique becomes less environmentally sustainable.

2.4. Standardization of rammed earth construction

Despite the widespread use of earth in construction, this material has been somewhat left aside from the evolution of the regulatory framework in most countries [28]. This situation of lack of legal framework for earth construction, and more specifically for rammed earth construction, generates technical and legal insecurity in promoters, planners and builders, causing the progressive abandonment of the technique.

The most relevant aspects of the standards and technical guides related to rammed earth construction in the world are mentioned and described in the present section.

2.4.1. Europe

In Europe, Germany was one of the first countries to develop earth construction standards, rammed earth included, with several publications between 1947 and 1956, which were annulled in 1970 [29]. From that moment on, there was a lack of normative development that lasted until 1999, when the "*Lehmbau Regeln*" (Earth Construction Standards) –last revised in 2009– were published [30]. This text, a reference for earth construction in the country, describes the general conditions for building with this material, the types of soils and their physical and mechanical properties, and construction and design methods for different construction typologies.

In Spain, the Ministry of Public Works and Transportation published the document "*Bases para el diseño y construcción con tapial*" (Basis for the design and construction with rammed earth) in 1992 [7], which gave general empirical guidelines on the properties of the material, calculation and design techniques and execution control, stands out. The application of this document is not compulsory and no further standards about earth construction have been published in the country since then, with the exception of standard UNE 41410 [31] about compressed earth blocks for walls and partitions, including definitions, specifications and test methods.

2.4.2. America

In America, most of the published standards regarding rammed earth have been developed at the state level in the United States.

The first relevant standard was elaborated in New Mexico in 1991, and updated in 2015 with two standards, one referring to building materials for earth construction [32] and the other specificcally focusing on historic buildings made of this material [33]. Another state with regulations on rammed earth is Arizona, where a first standard developed by the Maricopa Association of Governments in 1999 and updated in 2012 [34] indicates several geometric relationships to be applied in earthen constructions, mainly walls. The standard is applicable to what they define as"standard" structures, specifying that those other structures with particular local conditions must follow the indications of the Standard for Earthen IBC Structures [35].

In addition, the American Society for Testing and Materials (ASTM International) has published a design guide called "Design of Earthen Wall Construction" [36] that provides guidelines regarding the technical requirements for earthen buildings and considerations focused on sustainable earthen building development. The standard refers to both rammed earth and adobe and other earthen construction techniques.

In Central and South America, in contrast with the great tradition of rammed earth construction, there are not many standards on the subject. It is worth mentioning the publication "*Uso del tapial en la construcción*" (Use of rammed earth in construction) [37] by the National Training Service for the Construction Industry of Peru (SENCICO), which gathers a large amount of information related to rammed earth construction techniques, providing recommendations on the evaluation of the type of soil and the construction process, as well as the structural behavior of the rammed earth structures. In Brazil, there is a standard regarding rammed earth, but only in the case of to cement-stabilized earth walls [38].

2.4.3. Africa

In Africa, the initiative in the development of standards for rammed earth construction is held by the African Organization for Standardization (ARSO) and the Southern African Development Community Cooperation and Standardization (SADCSTAN), which in 2014 developed a code for the construction of rammed earth structures, which details the characteristics of the materials and formwork to be used, and design considerations for foundations and walls made with this technique, as well as a series of construction details. This standard has been adopted within their legal framework by countries such as Zimbabwe [39], which already had its own standard for rammed earth since 2000 (ZWS 724:2000).

2.4.4. Asia and Oceania

Few examples of standards for earth construction, in general, and for rammed earth, in particular, can be found in Asia. In India, there is the code of practice IS:2110-1980, which provides very general guidelines for the construction of cement-stabilized rammed earth walls [40], and the standard IS:13827-1993 on the improvement of the seismic strength of earth constructions [41], also with general indications.

More extensive and developed is the regulatory framework for earth construction in Oceania. In fact Australia was one of the first countries in the world to develop standards for adobe, rammed earth and compacted earth blocks, with the publication of the “Bulletin 5” in 1952 and its subsequent reissues in 1976, 1981 and 1987 [42]. After an attempt to develop a joint standard with New Zealand in the 1990s, Australia finally approved only –and independently– a guide for earth construction in 2002, “The Australian earth building handbook” [43]. This text sets out guidelines for the design, construction and quality control of one- and two-story buildings made of both stabilized and unstabilized rammed earth [42].

In New Zealand, there are since 1998 three standards that regulate the construction of rammed earth walls: NZS 4297, NZS 4298 and NZS 4299 [44–46]. The first of these documents describes structural design methods for walls, including durability criteria; the second one focuses on the material and the human resources for the construction of this type of structures; and the third one focuses on earth constructions that, due to their geometric and seismic risk characteristics, do not require a specific design. These three original 1998 standards have been replaced by new versions in February 2020.

2.5. Conclusions

Analyzing the numerous historical earthen constructions that have survived to the present day and the enormous expansion of this type of buildings throughout the world, it is possible to understand the relevance that earth construction has had not only in architecture and engineering, but also in human history itself.

There are several techniques using earth as the source material, but they can be classified into three groups: block construction (adobe, compressed earth blocks), monolithic construction (rammed earth, cob) and mixed techniques (e.g. wattle and daub). Also, looking at the water content, the earth building techniques can be considered dry or wet manufacture techniques and dry or wet construction techniques.

The combination between the good mechanical behavior provided by earthen buildings and their contribution to increasing environmental sustainability in constructions, has made these techniques a great alternative to the most common current techniques, attracting the interest of researchers and companies in the construction sector. However, there are still very few standards regulating earth construction, and most of them are not based on a real structural knowledge of the behavior of the material.

In this regard, New Zealand and Australia are the countries with the most developed standards about earth construction, with facilitates the incorporation of these techniques in numerous constructions in these countries. There are also some standards developed at state level in the United States, and few international standards developed in America by the ASTM or in Africa by the ARSO and the SADCSTAN. There are currently no European standards about earth constructions, and few countries have developed their own ones.

Chapter 3

Mechanical and physical properties of unstabilized rammed earth

3.1. Introduction

Rammed earth construction has historically been bound to the oral transmission of knowledge from generation to generation, with few structural notions, mostly based on geometric relations between the elements dimensions. In the same way, RE codes and standards have tend to put in writing these geometric relations, without thoroughly studying the mechanical behavior of the material.

However, considering RE as a building technique comparable to the other ones used in contemporary construction, implies that this material has to be considered and analyzed with the same rigor as any other construction material, and this means understanding its behavior and characterizing its properties. In this regard, several studies have carried out experiments in order to describe the mechanical properties of RE, with particular focus on the unconfined compressive strength. Nevertheless, and despite the increasing interest in RE construction, some of the material properties have not yet been exhaustively analyzed, and there is a very significant dispersion in the values obtain for those which have been more deeply studied and that are essential to characterize the behavior of this material.

Therefore, the aim of this chapter is to critically review the existing literature in unstabilized rammed earth (URE) characterization, considering the tests and experiments carried out by several authors and compiling and analyzing the results obtained and their variability; with the final purpose of identifying relevant values and possible relationships between them.

The first section of this paper analyses the requirements –such as particle size distribution, moisture content or density– that soils must meet in order to be considered acceptable for URE construction. The second part deals in detail with the test results of the main mechanical properties –compressive, tensile and shear strength, elastic modulus, Poisson's ratio, cohesion, friction angle and fracture energy– of URE. The third section evaluates the thermal, acoustic and humidity insulating properties of the material. The fourth section focuses on the durability of RE and the impact of aggressive environments. Finally, the last section analyzes the environmental benefits and economic impact that have been measured in diverse studies for URE constructions, comparing the results with other common construction materials.

The research presented in this chapter has been published in the following scientific article:

- F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of unstabilized rammed earth: A review.* Construction and Building Materials. 270 (2021) 121435. doi: 10.1016/j.conbuildmat.2020.121435.

3.2. Source material

3.2.1. Particle size distribution

Earth, as the source material for RE construction, must meet certain characteristics in order to be considered acceptable, obtained by means of geotechnical testing techniques. On the one hand, it is true that traditionally the soil used has simply been the one easily available near the construction site, and there are various studies [47, 48] indicating that particle size distribution (PSD) should not be considered as a discriminating parameter when selecting the suitability of a soil for RE construction.

On the other hand, however, it is equally certain that a soil mixture with heterogeneous PSD, including both fine and coarse particles, is generally recommended for earth construction [29, 49–51]. Houben et al. [29] propose one of the most well-known and recommended envelopes for the PSD of soils that might be suitable for RE walls. Figure 3.1 shows the aforementioned envelope together with the PSD used by several authors in recent studies. It can be noticed that most of the PSD present in literature are included within the recommended envelope; with the only significant exceptions of El Nabouch [26], using a soil with a great silt and clay content, and Toufigh and Kianfar [52], that utilize a mixture containing a limited amount of fine particles, even though additional clay was added to the original soil in that study.

A relevant aspect to be considered with regard to PSD is clay content. Due to its small particle size (< 0.002 mm), clay provides cohesion to the mixture, acting as the only binder between soil particles in URE [52, 56]. The optimum clay value, according to the soil mixtures used in literature (Table 3.1), is between 8 % and 14 % by mass [22, 27, 55, 57–59]; although there can be found some studies that select a coarser soil with only about a 5 % of clay [52–54] and few exceptions with a clay content near 20 % [26, 49]. According to Maniatidis and Walker [42], the percentage of fine particles (clay and silt combined) should be between 20 % and 35 %, and the percentage of sand between 50 % and 75 %. These ranges are in agreement with the

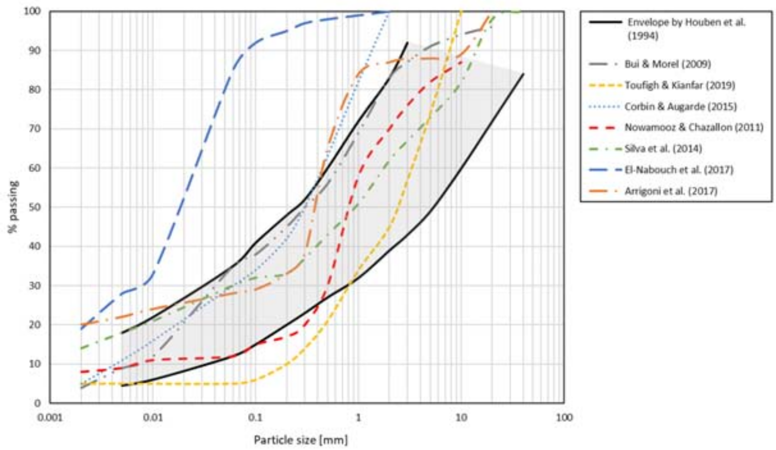


Figure 3.1: Particle size distribution for URE constructions: envelope recommended by Houben et al. [29] and values used by Bui & Morel [53], Toufigh & Kianfar [52], Corbin & Augarde [54], Nowamooz & Chazallon [22], Silva et al. [55], El Nabouch et al. [26] and Arrigoni et al. [49].

envelopes recommended by Houben et al. [29] and with the soil mixtures used by most authors in URE literature [27, 49, 53–55, 59].

Therefore, it is possible to conclude that, even though almost any type of local soil can be used as a source material for URE, controlling the PSD of the earth material is important in order to reach a better mechanical behavior. In this regard, as shown in Table 3.1, a PSD with about 30 % fine particles and 70 % coarse particles seems to be recommended. It has to be considered, however, that the use of non-local materials in order to improve the PSD of the soil may lead to an increase in the environmental and economic costs.

3.2.2. Optimum moisture content and dry density

Soil moisture content is another key aspect that affects the mechanical behavior of the RE constructions [51]. In contrast to other parameters related to RE, there is quite a good agreement on the water content that RE source materials should have. Walker et al. [51] recommend using the optimum moisture content (OMC) of the soil $\pm$ 1 to 2 %. This OMC is generally obtained via standard or modified Proctor compaction test, and leads to moisture values from 8 % to 12 % by weight in almost all the studies present in literature [9, 22, 26, 27, 49, 52–55, 57, 59].

Nevertheless, it is important to understand that the Proctor compaction tests do not apply the same energy as the one used in earth construction, which means that they lead to a OMC that could be excessively high [51, 61].

Table 3.1
Particle size distribution [%wt] for URE source material.

Ref.	Clay	Silt	Sand	Gravel
[53]	4	31	48	17
[52]	5	0	40	55
[57]	8	34	8	50
[22]	8	4	60	28
[58]	10	–	–	–
[27, 60]	11	25	65	
[59]	12	13	45	30
[55]	14	16	32	38
[49]	20	8	59	13
[20]	20	65	15	0

In addition, results of a standard Proctor test [62], which implies lower compaction energy, could be more accurate when a manual rammer is used for the construction [56]; while modified Proctor test results could fit better in cases where a pneumatic rammer is used. Despite all these facts, Proctor compaction tests are still a useful and reliable method to assess the appropriate manufacturing water content for RE structures [20].

Depending on the water content during the compaction of the material, and also on the compaction energy applied, a different dry density is obtained. As moisture values close to the OMC are used for RE, the soil reaches almost its maximum dry density (MDD), which is an indicator of the compressive strength of the earth material [20, 63]. A wide range of dry density values are quoted for URE, varying from 1 750 to 2 200 kg/m^3, as shown in Figure 3.2.

Studies analyzing the influence of compaction energy on the mechanical properties of earth materials [61, 63–65] indicate that a higher compaction energy increases the MDD of the mixture and thus its compressive strength. Also, when increasing the compaction energy, the OMC at which MDD is reached becomes lower [61].

3.3. Mechanical properties

3.3.1. Unconfined compressive strength

As is the case with most brittle materials, especially those with low cohesion, unconfined compressive strength (UCS) becomes the main parameter to characterize the mechanical behavior, and so happens with RE. Several studies have been carried out in the last years to determine URE compressive strength (Table 3.2), most of them using small-size samples with different shapes and only a few [59, 66, 67] with constructive-scale samples. Although there is a significant dispersion in the results, it is possible to observe that these are in a range from 1.0 MPa to 2.5 MPa, excluding some few exceptions.

Table 3.2
Density (ρ), moisture content (MC), compressive strength (f_c) and elastic modulus (E) of unstabilized rammed earth.

Ref.	Sample [cm]	ρ [kg/m^3]	MC [%wt]	f_c [MPa]	E [MPa]
[59][a]	$30 \times 30 \times 60$	1920	13	0.81	65
[57]	$40 \times 40 \times 65$	1900	11	1.00	100
[68][a]	$\varnothing 4$, $h = 8$	1649	21	1.04	103
[69]	$10 \times 10 \times 10$	1660	–	1.10	1050
[20]	$25 \times 25 \times 50$	1878	12	1.15	365
[55]	$55 \times 55 \times 20$	2100	10	1.26	1034
[66]	$100 \times 100 \times 100$	2000	–	1.30	500
[49]	$\varnothing 10$, $h = 20$	2080	8	1.40	–
[70][a]	$\varnothing 7.5$, $h = 15$	2043	12	1.77	–
[71]	$\varnothing 7.5$, $h = 15$	2143	7	1.85	34
[59]	$\varnothing 30$, $h = 60$	1850	13	1.90	–
[72]	$15 \times 15 \times 15$	2020	–	1.90	–
[20]	$\varnothing 10$, $h = 20$	1790	12	2.00	763
[52]	$\varnothing 7.5$, $h = 15$	1946	12	2.23	143
[59]	$\varnothing 10$, $h = 20$	1850	13	2.46	160
Mean		1942	12	1.55	392
CV		0.084	0.282	0.324	0.992

[a]Mean values for URE samples.

The test procedure followed to obtain UCS of the earthen material is in most cases the conduction of uniaxial compression tests. Since there are no ASTM standards specifically for testing UCS of RE samples, authors have followed ASTM D1633 [73] standard for compressive strength of soil-cement cylinders [74] or proposed specific procedures derived from ASTM standards for cement mortars [75] and from masonry design rules [59]. Although the dispersion in the UCS results of RE in literature is partly due to the heterogeneity of the material itself, a standardized test procedure would be necessary in order to actually make the results obtained by the diverse studies comparable.

It is well known that UCS is influenced by the manufacturing conditions (moisture content, compaction energy and sample size) [20, 76], but the relation between these parameters and the UCS of RE is still unclear. Figure 3.2 shows that an increase in the material density leads to a greater UCS, although there is a very significant dispersion. Maniatidis and Walker [59] conducted compression tests on samples with different sizes and shapes, concluding that there was a considerable variation in soil performance between small-scale cylinders (⌀10 cm, $h = 20$ cm) and full-scale prisms ($30 \times 30 \times 60\,\text{cm}^3$) and columns (⌀30 cm, $h = 60$ cm) made of the same material. That reduction in the UCS of the full-scale samples was attributed to the variation in material grading, which included aggregates greater than 20 mm. Also Bui et al. [77] performed tests with specimens of different scales, indicating that the UCS obtained for small samples was higher than the one calculated for the bigger ones, which might be more representative of the behavior of a real RE wall.

Not only size but also shape affects the UCS of the RE specimens. Studies present in literature [26, 59, 77] have reported substantial differences in the results for prismatic and cylindrical samples. One of the reasons can be that the friction between the earth and the formwork during ramming is greater in the prismatic specimens (especially in the corners), so the cylindrical specimens can be compacted better and thus have better mechanical behavior. Also the differences in load distribution patterns between the prismatic and cylindrical specimens might be the reason for such variances in the results.

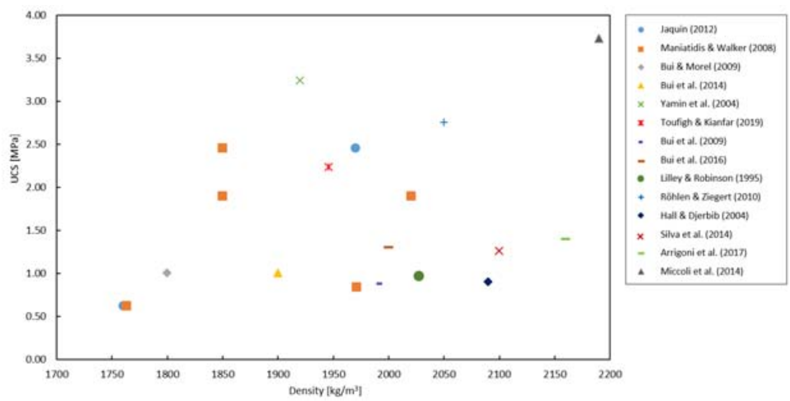


Figure 3.2: Unconfined compressive strength (UCS) as a function of density: values obtained by Jaquin [58], Maniatidis & Walker [59], Bui & Morel [53], Bui et al. (2014)[57], Yamin et al. [67], Toufigh & Kianfar [52], Bui et al. (2009) [77], Bui et al. (2016) [66], Lilley & Robinson [72], Röhlen & Ziegert [78], Hall & Djerbib (2004) [50], Silva et al. [55], Arrigoni et al. [49] and Miccoli et al. [27].

Almost all the studies on RE compressive strength have applied the load perpendicular to the direction of the earth layers, which is a reasonable criteria as this is the normal loading direction of real RE walls. However, and despite the expected anisotropy of the material, a study carried out by Bui et al. [57] tested the bearing capacity of RE in a direction parallel to the earth layers, concluding that the layer separation that occurs does not seem to affect the mechanical properties of the sample. In fact, most authors treat RE as an isotropic material when developing numerical models.

To summarize, the studies regarding the UCS of RE show that there is a wide range of parameters affecting this mechanical property: sample size and shape, compaction, density, moisture content and testing procedure. The wide range of combinations between these parameters makes it difficult to assess clear relationship between them and the UCS. However, and despite this fact, it is possible to establish the UCS of URE within the range from 1 MPa to 2.5 MPa.

3.3.2. Elastic modulus and Poisson's ratio

Most studies calculating the UCS of RE have also measured its elastic modulus (E), traditionally obtained as the slope of the tangent line with the elastic part of the stress-strain curve. An enormous dispersion is noted in the Young modulus of URE (Table 3.2), with values from about 60 MPa to 1 000 MPa.

Such a significant dispersion is related to factors associated with sample manufacturing (source material, moisture content and sample size) [20, 57, 59] and also to the testing procedure and varying definitions of elastic modulus. According to Alós Shepherd et al. [79], the elastic modulus determined following concrete testing standards is higher than the one obtained from geotechnical testing standards, due to the techniques used measure deformation (concrete standards measure specimen deformation with strain gauges or similar, while geotechnical standards commonly use the machine displacement).

Similarly to concrete or other quasi-brittle materials, the Young modulus of RE is expected to increase with increasing UCS. However, the above-mentioned dispersion of results depending on the sample manufacturing and test procedures, does not allow to define a clear correlation between these two parameters, in the way it is done for concrete. Despite this, the direct relationship between Young modulus and UCS is proved by some studies [26, 58, 59] that have carried out several uniaxial compression test on RE samples with homogeneous characteristics. These studies have obtained increasing values of the Young modulus when the UCS was higher. Figure 3.3 shows the relation between Young modulus and UCS for URE in literature.

Fewer reports of RE Poisson's ratio (ν) are noted in literature. The studies that did calculate it show values from 0.22 to 0.30 [20, 27, 57]. Poisson's ratio is obtained via uniaxial compression test of RE samples by measuring vertical and lateral displacements with extensometers [57] or LVDT sensors [27, 52, 57, 59].

3.3.3. Tensile strength

As happens with any other type of earth construction, RE has very low strength in tension and shear, especially when moist [42], meaning that RE

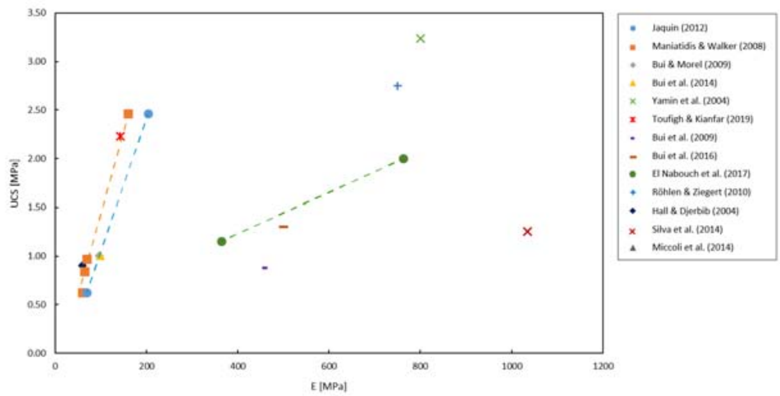


Figure 3.3: Unconfined compressive strength (UCS) as a function of elastic modulus (E): values obtained by Jaquin [58], Maniatidis & Walker [59], Bui & Morel [53], Bui et al. (2014)[57], Yamin et al. [67], Toufigh & Kianfar [52], Bui et al. (2009) [77], Bui et al. (2016) [66], El Nabouch et al. [26], Röhlen & Ziegert [78], Hall & Djerbib (2004) [50], Silva et al. [55] and Miccoli et al. [27].

elements should not be designed for pure tension.

Although the tensile strength is one of the most relevant parameters in the analyses of RE failure, particularly in extreme conditions (e.g. seismic) [57, 80], it is often neglected in design and has not been yet thoroughly studied. Authors studying this parameter have carried out Brazilian tests [52, 57] or pull-off tests [27] on RE specimens, concluding that the tensile strength of the material can be considered equal to approximately 10 % of its compressive strength. This criteria leads to values of the tensile strength between 0.10 and 0.35 MPa, which are in accordance with the values found in literature [1, 55, 67, 81, 82].

Bui et al. [57] suggested the need to distinguish between the tensile strength in an earth layer and the tensile strength at the interfaces between layers. The result of that study, however, showed that the tensile strength at layer interfaces was similar to the one measured within the layers, leading to the conclusion that it might be acceptable to consider RE as an isotropic material in tension.

3.3.4. Shear strength and cohesion

Shear strength of URE is also very limited, so its design values are considered close or equal to zero (e.g. 0.035 MPa in the New Zealand code [44] or zero in Australian Handbook [43]) in the absence of direct experimental data. Despite this fact, the few studies that have assessed the shear strength of RE have obtained results that, although small, are well above the ones recommended by the standards. These values, as shown in Table 3.3, are between 0.15 MPa and 0.85 MPa.

Table 3.3
Density (ρ), shear strength (f_s), cohesion (c) and friction angle (φ) of URE.

Ref.	Sample [cm]	ρ [kg/m^3]	f_s [MPa]	c [kPa]	φ [°]
[55]	55 × 55 × 20	2100	0.15	189	37
[57]	40 × 40 × 65	1900	0.18	170	51
[67]	250 × 250 × 50	1920	0.37	–	–
[27]	50 × 50 × 11	2190	0.65 – 0.85	–	39
[22]	⌀7.6, h14.7	2000	–	13	41
[20]	49 × 49 × 36	–	–	30	35
[71]	15 × 15 × 18	2143	–	50	65
[54]	6 × 6 × 2	2131	–	68	44
[66]	100 × 100 × 30	2000	–	130	45
[20]	10 × 10 × 3.5	–	–	135 – 260	45
[60]	50 × 50 × 12	2190	–	561	37

Two different test procedures are used to assess the shear behavior of RE: diagonal compression tests [27, 55, 67] or direct shear tests [20, 27]. Authors have used full-scale samples to perform the diagonal compression tests, which have been carried out in accordance with ASTM E519 [83]. Silva et al. [55] noted that the shear strain-stress curves are characterized by an early peak shear stress, related to the cohesion generated by the binder effect of clay, followed by a significant reduction of stiffness when the contribution of cohesion diminishes and the shear behavior relies on friction and interlocking.

A key factor affecting URE shear strength is the moisture content at the testing time [20, 42, 84]. Narayanaswamy [84] performed compression tests on inclined RE samples varying the moisture content in order to assess the variation of shear strength, concluding that there is a significant decrease in the shear strength when increasing the moisture content (about a 75 % when increasing moisture from 0.0 % to 4.2 %).

According to Mohr-Coulomb theory, shear strength depends on cohesion, friction angle and normal stress. It is, therefore, possible to determine cohesion and friction angle of RE from the relationship between shear and normal stresses, which can be obtained by either a shear box test [20, 85] or a triaxial compression test [22]. Another option, commonly found in literature, to obtain these two parameters is by calibration in a numerical discrete elements model (DEM) of finite elements model (FEM) [27, 55, 57, 66]. For URE cohesion, some authors suggest a direct relation with compressive strength of the form $c = (0.10 - 0.14)f_c$ [57, 66], or with tensile strength of the form $c \approx 1.5f_t$ [55, 80], but further investigation is needed to confirm the validity range of these relations.

As shown in Table 3.3, there is a significant dispersion in URE cohesion values, varying from 30 kPa to 560 kPa; while friction angle shows a bit more homogeneous values, mainly in between 35° and 45°. El Nabouch [20] used a shear box to test large-scale RE specimens with different densities, and arrived to the conclusion that a higher density significantly increases cohesion but does not affect the friction angle. In that study, also small-scale samples were tested, obtaining higher values for both cohesion and friction angle.

Another parameter related to the shear behavior of URE that has not been yet studied in depth is the dilation angle (ψ). In a recent study, Bui et al. [86] analyzed the effects of the dilation angle on the behavior of RE walls using a FEM model, noting that this parameter only influences the ultimate displacements, and that a value of $\psi = 30°$ provided a good agreement between numerical and experimental results. However, a previous study [66] indicated a value of 12°, and Miccoli et al. [80] considered it equal to zero; which shows that there are still not enough investigations to establish an acceptable value for RE dilation angle.

Regarding shear behavior of RE, Kosarimovahhed and Toufigh [71] also proposed the dissipated energy in shear (U_f) as a useful parameter to represent the deformability capacity of RE materials under shear loading. U_f is calculated as the area under the shear force - shear displacement curve until the failure point, and a value of 15 J was obtained for the URE samples.

3.3.5. Fracture energy

The tensile fracture energy (G_f), along with the compressive and tensile strength and the Poisson's ratio, is one of the most relevant parameters in the characterization of the mechanical behavior of RE [80, 87, 88], having a great influence on its maximum shear stress [60]. However, there are very few studies concerning the determination of both the tensile and compressive fracture energy of RE.

There are two main procedures for obtaining the fracture energy of a sample: the three-point bending test [89] and the wedge splitting test [87, 90]. The latter has the advantage of using much smaller specimens, so they are easier to manufacture and transport, and their shape and size eliminate any effects of the sample self-weight [87].

Miccoli et al. [80] proposed a relation between the fracture energy and the strength of the RE material, estimating the mode-I tensile fracture energy as $0.029 f_t$ and the compressive fracture energy (G_c) as $1.6 f_c$; this relationship was also used by Silva et al. [55]. Bui et al. [86] proposed to calculate the G_f according to CEB-FIP Model Code 90 [91].

The values obtained in literature for the tensile and compressive fracture energy are shown in Table 3.4. There is a relevant dispersion in the G_f values, which are between 0.002 N/mm and 0.020 N/mm, and very few data about G_c to draw conclusions. Therefore, further investigation is needed to assess the values of the URE fracture energy.

Table 3.4
Tensile (G_f) and compressive (G_c) fracture energy of URE.

Ref.	G_f [N/mm]	G_c [N/mm]
[87]	0.002	–
[55]	0.004	–
[80]	0.011	6
[86]	0.012	10 – 25
[90]	0.020	–

3.4. Insulating properties

3.4.1. Thermal insulation

Although most studies regarding RE characterization have focused on its mechanical properties, to a lesser extent there are also some investigations oriented to the assessment of the insulating properties (thermal and acoustic) of this material.

One of the main parameters which define the thermal insulation capacity of a material is its thermal conductivity (λ [$Wm^{-1}K^{-1}$]) [1]; so the lower is the thermal conductivity, the higher the insulation will be.

There is a relevant relationship between the density of the earth material and its thermal conductivity, as shown in Figure 3.4, so when density increases, the thermal insulating capacity of RE decreases. As well as density, the influence of water content is also important in the thermal behavior of RE, as an increase in the material moisture content leads to a significant reduction of the thermal insulation [1, 92]. Soudani [93] measured that the thermal conductivity increased by 30 % between dry conditions and a moisture content of 2 % and by 70 % if the moisture content reached the 5 %.

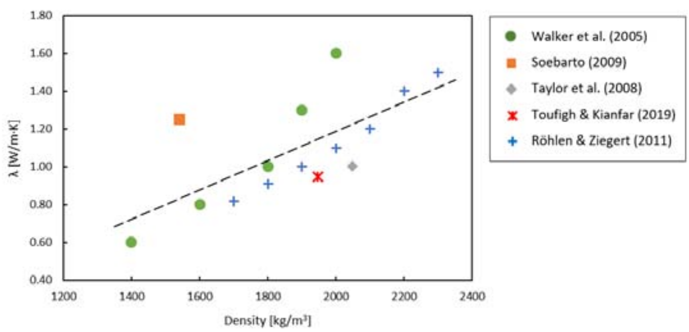


Figure 3.4: Thermal conductivity (λ) as a function of density: values obtained by Walker et al. [51], Soebarto [94], Taylor et al. [95], Toufigh & Kianfar [52] and Röhlen & Ziegert [78].

The values found in literature for the thermal conductivity of RE with a normal density are between 1.0 and 1.4 $\mathrm{W m^{-1} K^{-1}}$ (Figure 3.4), which means they offer similar insulation to a traditional ceramic brick [1, 96] and better than other common construction materials such as concrete (1.5 to 2.5 $\mathrm{W m^{-1} K^{-1}}$) or stone (1.1 to 3.5 $\mathrm{W m^{-1} K^{-1}}$) [96]. Also, recent studies [97] show that stabilized RE materials provide a satisfactory thermal performance in comparison to masonry materials, and conclude that the application of acrylic insulators have a great influence on RE thermal behavior while their effect on masonry is quite low.

Not only the material properties are relevant when measuring thermal insulation, but also the wall thickness. In this regard, thermal resistance ($R\,[\mathrm{m^2K/W}]$) is defined as the ratio between the thickness of the element and its thermal conductivity. Considering the aforementioned λ-values and usual URE wall thickness between 30 cm and 60 cm, the thermal resistance of an URE wall will be approx. between 0.2 and 0.6 $\mathrm{m^2K/W}$, which is in accordance with the order of magnitude indicated by various authors [92, 93, 97, 98]. This range is lower than the minimum values established in earth standards (e.g. 1.3 $\mathrm{m^2K/W}$ in the Australian standard [43]), which goes against the global opinion on the thermal comfort experienced in existing RE buildings, leading to the conclusion that R-value might not be representative enough to characterize the URE thermal behavior [93].

However, in order to solve these shortcomings, it is easy to include additional insulating elements to the RE walls with the aim of significantly increasing their thermal properties. In this respect, not only traditional acrylic insulating materials such as extruded polystyrene (XPS) [97, 99], polyurethane (PU) [99] or expanded polystyrene (EPS) [70] have provided good results, but also more eco-friendly solutions such as wood panels have shown an excellent thermal behavior when combined with RE [99, 100].

Another important aspect regarding earth thermal performance, which is well-known since the beginnings of earth construction, is its capacity to reduce the thermal amplitude inside the building, keeping the interior fresh during the day and warm at night [9, 101]. Recent studies [99, 102] have measured this thermal behavior, concluding that the reduction of thermal amplitude provided by RE is between 70 % and 77 % for 29 cm-thick walls and up to 75 % to 80 % for 50 cm-thick walls, which means that the temperature inside the building remains almost constant during the whole day [102]. The capacity of RE to buffer temperature variations is related to its ability to store heat (thermal mass), and can have a greater impact on thermal comfort than the insulation and thus counterbalance a low thermal resistance, especially in temperate climates with warm days and cold nights [103–105]. A case of study developed in Southern Portugal [101] proved that RE can provide satisfactory indoor thermal comfort during almost the whole year, although a heating system could be necessary to overcome some periods of thermal discomfort during winter.

Some studies [70, 106] have evaluated the impact of adding thermal energy storage materials such as EPS and phase-change materials (PCM) to the earth mixture, concluding that they enhance the thermal behavior of RE. However, their use entails a significant increase in manufacturing costs, especially in the case of PCM, and their effect on the UCS of the RE material is still unclear.

The thermal behavior of RE described in this section has been mainly studied by the diverse authors via laboratory tests and cases of study, but there are some few attempts to develop numerical models to predict the hygrothermal performance of RE materials. Soudani [93] proposed a coupled model based on heat and mass balances which considers separately the kinematics of each phase in interaction with each other, obtaining a good concordance between the numerical results and the experimental data. Another recent study [107] carried out numerical simulations of a RE wall with and without a moisture barrier using a numerical model driven by temperature and relative humidity, on the basis of the theory of heat and mass transfer in porous media. The results from a small-scale experiment where used by the authors to verify the validity and accuracy of the numerical model.

3.4.2. Acoustic performance

Acoustic insulation provided by RE elements is another relevant property for the functional behavior of the material that has not been thoroughly studied in literature. This parameter can be measured using the sound reduction index (R [dB]), defined as ten times the decimal logarithm of the ratio between the incident acoustic power on an element and the acoustic power radiated by the other side of that same element [108]. In some countries it is also common to measure acoustic insulation via the Sound Transmission Class (STC [dB]) [109, 110]. Both parameters indicate the decibel reduction of noise that a partition can provide; although there are some systematic differences in their calculation procedures, the sound reduction index is normally similar or slightly lower number than the STC rating value [111, 112].

Table 3.5 shows the values of R and STC found in literature. According to these results, it seems acceptable to consider 57 dB as a value of consensus. Taking into account that STC-50 means that loud speech is not audible and STC-60 that even amplified sounds are barely audible [113, 114], it is possible to conclude that RE has have a good acoustic behavior. Regarding the relation between the acoustic insulation and the material density (ρ) and wall thickness (t), several authors [51, 115–117] propose to use the expression suggested by the British Standard 8233 [118] for ordinary masonry walls (Equation 3.4.1).

$$R = 21.65 \log_{10}(\rho \cdot t) - 2.3 \tag{3.4.1}$$

One more parameter that defines the acoustic performance of a material

Table 3.5
Sound reduction index (R) and Sound Transmission Class (STC) of URE depending on its density (ρ) and the wall thickness (t).

Ref.	ρ [kg/m^3]	t [cm]	R [dB]	STC [dB]
[110]	–	25 – 30	–	50.0 – 57.0
[119]	–	30	–	57.0
[78]	1900	50	57.0	–
[51]	2000	30	57.9	–
[117]	2100	30	58.3	–

is the reverberation time. There are not yet enough studies on this regard to assess a value for this parameter of RE, but some authors [115, 117, 120, 121] indicate that, due to its porosity, RE has excellent sound reverberation properties, generating far fewer harsh echoes than conventional wall materials.

3.4.3. Air humidity balance

Earth has the ability to absorb and desorb humidity faster and to a greater extent than any other conventional construction material, enabling it to balance indoor climate [1]. Measurements taken in a house of new construction in Germany with all its walls made of earth, and reported by Minke [1], showed that the relative humidity inside the house fluctuated by only 5 % to 10 % throughout the year.

Rode et al. [122] proposed the Moisture Buffer Value (MBV) as an appropriate parameter to measure the capacity of building materials to absorb and desorb humidity, and thus to balance it inside a building. MBV is measured in mass of water per open surface area and per relative humidity variation (%). According to Arrigoni et al. [123], diverse studies have measure a MBV for URE between 1.0 and 3.7 g/(m^2·%RH), which can be considered within the categories *good* and *excellent* defined in [122]. Although there is a significant dispersion in MBV for URE, all the values within the range are considerably better than the ones reported for other common constructions materials such as concrete, baked bricks or gypsum boards, whose MBV are always lower than 0.7 g/(m^2·%RH) [123].

Although there are some studies regarding the numerical modeling of the hygrothermal behavior of earthen materials and the effect of moisture in their thermal performance, there are not yet numerical models specifically design to describe RE moisture buffering capacity. In [124], a coupled model is develop to simulate the heat and mass transport considering the effects of the phase change of water inside the earthen walls. Abahri et al. [125] proposed a one-dimensional model for evaluating coupled heat and moisture transfer in porous building materials, concluding that the thermal diffusion affects strongly the moisture migration in the walls. A study regarding the numerical assessment of earth materials buffering potential [126] concluded that earth mixtures can be advantageously used in buildings due to their capacity to lower heat transfer and moderate indoor humidity variations, although the material analyzed was not RE but a straw-clay mixture. A numerical model recently proposed by Jiang et al. [107] showed that the addition of a moisture barrier is beneficial in protecting a RE wall, but it reduces its moisture buffering capacity.

3.5. Durability

The durability of RE materials and the effect of harsh environments on their properties is also a relevant aspect that should be taken into consideration, as it has always been one of the main concerns for designers and consumers [127, 128]. Several authors have evaluated RE durability using laboratory tests such as the accelerated erosion tests (AET) [25, 129, 130] or the wire brush test (WBT) [129, 131] presented by ASTM D559 [132] for compacted soil-cement mixtures. The results from these tests show that RE materials may need protection against rain (waterproofing agents or sloping roofs) or the addition of a stabilizer such as cement or lime to reduce erosion and so avoid excessive maintenance. However, Bui et al. [133] measured the real erosion of different RE walls exposed for 20 years to natural weathering and found much lower erosion than the one obtained via AET, assessing a potential lifetime for URE walls greater than 60 years (precipitation about 1 000 mm/year).

To date, few studies have analyzed the durability of RE in aggressive environments. A recent study developed by Ghasemalizadeh and Toufigh [127] evaluated the effect of different aggressive environments on the durability of cement-stabilized RE, observing that the specimens with low cement content disintegrated between 6 and 9 months of exposure in sulfate, alkaline and acidic environments. Luo et al. [134] carried out drip tests and rainfall simulation tests to investigate the degradation of RE under wind-driven rain, and obtained that a the critical rain direction was between 30° and 45° in drip tests and between 15° and 30° in rainfall simulation tests. The authors attribute this variation in the results to the formation of a water film that lowers the influence of the increase of kinetic energy. This study also concluded that a lower water content and higher clay content reduces the erosion due to wind-driven rain.

3.6. Environmental and economic benefits

3.6.1. Environmental benefits

Sustainable development and respect for the environment are two aspects that are becoming increasingly important in the field of construction, and this is precisely one of the strong points of earth construction, which helps to save energy and reduce environmental pollution [1, 51, 135]. As a wide variety of soils are acceptable for RE construction without a significant industrial manipulation, these can be easily found near the construction area, so the production and transportation costs (both economic and environmental) are significantly reduced. According to Minke [1], the process of preparation, transport and handling of earth for construction requires only ca. 1 % of the energy needed for the same process for baked bricks or reinforced concrete.

Therefore, if one looks at CO_2 emissions as a key indicator of the material environmental performance, it is possible to observe (Table 3.6) that URE generates lower emissions than any other building material or technique.

Table 3.6
CO_2 emissions of main building materials. Emissions per weight, per volume and per volume and compressive strength. Adapted from [135].

Material	kg CO_2/kg	kg CO_2/m^3	kg $CO_2/(m^3 MPa)$
URE	0.004	9	4 – 9
7.5 % fly ash SRE [71]	0.045	106	12 – 22
7.5 % cement SRE [71]	0.06	127	13 – 43
Adobe	0.06	72	36 – 144
Hollow brick	0.14	94	19
Mass concrete	0.14	330	9 – 17
Reinforced concrete	0.18	450	9 – 18
Solid brick	0.19	304	30

Taking into account that between 20 % and 40 % of solid waste generated in developed countries comes from the construction and demolition sector [136–138], it is clear why minimizing waste generation is becoming a priority for the building industry. URE construction could help reducing demolition waste, which represents a significant percentage of the total waste, as unbaked earth can be reused an indefinite number of times, never becoming a waste material harmful to the environment [1, 135].

3.6.2. Economic impact

Building with earth has a significant impact on the reduction of the construction costs, due to the low price of the source materials and the reduction of the transportation costs when using local soils [1]. This economic advantages make RE an excellent choice for lower-income countries and regions

[10, 11, 77], where costs can be reduced from 30 % to 60 % compared to conventional concrete-based construction [11]. In addition, the predominant use of manual labor contributes to the creation of local jobs [82]. In countries where labor costs are high, the industrialization of the process (e.g. prefabricated RE) may help to reduce the overall costs [1, 139, 140].

Nevertheless, it is worth to mention that when better mechanical properties are needed due to building requirements, the local soil might not be acceptable without a previous modification. This means that non-local material would have to be used in order to improve the PSD of the soil, leading to higher material and transportation costs. Another way to improve the RE material properties is the use of additives, although it also increases the manufacturing costs, as shown in Table 3.7.

Table 3.7
Material cost of RE mixtures. Source: [a][70], [b][71].

Material	Cost [$/t]
URE	3.54[a]
RE with 7.5 % cement	5.46[a] – 11.25[b]
RE with 7.5 % fly ash	9.55[b]
RE with 15 % expanded polystyrene	4.54[a]
RE with 10 % phase-change materials	653[a]

3.7. Conclusions

Sustainable development and waste reduction are becoming increasingly important in the construction sector. This growing concern over environmental sustainability is attracting the attention of researchers to earth as an available building material with a low environmental impact. The review presented in this chapter shows and analyses the state-of-the-art of URE characterization, as one of the earth construction techniques with more tradition and future projection, and whose understanding is essential for its use in modern construction. The following conclusions can be reached based on this review.

The first aspect to be considered when constructing an URE wall are the characteristics of the source materials. In this regard, the PSD of the soil should not be considered as a discriminating parameter, but heterogeneous distributions are recommended. In fact, most studies are in accordance with the PSD envelopes proposed by Houben et al. [29]. Clay content is also a relevant aspect, as it acts as the only binder in URE, normally lying between 8 % and 14 % by mass.

URE is compacted up to approx. its OMC, which is between 8 % and 12 % by mass, reaching a MDD from 1 750 kg/m^3 to 2 200 kg/m^3. Moisture content and dry density are proved to be very relevant for determining the mechanical, thermal and acoustic behavior of RE.

Most studies on RE are focused on calculating the UCS of the material, which is traditionally considered as the main parameter to characterize the mechanical behavior of brittle materials. There is a significant dispersion in the compressive strength of URE measured in diverse studies, but the values are generally in range from 1.0 MPa to 2.5 MPa. This dispersion is due to the heterogeneity of the material and also to the manufacturing and testing conditions, been necessary to establish standardized test procedures to make the results actually comparable. The material Young modulus has also been measured in several studies, but the dispersion is even greater, with values from 60 MPa to 1 000 MPa. There is expected to exist a direct relation between density, UCS and Young modulus, but a clear correlation between these parameters has not yet been defined.

URE tensile and shear strength are known to be very low, so they are frequently neglected in design. However, they are essential to characterize the material failure, so further investigations are needed on this topic. The studies present in literature give values between 0.10 MPa and 0.35 MPa for the tensile strength (approx. 10 % of the UCS) and between 0.15 MPa and 0.85 MPa for the shear strength.

The shear behavior of URE is related to the cohesion and friction angle of the earthen material. Some authors [55, 57, 66, 80] suggest a relationship between cohesion and compressive strength, $c = (0.10 - 0.14)f_c$, or between cohesion and tensile strength, $c \approx 1.5f_t$; but the accurate value of this parameter is not yet defined if one looks at the wide range that it adopts in literature (from 30 to 560 kPa).

Another parameter for which a deeper investigation is needed is the fracture energy, especially in tension, as it has a great influence in the RE mechanical behavior [60, 80] and only few studies have carried out tests to calculate its value. The results obtained are between 0.002 N/mm and 0.020 N/mm.

Several experiences in earth construction have proved that RE elements provide excellent thermal and acoustic behavior, but more studies are also required to support these considerations. The thermal conductivity of URE (between 1.0 and 1.4 $\mathrm{Wm^{-1}K^{-1}}$) is better than the one measured for other construction materials, but still not enough to reach the values required in most standards. However, its capacity to dump temperature variations, and thus to reduce the thermal amplitude inside the buildings (about 75 %), can counterbalance the low thermal resistance and have a considerable impact on thermal comfort [103–105].

Not only temperature, but also air humidity inside an URE building is well balanced and buffered, due to the ability of earth to absorb and desorb humidity in a very fast way. This feature has been measured in literature using the MBV, and better values have been obtained for URE than for any other common construction material.

The acoustic insulation provided by RE walls has been calculated only in some few studies, using the Sound Reduction Index or the Sound Transmission Class. In this case the results have been quite homogeneous, with values equal to ca. 57 dB, which proves a good acoustic behavior of the material [113, 114].

The durability of RE is one of the main concerns for designers and customers. The studies in literature highlight the importance of protecting RE against rain, using physical protections or stabilizers such as cement or lime.

Finally, some of the environmental benefits of URE construction measured in literature have been analyzed; regarding the reduction of energy consumption, CO_2 emissions and waste generation. Despite the fact that it is clear that earth construction is a low-impact building technique which helps protecting the environment, further investigations would be needed in order to quantify the real magnitude of these benefits. Also some economic benefits have been found, especially when using local soil and in countries where labor costs are low.

In conclusion, URE construction seems to meet the requirements to be considered as a useful eco-friendly building solution, so a greater effort is needed to further understand its behavior and thus to be able to extend the use of this technique for modern constructions.

Chapter 4

Stabilization and reinforcement of rammed earth

4.1. Introduction

As it has been previously described in the present document, traditional rammed earth building technique, which only uses soil and water as the source material –with clay acting as the only binder of the mixture–, is called unstabilized rammed earth (URE). The relevance of this technique, with hundreds of years of history, is not a only thing of the past, nowadays, earth construction is attracting the attention of a great number of builders and researchers that are looking for alternative sustainable construction techniques, in the framework of a growing environmental awareness in the construction sector [51, 53, 141, 142].

However, when rammed earth technique is to be applied in new constructions, its mechanical performance is frequently not good enough to reach the values defined by the building standards. To improve these mechanical properties, and also some other aspects such as the thermal and acoustic behavior, diverse additives can be added to the soil and water mixture, leading to the so-called stabilized rammed earth (SRE). There exist diverse additives or stabilizers that improve the behavior of RE by physical and chemical interactions with the soil particles and the water present in the mixture; some of these additives have been used since antiquity (e.g. lime or natural fiber [143–145]) and some others have been introduced in the last decades or years (e.g. cement, coal combustion residuals, artificial fibers or advanced materials) [2, 3, 42].

The use of stabilizers in RE is becoming more and more frequent, improving its properties and allowing to use this technique in a wider range of constructions. However, if additivation is used systematically and without taking enough care about which are the requirements that URE cannot fulfill, there is the risk that RE constructions lose some of the most important properties (i.e. low cost and low environmental impact) that make this technique interesting and useful nowadays [129, 146, 147].

Considering the above, this chapter analyzes the state of the art of SRE, aiming to present the different options for RE stabilization, from the point of view of the property that needs to be improved, in order to make it easier for researchers and builders to choose the best alternative and to understand the consequences (mechanical, environmental and economical) derived from the stabilization.

To reach this goal, the present chapter is divided into five parts, including the main aspects to be considered when choosing a construction technique or material. The first one presents the main stabilizers that have been commonly used in rammed earth construction, their characteristics and the characteristics of the soil to be used for stabilization. The second and third parts regard the mechanical behavior and insulating properties of SRE, focusing on how each kind of stabilizer is used to enhance each parameter. Then the durability is analyzed, as one of the greatest concerns about rammed earth structures. Finally, the last sections evaluates the environmental and economic impact of this building technique, focusing on how the use of stabilizers could affect some of the main benefits of traditional RE construction.

The research presented in this chapter has been published in the following scientific article:

- F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of stabilized rammed earth: A review.* Construction and Building Materials. 325 (2022) 126693. doi: 10.1016/j.conbuildmat.2022.126693.

4.2. Materials

4.2.1. Stabilizers, additives and reinforcements

As mentioned above, natural soil can be directly used to build RE structures, but when higher strength or durability are required it is common to add different kinds of additives to the mixture. The growing interest in the use of additives and reinforcements to improve the mechanical and physical behavior of RE can be noted observing the increasing number of scientific publications regarding RE construction, and their citations, that refer to stabilization (Figure 4.1).

Portland cement is, by far, the most frequently used stabilizer nowadays [42, 52], substantially improving the compressive strength and durability of RE elements [69, 71, 129]. Natural soil to be used for cement stabilization must have a reduced clay content, so the shrinkage of the resulting RE material is also lower than the one observed in URE. These mechanical improvements have made cement stabilization a generally accepted routine practice in RE construction in countries such as Australia, New Zealand or the United States, but its use should be limited due to the severe increase in environmental costs [129, 146, 147].

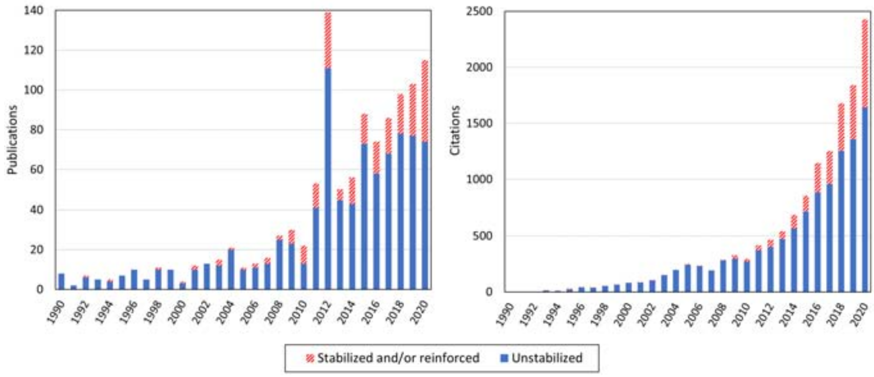


Figure 4.1: Publications and citations in Web of Science regarding rammed earth that include or not the words “stabilized” and/or “reinforced”, between the years 1990 and 2020.

Another RE stabilizer with a long tradition is lime. There is a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [148–152]. When lime is added to a soil, the concentration of Ca^{2+} and OH^{-} increases due to the hydration reaction of lime. This generates the flocculation of particles, affecting soil plasticity, and an increase in pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [149, 153].

The benefits of lime stabilization of RE have been known since ancient times, being possible to find several examples of historic buildings made of LSRE [154–157]. However, and despite its historical use, lime has been superseded by cement as the main additive to improve the mechanical properties of RE during the last decades, and as a consequence there are few scientific studies dealing with lime-stabilized rammed earth (LSRE).

Usually combined with cement or lime, fly ash (FA) is sometimes added to the RE mixture to increase the amount of amorphous material available and to enhance the cementitious reactions between soil and the main stabilizer [158]. Since FA is a residue generated by coal combustion, its use helps reducing the environmental impacts of cement-stabilized rammed earth (CSRE) [71, 129, 159]. With the same aim of obtaining a more sustainable stabilized material, several studies have proposed over the last years the addition of other waste materials to RE, such as bottom ash (BA) [160], recycled concrete aggregates [123], calcium carbide residue (CCR) [49, 161], ground granulated blast furnace slag [162] or brick waste [159].

In addition to the aforementioned binders used to improve the properties of RE by chemical stabilization, there is another type of additives that enhance the mechanical behavior of RE by means of their shape: fibers. To highlight the different approaches between cement or lime stabilization and fiber stabilization, the latter is sometimes referred to as "fiber-reinforced" rammed earth [144], instead of "fiber-stabilized". It is important to distinguish, nevertheless, whether fibers are used in the form of single short pieces included in the earth mixture or if they are use in the form of fabrics acting as external or internal structural reinforcements [88, 163–165]. Considering the enormous variety of plant aggregates and natural fibers that have been commonly added to earthen construction materials since antiquity [1, 17], it is difficult to establish a comprehensive list or classification; however, Laborel-Préneron et al. [145] proposed to group them in eight categories: cereal straws, wood aggregates, bast fibers, palm tree fibers, waste and residues, leaf fibers, aquatic plant fibers and chips, and sheep wool. Over the last years, some authors have also proposed the stabilization of RE with non-natural fibers, such as as fiberglass [52], polypropylene fiber [166] or waste tire fibers [167], although they have very small use yet and the knowledge regarding their mechanical effects on RE is still limited.

4.2.2. Soil

Stabilization techniques can be used to improve the mechanical properties of a soil that initially would not be appropriate for RE construction. However, if the goal is to obtain an excellent mechanical performance, the soil should meet some requirements. Burroughs [168] recommended, for cement or lime stabilization, using a soil with linear shrinkage lower than 11 % according to Australian Standard [169], sand content lower than 64 % and fine particles preferably between 21 % and 35 %.

These values of the particle size distribution are in agreement with the ones proposed by Maniatidis and Walker [42] for URE (clay and silt combined between 20 % and 35 % and sand between 50 % and 75 %) and with the envelopes recommended by Houben et al. [29], which are frequently used in URE literature [170]. Maniatidis and Walker [42] also noted that, in order to optimize the benefits of stabilization, soil should mainly consist of sand and fine gravel, with only enough clay to provide cohesive strength and a percentage of silt to act as void filler. As the additive is acting as a binder in SRE, the binding effect of clay is not as important as for URE, and also the presence of clay generally impedes effectiveness of cement stabilization. According to The Australian Earth Building Handbook [43], when using lime as stabilizer the ideal soil should have a plasticity index from 20 % to 30 % and liquid limit between 25 and 50, so lime would be particularly appropriate for stabilization of expansive soils [171].

Also, for SRE, soil should generally be free of humus and plant matter to prevent later deterioration; although under certain conditions, plant matter such as dry straw could be added [172].

4.2.3. Moisture content and density

The moisture content during manufacturing is known to be an important factor for the strength development of RE [51]. Generally, a value close to the optimum moisture content (OMC), which allows the maximum dry density of the soil for a certain compaction energy, is chosen [170]. Walker et al. [51] recommend adding the OMC $\pm$ 1 % to 2 %, while the New Zealand Standard NZS4298 [45] indicates that the moisture content before compaction should usually be within the range [OMC $-$ 3 %; OMC + 3 %] and never lower than OMC $-$ 4 % or higher than OMC + 6 %.

This OMC is determined in most of the studies via standard [62] or modified [173] Proctor tests. The Modified Proctor test uses higher compaction energy so the OMC obtained is slightly lower, which, according to some authors [20, 174] would be closer to the compaction effort applied in the construction of a real wall by mechanics means. However, some standards, as the aforementioned NZS4298, specify that the OMC should be obtained via Standard Proctor or equivalent. An alternative to easily assess the correct water content for the mixture is performing the so-called "drop test" [42, 43, 45, 175], consisting on compacting by hand a ball of moist soil that is then dropped onto a hard flat surface from a height of ca. 1.5 m. When the soil is too dry the ball breaks into several pieces, if it is close to the OMC the ball breaks into only a few pieces, and if the soil is too wet then the ball remains in one piece.

Despite the existing agreement in using moisture contents similar to the OMC, when additives are included it is not always easy to evaluate the OMC of the mixture. For example, for lime or cement-SRE, oven drying cannot be used to assess the water content due to the loss of non-evaporable water via chemical reactions (cation exchange, flocculation and pozzolanic reactions) [174]. Some authors, therefore, calculate the OMC of the soil (unstabilized) and directly use it for all the mixtures [131, 158, 159], or calculate the OMC of the soil and then use that value +1 % for the stabilized samples [144].

These procedural simplifications can be considered reasonable if one observes the values obtained by the authors that did vary the moisture content depending on the amount of stabilizer added: Ciancio et al. [174] obtained an OMC between 7.6 % and 9.6 % for lime contents from 0 % to 6 %, Toufigh and Kianfar [52] used a moisture content between 12 % and 13 % for cement contents from 2.5 % to 10 % and also for other additives (guar gum, pozzolanics or fiberglass), and Tripura and Singh [69] indicated water contents around 19 % for 4 % to 10 % CSRE. It can be observed that the variation in the OMC is very small, as indicated by Hallal et al. [131], and always within the range of acceptance suggested by Walker et al. [51] and NZS4298 [45]. In fact, most studies regarding SRE use moisture values between 8 % and 14 % [49, 52, 70, 130, 143, 159, 162, 165, 174, 176], which is an interval very similar to the one observed for URE studies [170].

4.3. Mechanical properties

4.3.1. Unconfined compressive strength

The unconfined compressive strength (UCS) has always been the main parameter to characterize the mechanical behavior of RE (stabilized and unstabilized), as it happens with most brittle materials. Additives used with the aim of increasing the tensile or flexural strength of RE have also been studied but their presence in literature is much more limited.

The compressive strength is obtained via uniaxial compression tests perpendicularly to the direction of the earth layers, mainly on small cylindrical samples with diameter equal to twice the height, although cubic specimens of diverse sizes have also been used [170]. The manufacturing and testing techniques also vary, due to the lack of an international standard that prescribed the test procedure for the determination of the UCS of RE samples. It would be essential to develop a standardized test procedure for this material in order to actually make the results obtained by the diverse studies fully comparable.

Table 4.1 shows the UCS and elastic modulus obtained in several recent studies regarding SRE. The table shows that the most commonly used additive to maximize the compressive strength of the soil mixture is cement, sometimes combined with other additives (particularly fly ash). With high cement contents, around 10 %, it is possible to obtain very high compressive strength, over 5 MPa, meaning an improvement between 1.5 and 5 times the UCS of URE, even reaching a strength 10 MPa in some cases. Lime is also used to enhance the compressive strength of RE, but the improvement is smaller, always under 5 MPa, with common lime contents between 3 % and 5 %.

As mentioned before, the water content at manufacturing is quite homogeneous, generally between 10 % and 13 %, with only a few exceptions [69, 131] using moisture contents near 20 %.

It should be noted that available data from literature does not allow the present study to evaluate or compare the suction conditions of the samples. Nevertheless, it can be mentioned that suction is a key parameter affecting the structural integrity of RE under moisture movement and is the source of strength in URE materials [90, 177]. The influence of suction is more relevant in LSRE, while its effect is almost negligible on cement stabilization due to the disproportionate increase in strength and stiffness for the latter method.

Because of the relevance, effectiveness and widespread use of cement to improve the compressive strength of RE, it is worthwhile to specifically evaluate the relationship between cement content and UCS. Figure 4.2 represents the results of several studies regarding cement stabilization of RE. Although there is a significant dispersion, some conclusions can be drawn: there seems to be an upper limit for the compressive strength depending on the percentage of cement ($\text{UCS}\,[\text{MPa}] < 1.59\,\text{Cement}\,[\%] - 0.97$) and a lower limit of ca. 2 MPa (so always above the minimum requirements indicated in most ex-

Table 4.1
Moisture content, unconfined compressive strength and elastic modulus of SRE samples (in parenthesis improvement of UCS and E with respect to URE, when available). Mixture with highest UCS for each study.

Ref.	Sample [cm]	Additives (%wt)	MC [%wt]	UCS [MPa]	E [MPa]
[174]	⌀10, h20	L (5)	10	1.2 (71 %)	175 (84 %)
[158]	⌀5, h10	L (3)+FA(28)	14	1.3	–
[160]	⌀3.8, h7	C(6)+FA/BA(12/18)	10	2.5	118
[130]	100 × 160 × 65	C (10)	13	3.1	–
[144]	⌀10, h20	C (6)	12	3.2 (60 %)	801 (136 %)
[159]	15 × 15 × 15	C (20)	13	3.3 (240 %)	–
[131]	⌀10, h20	L(4)+C(4)	18	4.8 (272 %)	355 (788 %)
[166]	⌀10.2, h11.6	C(6)	12	4.9	–
[161]	⌀4, h8	FA(5)+CCR(7)	14	5.2	–
[52]	⌀7.5, h15	C (10)	13	5.2 (133 %)	740 (417 %)
[49]	⌀10, h20	C(5)+FA(5)	8	5.3 (300 %)	–
[70]	⌀7.5, h15	C (10)	13	5.4 (182 %)	–
[167]	⌀7.1, h14.2	C(7)+WTTF(1)	–	6.2 (65 %)	416 (22 %)
[142]	10 × 10 × 10	C (10)	16	6.5 (69 %)	–
[69]	10 × 10 × 10	C (10)	19	7.4 (575 %)	–
[176]	⌀10.4, h20	C (8)	9	9.4	1166
[123]	⌀10, h20	C (7)	7	10.0	–
[162]	⌀10.4, h20	C (8)	10	11.1	7500

L - lime; C - cement; FA - fly ash; BA - bottom ash; CCR - calcium carbide residue; WTTF - waste tire textile fibers.

isting standards, which are between 1.3 MPa and 2.0 MPa [32, 34, 39, 45]); and for a certain soil and testing conditions there is a linear relationship between the cement content and the UCS of the SRE, according to all the studies in which more than two cement contents were tested.

4.3.2. Elastic modulus and Poisson's ratio

When performing uniaxial compression tests to obtain the UCS of SRE, it is common to calculate also the elastic modulus (E) of the material as the slope of the tangent line with the elastic part of the stress-strain curve [131, 160, 167, 174, 176]. Toufigh and Kianfar [52], who performed UCS test for several SRE mixtures, proposed calculating the elastic modulus according equation 4.3.1, following the procedure indicated for concrete in standard ASTM C469 [179], also used in [71].

$$E = (\sigma_2 - \sigma_1)/(\varepsilon - 5 \cdot 10^{-5}) \tag{4.3.1}$$

where σ_2 is the stress corresponding to 40 % of ultimate load, σ_1 is stress corresponding to a longitudinal strain of $5 \cdot 10^{-5}$ and ε is longitudinal strain produced by stress σ_2. However, there is not a consensus in the formulation of the elastic modulus; other authors [144] propose using the secant modulus (ratio between maximum stress and corresponding peak strain) as the

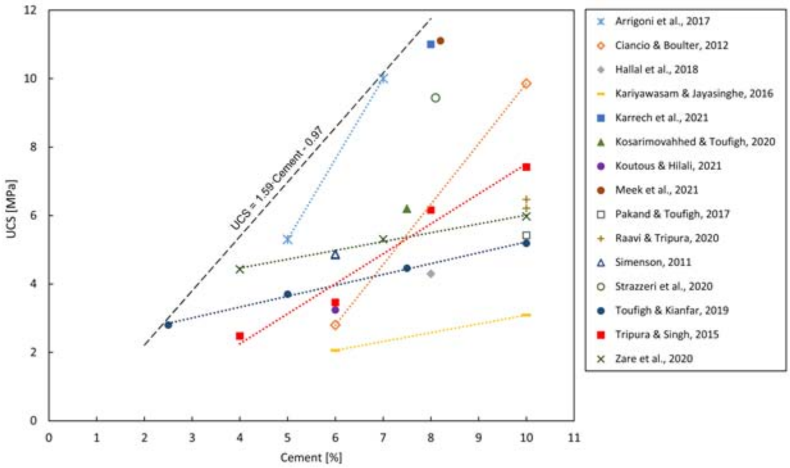


Figure 4.2: Unconfined compressive strength of CSRE as a function of cement content. Values obtained by Arrigoni et al. [49], Ciancio & Boulter [146], Hallal et al. [131], Kariyawasam & Jayasinghe [130], Karrech et al. [178], Kosarimovahhed & Toufigh [71], Koutous & Hilali [144], Meek et al. [162], Pakand & Toufigh [70], Raavi & Tripura [142], Simenson [166], Strazzeri et al. [176], Toufigh & Kianfar [52], Tripura & Singh [69] and Zare et al. [167].

best parameter to describe the elastoplastic mechanical behavior of earthen materials, indicating a value of the secant modulus equal to approximately 0.62 times the initial tangent modulus for URE, CSRE and LSRE. Xu et al. [180] calculated the Young modulus of URE performing loading-unloading triaxial test and applying the following equation:

$$E = \Delta\sigma_{xx}^{cycle} / \Delta\varepsilon_{xx}^{cycle} \tag{4.3.2}$$

where $\Delta\sigma_{xx}^{cycle}$ and $\Delta\varepsilon_{xx}^{cycle}$ are the differences in axial stress and axial strain, respectively, between the maximal and minimal load cycles.

As it can be observed in Table 4.1 and Figure 4.3, there is a significant dispersion in the values of the elastic modulus obtained by diverse studies. This dispersion is partially due to the use of different additives, but might be also caused by the variability in the manufacturing and testing techniques and also intrinsic to the heterogeneity of the material, as it was also noted for URE [170]. In Figure 4.3 it is also possible to observe that most studies indicate a direct relation between UCS and the elastic modulus, so E is expected to increase with increasing UCS, although the dispersion in the results does not allow to define a clear correlation.

As it happens with the compressive strength, cement is the most common stabilizer added to RE to improve its elastic modulus. Studies regarding CSRE [52, 131, 144, 167, 176] indicate elastic modulus within the range from 250 MPa to 750 MPa using cement contents between 2 % and 10 %. The

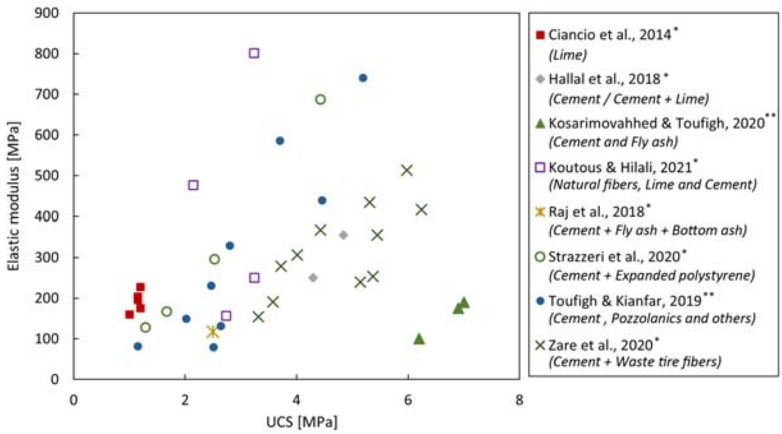


Figure 4.3: Elastic modulus of SRE as a function of unconfined compressive strength. Values obtained by Ciancio et al. [174], Hallal et al. [131], Kosarimovahhed & Toufigh [71], Koutous & Hilali [144], Raj et al. [160], Strazzeri et al. [176], Toufigh & Kianfar [52] and Zare et al. [167]. *Elastic modulus as the slope of $\sigma - \varepsilon$ curve in its elastic area (tangent modulus). **Elastic modulus calculated according to Equation 4.3.1.

same studies indicate that those values lead to an improvement of 150 % to 500 % with respect to URE specimens. Smaller improvements of the elastic modulus (40 % to 140 %) are obtained when using lime as stabilizer [144, 174].

Regarding the Poisson's ratio (ν), there are only a few studies calculating its value. Raj et al. [160] and Meek et al. [162] obtained values between 0.16 and 0.20 for RE stabilized with diverse additives including cement, fly and bottom ash, ground-granulated blast-furnace slag and kaolin clay, while Strazzeri et al. [176] obtained a ν value of 0.33 for CSRE with and without expanded polystyrene.

4.3.3. Tensile and flexural strength

Rammed earth is known to be very weak in tension, so RE elements should not be designed for pure tension [42]. However, the tensile strength (f_t) is a very relevant parameter involved in RE failure, especially under extreme loading conditions, such as earthquakes [57, 80]. These are the main reasons why several authors have tried to improve RE tensile strength by stabilization, as shown in Table 4.2. It can be seen that the value of f_t in these studies reaches values in the range from 0.25 to 1.16 MPa, and in most of them above 0.4 MPa, which is an improvement over URE frequently above 150 %.

The most commonly used additive to improve RE tensile strength are fibers [42, 145, 164], both natural (straw, palm, coir, jute, barley,...) [131,

Table 4.2
Tensile strength (f_t) and unconfined compressive strength of SRE samples (in parenthesis improvement of UCS and f_t with respect to URE, when available).

Ref.	Sample [cm]	Additives (%wt)	f_t [MPa]	UCS [MPa]	Ratio f_t/UCS
[52]	⌀7.5, h15	Pozz(10)+MS(1.5)	0.25 (4 %)	2.5 (11 %)	0.10
[131]	⌀10, h20	C (8)	0.33 (106 %)	4.3 (231 %)	0.08
[142]	10 × 10 × 10	Coir fiber (3)	0.39 (179 %)	4.1 (7 %)	0.10
[144]	⌀10, h20	L (4)	0.40 (0 %)	2.2 (6 %)	0.18
[144]	⌀10, h20	C (6)	0.45 (13 %)	3.2 (60 %)	0.14
[144]	⌀10, h20	Palm fiber (0.75)	0.45 (13 %)	3.3 (60 %)	0.14
[143]	44 × 10 × 10	L (25*)	0.49	–	–
[144]	⌀10, h20	Barley fiber (0.75)	0.50 (25 %)	2.7 (35 %)	0.19
[52]	⌀7.5, h15	Fiberglass (1.5)	0.53 (121 %)	2.5 (13 %)	0.21
[167]	40 × 10 × 10	WTTF (4)	0.68 (155 %)	3.3 (−12 %)	0.21
[52]	⌀7.5, h15	C (10)	0.77 (221 %)	5.2 (133 %)	0.15
[167]	40 × 10 × 10	C(7)+WTTF(4)	0.89 (231 %)	5.2 (36 %)	0.17
[131]	⌀10, h20	C(4)+L(2)+HF(1.25)	0.96 (500 %)	–	–
[142]	10 × 10 × 10	C(10)	0.99 (607 %)	6.5 (69 %)	0.15
[142]	10 × 10 × 10	C(10)+Coir fiber(3)	1.16 (729 %)	6.2 (63 %)	0.19

MS - microsilica; Pozz - pozzolanics; C - cement; L - lime; HF - hemp fiber; WTTF - waste tire textile fibers.
*Percent by volume.

142, 144] or synthetic (fiberglass, plastic fibers) [52, 167]. According to The Australian Earth Building Handbook [43], the ideal soil for fiber stabilization should have liquid limit between 30 % and 50 % and plasticity index between 15 and 35.

Fiber stabilization, however, frequently implies a reduction of the compressive strength with increasing fiber contents [167, 172]. This fact can be counterbalanced with the combined use of fibers and cement as evaluated by Zare et al. [167] who tried different combinations with diverse contents of cement and waste tire fibers. Actually, the highest f_t values, according to literature, are obtained adding both fibers and cement to the soil mixture [131, 142, 167].

The improvement of RE tensile strength also leads to an increase in the f_t/UCS ratio. If this ratio was approximately equal to 0.10 for URE [170], it raises to between 0.10 and 0.21 in the case of SRE.

There are few studies regarding the flexural strength of RE materials, both unstabilized and stabilized. Jayasinghe and Mallawaarachchi [181] performed four-points bending tests in URE walls obtaining a value of 0.46 MPa when the load was applied parallel to the layers and 0.92 MPa if perpendicular. Ciancio and Augarde [182] performed the same tests obtained values of flexural strength similar to the latter, between 0.80 and 1.00 MPa.

With the aim of improving the flexural strength of RE, authors have proposed using fiber reinforcements. Tripura et al. [183] carried out four-points bending tests (parallel and perpendicular to the earth layers) on RE samples combining cement stabilization, cocoa fiber reinforcement (short fibers mixed in the matrix) and bamboo external reinforcements. All combinations of additives resulted in an increase of the flexural strength if compared with URE; the maximum values were reached with combining all three additives, reaching 1.29 MPa for parallel loading (+139 % with respect to URE) and 2.11 MPa for perpendicular loading (+167 %). Also Vernat-Maso et al [163] performed three-points bending tests to analyze the effect of textile reinforcement in the flexural behavior of rammed earth, concluding that, when the failure mode was not associated with the possible least earth-grid adherence, the reinforced specimens showed a greater load-bearing capacity than that of the unreinforced ones, with an increase in the maximum bending moment of ca. 94 %.

These results indicate that fiber reinforcements (both internal short fibers or structural fabrics) may be very useful to enhance the flexural behavior of RE elements, although further studies would be necessary to draw general conclusions. Also, regarding fabric reinforcements, it essential to ensure the proper adhesion between the reinforcement and the soil matrix in order to obtain the desired improvements in the mechanical behavior of the compound [165].

4.3.4. Shear strength, cohesion and fracture energy

Rammed earth presents very low shear strength [170], so for RE walls it is frequently considered close or equal to zero in absence of further experimental data [43, 44]. Although there are currently no studies regarding the enhancement of RE shear strength through additivation, some few studies have evaluated the shear behavior of CSRE.

Lepakshi and Venkatarama [184] carried out triaxial compression tests on several RE cylindrical specimens with cement contents from 4 % to 15 %. The results indicate that increasing cement contents lead to an increase in the shear strength (from 0.59 MPa with 4 % cement to 2.18 MPa with 15 % cement). This last value is much higher than common shear strengths indicated by several authors for URE (0.15–0.85 MPa) [27, 55, 57, 67].

Pavan et al. [185] performed diagonal compression tests on 10 % CSRE panels according to ASTM-E519 [83] using two different techniques to improve the bond between layers: making blunt conical shaped dents and applying a coat of fresh cement slurry. The shear strength obtained in both cases was equal to 1.24 MPa.

These two studies also evaluated the cohesion and friction angle of CSRE, obtaining the results shown in Table 4.3. Particularly interesting are the results of Lepakshi and Venkatarama [184], indicating that cohesion linearly grows with increasing cement contents while the angle of internal friction remains almost invariant and equal to ca. 50° for cement contents over 7 %. Also Kosarimovahhed and Toufigh [71] evaluated the cohesion of cement and lime SRE, obtaining a maximum of 1 150 kPa with a combination of 2.5 % cement and 5 % lime.

According to the values of these few studies, shown in Table 4.3, cement seems to significantly increase the cohesion of RE, which is in the range from 30 kPa to 260 kPa for URE [170]. The increments in the values of the friction angle, on the other hand, are almost negligible.

Table 4.3
Shear strength (f_s), cohesion (c) and friction angle (φ) of SRE.

Ref.	Cement [%wt]	Lime [%wt]	f_s [MPa]	c [kPa]	φ [°]
[184]	4.0	–	0.59	480	27
	7.0	–	1.16	640	55
	10.0	–	1.67	940	52
	15.0	–	2.18	1320	46
[185]	10.0[a]	–	1.24	794	26
	10.0[b]	–	1.24	762	49
[71]	7.5	–	–	205	–
	5.0	2.5	–	490	–
	–	7.5	–	805	–
	2.5	5.0	–	1150	–

[a] Blunt conical shaped dents between layers.

[b] Coat of fresh cement slurry between layers.

There are still only a few studies evaluating the fracture energy (G_f) of RE, but all of them indicate that the fracture energy of RE could be improved by chemical additivation (lime or cement). Three-points bending tests and splitting tensile tests were performed to determine this parameter. Arto et al. [143] identified a clear correlation between the fracture energy and the soil-lime ratio, reaching values over 30 N/m with 25 % vol lime. Corbin and Augarde [87] obtained an approximately linear relationship between G_f and cement content, from only 1.5 N/m for URE to 36 N/m for 10 % CSRE. Higher values were reported by Sajad and Toufigh [90]: $G_f = 20$ N/m for URE and $G_f = 63$ N/m for 10 % CSRE.

According to these investigations, other additives, such as pozzolan, microsilica, guar gum, fiberglass or PCM do not significantly affect the fracture energy [90]; while the addition of wool decreases the G_f values over a 50 % [87].

4.4. Insulating properties

4.4.1. Thermal insulation

As is was analyzed in the previous chapter, URE provides an acceptable thermal insulation, with a thermal conductivity (λ) between 1.0 and

1.4 $\mathrm{Wm^{-1}K^{-1}}$ [170], similar to traditional ceramic bricks [1, 96] and better than other common construction materials such as concrete [96]. Considering this, most studies regarding RE stabilization have focused their efforts on improving the mechanical properties and not so much the thermal behavior.

However, it is possible to enhance the thermal performance of RE walls by incorporating thermal energy storage materials, that store energy by sensible or latent heat, such as expanded polystyrene (EPS) or phase change materials (PCM) [70]. This additives can significantly reduce the thermal conductivity of RE, obtaining λ values lower than 0.4 $\mathrm{Wm^{-1}K^{-1}}$, as shown in Figure 4.4 (left).

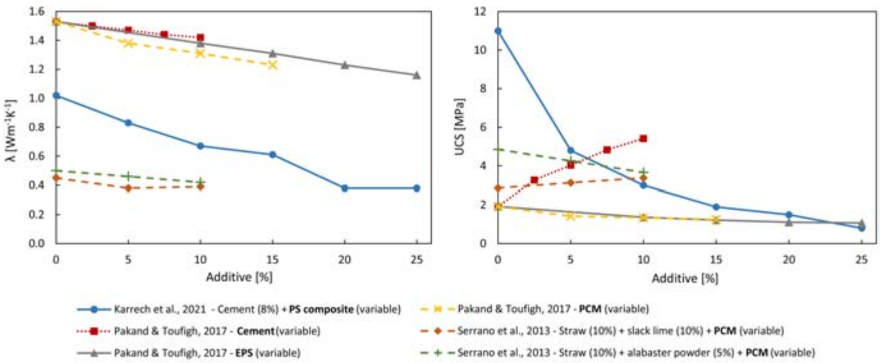


Figure 4.4: Stabilization of RE for the improvement of thermal conductivity (left) and its effect on UCS (right). Values obtained by Karrech et al. [178], Pakand & Toufigh [70] and Serrano et al. [106].

Karrech et al. [178] reached a 62 % reduction of the thermal conductivity of CSRE with a 20 %vol of polystyrene composite (expanded polystyrene beads coated with a bituminous binding agent); and Pakand and Toufigh [70] reduced λ by 24 % using 20 %vol EPS. If PCM are used (about 10 %), the reduction of the thermal conductivity is between 15 and 20 % [70, 106].

The problem with this kind of additives is that they significantly worsen the mechanical performance of the RE structure, causing a decrease in the UCS (Figure 4.4 (right)). However, when high compressive strengths are important, it should be noted that Pakand and Toufigh [70] indicated that cement stabilization also provides a certain improvement in the thermal behavior, while increasing the mechanical properties.

The effect of moisture content on the thermal behavior of RE should also be taken into account. It has been observed that the thermal conductivity of CSRE linearly increases with the saturation ratio of the material, due to the formation of menisci acting as thermal bridges between particles in partially saturated soils [92, 186].

4.4.2. Acoustic performance

As with the thermal behavior, URE shows a very good acoustic performance, and therefore it has not been a priority of researchers to study the improvement of this characteristic via additivation. URE has a sound reduction index (R) of about 57 dB for 30 cm to 50 cm-thick walls [51, 78, 117, 119], and its porosity provides an excellent reverberation behavior, generating far fewer harsh echoes than other common wall materials [115, 117, 120].

No studies in literature have been found specifically regarding the improvement of these acoustic properties, but deeper investigation in this field would be necessary. In the absence of further research, it would be possible to enhance the acoustic insulation by covering the RE walls with insulating panels, as it is done for any other type of wall.

4.5. Durability

RE construction are quite sensitive to rain and wind erosion and to the effect of aggressive environments, so they frequently need some kind of protection against weathering [127–129, 134]. This protection can be obtained with external barriers (waterproofing agents or sloping roofs) or through additivation.

Some studies indicate that the use of cement significantly improves the durability of RE against water erosion. Arrigoni et al. [129] measured the accelerated erosion due to sprayed water and mass loss due to wire brushing on URE and SRE mixtures with 5 % cement + 5 % FA and 6 % CCR + 25 % FA, observing that both SRE mixtures (but not URE) passed the tests and achieved sufficient strengths for construction according to The Australian Earth Building Handbook [43]. Also Narloch and Woyciechowski [187] performed water erosion resistance tests on URE and 6 % and 9 % CSRE according to New Zealand Standard NZS 4298 [45], obtaining that none of the CSRE samples showed any surface damage while all the URE specimens had deep cavities despite their shorter exposure time in water, concluding that in a humid continental climate the use of URE is unsuitable due to lack of durability.

However, some studies evaluating the long-term durability (over 20 years) of RE against water, suggest that external protection is needed also for CSRE [188] or even that the stabilization by cement or lime might be inadequate [133].

Erosion is the major cause of concern for earthen structures, but aggressive environments may also decrease the durability of RE. Although additional durability issues (e.g. alkali-aggregate reactions and sulfate induced swelling) could be expected when cement-like additives are used [129], Ghasemalizadeh and Toufigh [127] concluded that the presence of a sufficient amount of cement improves the behavior of RE in sulfate, alkaline and acidic environments. These authors observed that 7.5 % and 12.0 % CSRE remained integrated after 1 year of exposure to the aforementioned environments, while 2.5 % CSRE disintegrated after 6 months of exposure to sulfate and alkaline environments and 9 months in an acidic environment. The sulfate solution was observed as the most destructive environment for RE materials. Luo et al. [189] also measured a reduction of RE compressive strength and cohesion in the presence of sodium chloride, sodium sulfate and calcium chloride, which was much more severe when the sodium sulfate and calcium chloride were applied simultaneously.

Finally, Narloch and Woyciechowski [187] evaluated durability of RE against frost-defrost cycles. The study concluded that a minimum of 9 % cement is needed to reach the frost resistance level required by European Standard EN 206:2013+A1:2016 [190]. According to this research, the presence of gravel in the particle size distribution of the earthen material also plays a key role in the frost resistance of CSRE.

4.6. Environmental and economic impact of stabilization

4.6.1. Environmental cost

One of the main benefits of rammed earth construction, and also one of the most important reasons why this technique is experiencing a significant growth over the last years, is its very limited environmental impact [1, 51, 135, 141]. This is due to the fact that the source material is raw earth that can be frequently obtained in the construction site and which needs very low industrial processing, reducing resource and energy consumption, pollution and waste generation.

However, when the mechanical properties of raw earth are not enough to reach the required standards and so additives are included to the mixture, some of the aforementioned environmental advantages are severely reduced. Two of the main indicators that may help understanding how environmentally friendly a construction technique is are the CO_2 emissions and the embodied energy, and both parameters significantly increase for SRE compared to URE, as it is shown in Table 4.4.

When cement or other industrially manufactured products are used as stabilizers, the environmental costs increase due to the manufacturing process and the transportation distance. Actually, the embodied energy of CSRE walls linearly increases with the cement content [23]; and, for example, a 8 %-cement SRE wall implies more than 14 times the CO_2 emissions and 10 times the embodied energy than the same wall made with URE (Table 4.4). Nevertheless, the embodied energy in CSRE is only about 15 % to 25 % of the embodied energy in common brick masonry [23].

Although other factors, such as a higher presence of clay or an increase in the required compaction level, may affect the energy consumption, their

Table 4.4
CO_2 emissions and embodied energy per cubic meter of RE.

	CO_2 emissions		Embodied energy	
Additives	Values [kg]	Ref.	Values [MJ]	Ref.
None (URE)	3–9	[70, 135]	49	[129]
2.5 % cement	42	[70]	–	
4 % cement	–		280	[23]
5 % cement	86	[70]	–	
6 % cement	–		400	[23]
7.5–8 % cement	131	[70, 71]	500	[23]
10 % cement	179	[70]	630	[23]
12 % cement	–		750	[23]
5 % cement + 2.5 % FA	129	[71]	–	
5 % cement + 5 % FA	–		155	[129]
2.5 % cement + 5 % FA	120	[71]	–	
7.5 % FA	106	[71]	–	
25 % FA + 6 % CCR	–		68	[129]
20 %vol EPS	18	[70]	–	
10 % PCM	1630	[70]	–	

contribution to the total energy expenditure of the whole process is negligible if compared to the energy content of cement [23]. This is the reason why several recent studies aiming to develop an eco-friendly RE with greater mechanical properties than traditional URE have tried to replace cement or lime with natural stabilizers or waste materials.

Despite the fact that many studies have recently presented alternative additives as a sustainable way to improve RE mechanical characteristics, the huge differences in the methodologies applied to measure the environmental benefits (or even its absence) make it very difficult to compare the results.

One of the most common and direct ways to reduce cement consumption in RE construction is replacing it with CCR and/or FA, which significantly reduces the cumulative energy demand especially if the CCR is a waste, in which case the environmental impacts of URE and SRE are similar when local soil is not suitable by itself for construction [129]. Although the UCS is generally lower when replacing cement with CCR and FA [129, 161], Kosarimovahhed and Toufigh [71] obtained that a combination between cement and alkali-activated FA could lead to a higher strength than only cement, while reducing the CO_2 emissions.

Other waste materials or industrial by-products have been tested, such as crushed brick and concrete from demolition, ground granulated blast furnace slag, silica fume, bottom ash or granitic residual soils [123, 160, 162, 175]. The use of this kind of materials helps reducing the amount of industrial waste products ending up in landfills and minimizing the material and energy consumption and waste generation due to the manufacture process of stabilizers. In addition, natural fibers could be also considered as useful additives for RE, as they have been traditionally used to improve the mechanical behavior of earth constructions and have a small impact in the environmental cost [144, 145].

4.6.2. Economic impact

Economic and environmental costs are strongly related when considering the stabilization of RE, as the manufacturing process of the stabilizers and the need for transportation not only reduces the sustainability of the construction technique, but also has a significant economic impact. Table 4.5 shows the cost of some SRE mixtures according to literature (Labor and transportation costs not included).

Table 4.5
Material cost per tonne of RE.

Additive	Ref.	Cost [$/t RE]
None (URE)	[70]	3.51
2.5 % cement	[70]	4.16
5 % cement	[70]	4.81
7.5 % cement	[70]	5.46
7.5 % cement	[71]	11.25
10 % cement	[70]	6.11
5 % cement + 2.5 % FA	[71]	10.88
2.55 % cement + 5 % FA	[71]	10.47
7.5 % FA	[71]	9.95
15 % EPS	[70]	4.94
10 % PCM	[70]	653

Analyzing the results obtained by Pakand and Toufigh [70], it is possible to observe that the ratio cost-UCS significantly decreases from URE to 2.5 % CSRE and then gradually stabilizes for increasing cement contents, reaching a value of 1.13 $/(MPa · t) (Figure 4.5). This means that the increase in the cement content (and therefore the cost) leads to a greater strength gain at the beginning but this effect is much less significant for higher cement contents. It must be noted that transportation and labor costs are not included, only the cost of the materials.

Defining a single value for the economic impact of stabilizers is not possible due to the great variability in the source material, labor and transportation costs in the different countries, but more thorough investigation may help understanding the relationship between the increase in the costs and the improvements obtained for the material. This applies also to the environmental costs of RE stabilization.

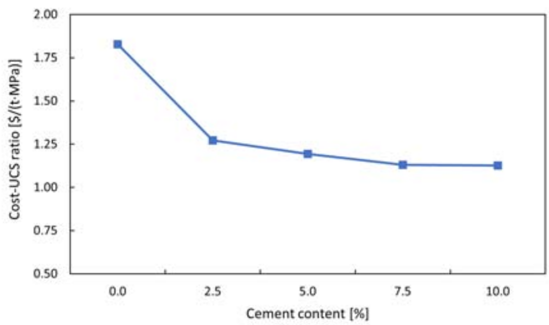


Figure 4.5: Cost–UCS ratio of RE as a function of cement content. Data: [70].

4.7. Conclusions

Introducing rammed earth construction technique in new buildings implies a need to meet the requirements defined in the current construction standards, and this is the reason why stabilization is becoming increasingly important in RE construction. This chapter presents a review of the most relevant properties of stabilized rammed earth and their impact in the environmental an economic cost of the technique.

It has been observed that the use of cement is widespread in RE construction, making it possible to achieve high values for some of the most relevant mechanical properties, such as the compressive strength and stiffness, although its negative effect in the environmental performance of the material is frequently not taken into consideration. Recent studies, though, have evaluated the addition of alternative more eco-friendly stabilizers (fly or bottom ash, natural fibers, . . .), frequently used together with cement in order to improve the mechanical behavior and reduce the environmental impacts.

Natural o synthetic fibers are often the solution if the parameter to be enhanced is tensile, flexural or shear strength, although cement and other additives are also used. Rammed earth shows low values of these properties, but they are essential in the behavior and failure of RE elements.

The main conclusions obtained in the present analysis are listed below:

- There exist several additives that can be included in the mixture, but cement is by far the most common and most thoroughly studied.
- The soil and water content used for SRE is similar to those used for URE, not very specific characteristics are required.

- Cement is frequently used to improve the UCS of RE, with an increase from 60 % to 250 % in most studies compared to URE. The relationship between cement content and UCS seems to be approximately linear. Cement is frequently combined with FA.
- Increasing cement contents lead to an increase in the elastic modulus, but the relationship is not so clear and some dispersion is observed.
- RE tensile strength is usually improved by the use of natural or synthetic fibers. It is observed, however, that increasing fiber contents frequently imply a reduction of the compressive strength, which is sometimes counterbalanced combining fibers and cement.
- Thermal insulation can be enhanced using thermal energy storage additives, such as EPS or PCM, reducing the thermal conductivity over a 15 %. It must be noted, however, that this kind of additives significantly worsen the mechanical behavior of RE. The enhancement of the acoustic properties of RE, on the other hand, has not be thoroughly studied yet.
- Some studies indicate that the use of cement can improve the durability of RE against water erosion, aggressive environment and frost-defrost cycles. The effect of other stabilizers on RE durability remains to be studied.
- The use of stabilizers significantly increases the environmental and economic cost of RE construction, due to the manufacturing process and transportation distances. This impacts can be reduced by replacing industrial stabilizers, such as cement, by industrial by-products (e.g. FA, bottom ash or crushed bricks) or natural additives (e.g. natural fibers).
- Standardizing the testing procedures would be essential to obtain comparable values of the mechanical parameters of rammed earth.

Chapter 5

Lime-stabilized rammed earth: lime content and strength development. Experimental campaign

5.1. Introduction

Analyzing the existing buildings made of rammed earth, it is possible to observe that one of the additives with longest tradition for rammed earth stabilization is lime, existing several examples of historic constructions made of lime-stabilized rammed earth (LSRE) [3, 24, 155–157, 191]. The RE used in these heritage buildings usually contained very significant percentages of lime, e.g., between 10 % and 15 % in the medieval walls of Seville (Spain) [192] and in traditional RE houses in Southern Portugal [193], 20 % in the Alcazaba Qadima and the Alhambra of Granada (Spain) [156, 194], also 20 % in the Saadian sugar refinery of Chichaoua (Morocco) [155], and ca. 25 % in the Fujian Tulou (China) [195] or in the Cáceres city walls (Spain) [192].

As it was described in the previous chapter, there is a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [148–152]. When lime is added to a soil, the concentration of Ca^{2+} and OH^- increases due to the hydration reaction of lime. This generates the flocculation of particles (affecting soil plasticity) and increases the pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [149, 153, 196].

However, and despite its historical use, today lime has been superseded by cement as the most common stabilizer for rammed earth [197], and as a consequence there is a lack of scientific research specifically analyzing the effects of lime stabilization in the mechanical properties of RE. Ciancio et al. [174] carried out a study evaluating the optimum lime content for LSRE, obtaining a value equal to 4 % by weight, but lime contents greater than 6 % were not considered. Da Rocha et al. [158] also analyzed LSRE materials, from 3 %wt to 9 %wt, concluding that the uniaxial compressive strength increased with increasing lime contents and indicating the need of long curing times. Also Canivell et al. [198] and Arto et al. [143] have recently evaluated the compressive strength and fracture energy, respectively, of RE materials stabilized with high percentages of lime.

Understanding the mechanical behavior of LSRE is essential in order to properly preserve the large number of heritage buildings made with this technique, but also because of its potential benefits in the development of an environmentally-friendly way of constructing. Lime is considered to be a much less energy-intensive binder compared to the frequently used Portland cement [174], as its manufacturing temperature is significantly lower (ca. 900 °C as opposed to 1 500 °C) [199], which reduces the CO_2 emissions during production. It is estimated that ca. 0.9 t of CO_2 are produced per tonne of cement, while the manufacturing process of lime produces less than 0.7 t of CO_2 per tonne of lime [200–203]. In addition, the carbonation reaction (through which lime uptakes atmospheric CO_2) during the lifetime of the building can counterbalance the carbon emissions generated in the manufacturing and transportation process, leading to a reduction of the net carbon footprint of lime-stabilized materials [199, 204, 205].

Against this background, the study described in this chapter presents an analysis of the effect of lime stabilization in the mechanical behavior of rammed earth, evaluating the compressive strength and stiffness of the material with diverse lime contents and analyzing its strength development process. In addition, the present chapter includes an evaluation of nondestructive ultrasonic pulse velocity testing technique as a tool to assess the mechanical properties of RE without damaging the sample.

All the experimental evaluation included in this chapter was carried out in the Sustainable Engineering Structures Laboratory (SES-Lab) of the University of Granada.

The research presented in this chapter has been published in the following scientific article:

- F. Ávila, E. Puertas, R. Gallego, *Mechanical characterization of lime-stabilized rammed earth: Lime content and strength development.* Construction and Building Materials. 350 (2022) 128871.
  doi: 10.1016/j.conbuildmat.2022.128871.

5.2. Materials

5.2.1. Soil

The main source material used for the RE in this study was a natural soil from a quarry in Padul (Granada, Spain), classified according to the European Soil Classification System (ESCS, ISO 14688-2) as clayey well-graded sand, after been passed through a 10 mm sieve in order to remove the coarser particles. The particle size distribution of the resulting earthen material is shown in Figure 5.1, been in agreement with recent studies regarding rammed earth stabilization [52, 71, 160] and fitting withing the envelope recommended by Houben et al. [29], widely accepted for URE construction and frequently used also for SRE [197]. The soil had chloride and sulfate contents lower than 0.002 % and was free of organic matter and light contaminants. This soil can be considered to be representative of the material traditionally used in RE construction in Southern Spain [143, 157, 192, 194, 206].

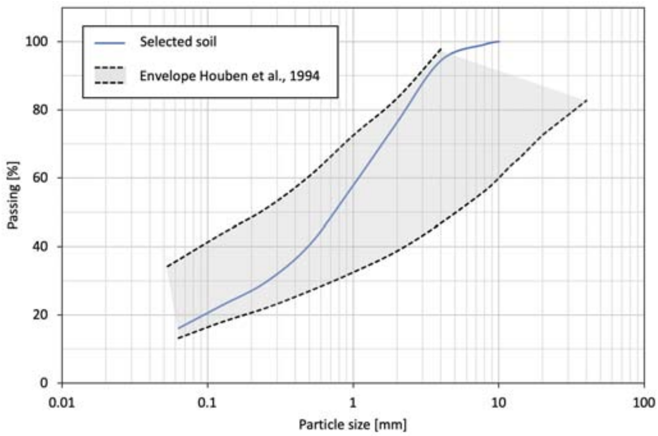


Figure 5.1: Particle size distribution of the soil.

5.2.2. Lime

Natural hydraulic lime with minimum compressive strength of 3.5 MPa at 28 days, referred to as NHL 3.5 according to European standard EN 459-1, was used as stabilizer. The main components of NHL are portlandite, reactive silicates and aluminates formed during calcination from the reaction of crushed limestone containing clay or other impurities. Table 5.1 shows the most relevant chemical and physical properties of the lime used in the present study.

Table 5.1
Chemical and physical properties of the natural hydraulic lime used in the study, as indicated by the manufacturer.

Parameter	Avg. value
SO_3 [%]	1.7
Free lime, $Ca(OH)_2$ [%]	30
Free H_2O [%]	0.7
Residual at 90 µm [%]	5.7
Residual at 200 µm [%]	0.8
Bulk density [kg/dm^3]	0.671
Real density [kg/cm^3]	2.51
Blaine value [cm^2/g]	8500
Setting time [min]	296
End of taking [min]	438
Compressive strength at 28 days [MPa]	4.8

5.3. Experimental procedure

5.3.1. Specimen preparation

In order to perform the experimental tests, 10 cm-side cubic LSRE specimens were manufactured. It is generally assumed that the size and shape of the samples may affect the mechanical properties obtained [170], although the relation between these parameters is still unclear and it is out of the scope of this research. Similar geometries to the one used for the samples in the present study have been previously used by several authors [20, 50, 69, 71, 142, 198, 207].

For the assessment of the correct amount of water to be added to the mixture, modified Proctor tests (UNE 103501 [208]) were performed on specimens with diverse lime contents. Modified Proctor is a widely established and easily repeatable test that provides a compactive effort very close to the one that might be applied in the construction of a real wall [20, 174]. It was observed that greater amounts of water were needed in order to obtain the maximum dry density (MDD) with increasing lime contents, that is to say, the optimum moisture content (OMC) linearly increased with the lime content. However, this increase in the OMC with the lime content is quite small (equal to ca. 3 %), as it was noted by Ciancio et al. [174], that reported variations lower than 2 % for lime contents between 0 % and 6 %. Furthermore, other authors [131, 144, 158] propose using constant OMC regardless the lime content, as they indicate that the variation is negligible. The results of the compaction tests also showed that the MDD of the LSRE decreases with the increase in lime content, in a very pronounced way for small lime contents and then gradually stabilizing. The variation of the OMC and MDD as a function of the lime content is shown in Figure 5.2.

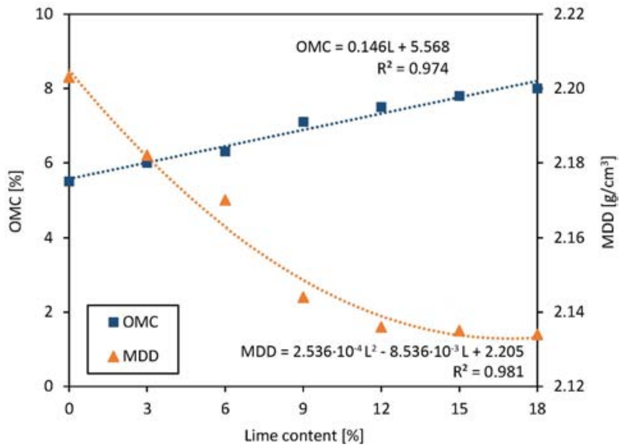


Figure 5.2: Optimum moisture content and maximum dry density, from Proctor test, as a function of the lime content.

The material was prepared by uniformly mixing the natural soil with a certain amount of lime. Water was added to the mixture until reaching a water content equal to the OMC+2 %, following the recommendations of Walker et al. [51] and the New Zealand Standard NZS-4298 [45].

The mixture was then poured into cubic molds and compacted by layers of ca. 2 cm, so each specimen was made up of five earth layers. The small thickness of the layers was chosen in order to provide a more uniform compaction and to reach a high compaction level by manual means. The material was compacted to 98 % of the MDD, according to NZS.4298 [45]. Once the upper layer was compacted and its surface smoothed, the samples were carefully removed from the mold and stored on wire racks, so all the faces could be in contact with the environment. The specimens were cured under constant conditions of about 25 °C and 40 % relative humidity, replicating common natural ambient conditions in Southern Spain.

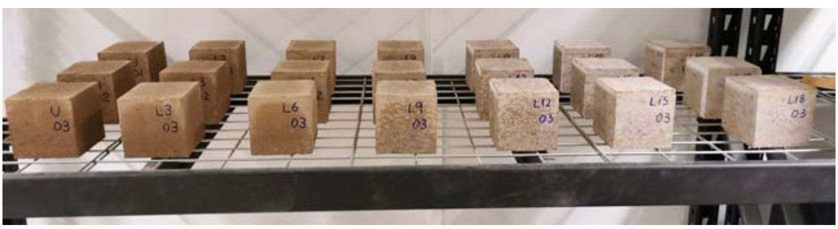


Figure 5.3: Some of the LSRE specimens, with different lime contents, stored on wire racks during the curing period.

5.3.2. Experimental evaluation

The uniaxial compressive strength (UCS) and stiffness of the LSRE specimens were determined performing uniaxial compression tests, applying a homogeneously distributed load on the upper face of the sample, perpendicular to the direction of the earth layers. The tests, in the absence of specific standards for RE testing, were performed according to European Standard EN 12390-3 “Testing hardened concrete. Part 3: Compressive strength of test specimens” [209]. A linear variable differential transformer (LVDT) was used to measure the longitudinal displacements for the calculation of the stiffness modulus. In the first part of the study, UCS tests were carried out on specimens with increasing lime contents, from 0 % to 18 % every 3 %.

Once the results were evaluated, more samples were manufactured with the lime content that led to a better mechanical performance (i.e. 12 %). These specimens were subjected to UCS tests at different curing times, from 2 to 100 days, with a minimum of three specimens per curing time. The time intervals between the tests were smaller during the first weeks (every 2–5 days), as a greater variation of the mechanical properties was expected – and observed–, and longer for older specimens (every 10 days approx.). After the compression tests, the depth of the carbonation front in the specimens was measured by using phenolphthalein solution 1 % in ethanol as indicator, carefully cleaning the surfaces before testing using a compressed air gun. The carbonation depth is measured using a sliding gauge at 3 to 5 equidistant points on each of the four faces on a slice of the specimen, perpendicularly to the exposed surface of the cube, as indicated in standard EN-12390-12 [210]. The carbonation depth considered to be representative of the specimen was obtained as the average of those measurements.

During the curing period, the specimens were periodically weighted to control the loss of moisture, and subjected to ultrasonic pulse velocity (UPV) tests [?]. UPV method is one of the non-destructive testing techniques whit a longest tradition for assessing the mechanical properties and inner cracks of building materials. A ultrasonic device, consisting of a transmitting and a receiving transducer, was used to measure the time of pulse of ultrasonic waves over a known path length [211]. Although UPV method has been widely used for concrete, metal of wooden materials, only a few recent studies have applied it to determine RE mechanical properties [198, 207]. The UPV was measured for the manufactured LSRE specimens in a direction parallel to the earth layers.

5.4. Results and discussion

5.4.1. Stress-strain behavior

The compressive behavior of RE specimens was obtained from the compression tests carried out according to standard EN 12390-3 [212], as mentioned above. This standard indicates that the results of the tests can be considered valid if all four exposed faces are cracked approximately equally, generally with little damage to faces in contact with the platens, as shown in Figure 5.4.

Figure 5.4: Satisfactory failures of cubic specimens, according to EN 12390-3 [209].

Stress-strain curves were obtained from uniaxial compression tests for the specimens with different lime contents after 28 days of curing. Figure 5.5 shows the stress-strain curves of all tested samples. It is possible to observe that, for almost all the specimens, at the beginning of the test, the material suffers significant strains for small load increments, while the earth particles are settling and so the fine grains fill the empty spaces between the coarser ones. Then, at ca. 0.01 mm/mm strain, the stiffness significantly increases and the material shows linear behavior until approximately 75 % of the maximum stress. This linear phase, however, also comprises plasticity due to the formation of microcracks, so it cannot be considered as linear-elastic [80, 144, 213, 214]. This is followed by a plastic phase with a reduction of the stiffness until maximum stress is reached, then crack propagation occurs rapidly until failure.

5.4.2. Compressive strength and stiffness

According to the evaluation of the stress-strain curves obtained from the experimental tests, the material shows a linear behavior approximately between 35 % and 75 % of the maximum stress, so the stiffness modulus (E) of the samples was calculated according to the following equation, which is based on the formulation proposed in ASTM C469 [179] for concrete samples, and used for rammed earth in previous studies [52, 71]:

$$E = (S_{75} - S_{35})/(\varepsilon_{75} - \varepsilon_{35}) \tag{5.4.1}$$

where S_{35} and S_{75} are the stresses corresponding to 35 % and 75 % of the maximum stress, respectively; and ε_{35} and ε_{75} are the longitudinal strains

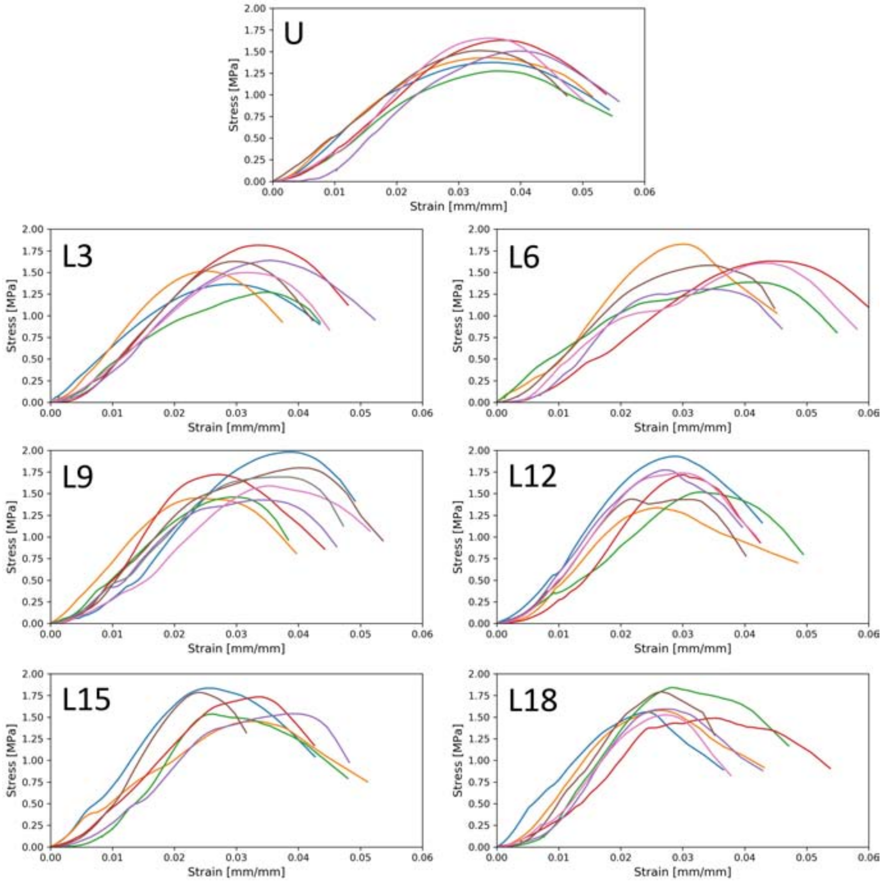


Figure 5.5: Stress-strain behavior of RE specimens with diverse lime contents at day 28.

produced by stresses S_{35} and S_{75}, respectively.

The parameter E defined in Equation 5.4.1 is a secant stiffness modulus, following the recommendation of the aforementioned standard and Koutous and Hilali [144], which indicates that the secant modulus is the best parameter to describe the elastoplastic mechanical behavior of earthen materials. These authors also noted that the value of the secant modulus is equal to approximately 0.62 times the initial tangent modulus for unstabilized, cement-stabilized and lime-stabilized rammed earth.

Table 5.2 shows the main results obtained from the uniaxial compressive tests for each lime content evaluated. The average coefficient of variation (CV) is equal to 11.0 % for the UCS and 17.4 % for the stiffness modulus. These values are reasonable taking into account the intrinsic heterogeneity of the material, and are comparable (and slightly lower) to the CV presented for SRE in previous studies [52, 215].

Table 5.2
Uniaxial compressive strength (UCS), stiffness modulus (E) and strain at max. stress (ε_c) obtained for URE and LSRE specimens after 28 days of curing. Coefficient of variation in parenthesis.

Spec.	UCS [MPa]		E [MPa]		ε_c [mm/mm]	
U	1.48	(9.3 %)	64.97	(9.8 %)	0.036	(5.5 %)
L3	1.53	(11.9 %)	73.43	(18.0 %)	0.031	(11.8 %)
L6	1.56	(13.2 %)	72.99	(21.5 %)	0.038	(13.5 %)
L9	1.64	(11.9 %)	81.49	(16.9 %)	0.033	(17.8 %)
L12	1.64	(12.8 %)	91.01	(17.0 %)	0.028	(12.4 %)
L15	1.65	(9.6 %)	92.56	(26.5 %)	0.030	(18.9 %)
L18	1.63	(8.5 %)	93.45	(12.2 %)	0.028	(12.7 %)

It is possible to observe that an increase in the lime content increased the UCS and E of the RE specimens and decreased the strain reached at maximum stress. The UCS at 28 days obtained for U specimens is comparable to the values commonly obtained for URE [170], and was increased by about 11 % when adding 9 % of lime, while larger lime contents did not seem to provide greater strength. The reason why increasing lime contents did not improved strength is probably indicating that above that critical lime content there is an insufficient amount of aluminosilicate material in the soil to support additional stabilization reactions with the lime.

The UCS results obtained in the present study have been compared with those ones reported in literature, although the latter are very scarce and present a great dispersion. Ciancio et al. [174] obtained higher improvements (ca. 70 %) in the UCS with an optimum lime content of 4 %, but the initial strength for URE was extremely low (0.70 MPa), and so it was the maximum strength reached adding lime. Arto Torres [216] also performed compression tests on 10 cm-side cubic samples, with very high lime contents –20 and 25 %vol–, obtaining UCS equal to 2.64 MPa and 2.38 MPa, respectively. A similar dosage (18 %vol lime) was used by Canivell et al. [198], obtaining an average compressive strength of 1.87 MPa. Not very different results were obtained by Koutous and Hilali [144], leading to UCS between 1.58 MPa and 2.55 MPa for 4 %-LSRE specimens. Da Rocha et al. [158] also evaluated the UCS of LSRE, obtaining surprisingly low values (under 1.00 MPa for all lime contents from 3 to 9 %). Despite of the differences, two aspects observed in the present study were also noted by [158]: UCS increases as the lime content increases and UCS increases as the curing time increases.

The huge differences in the results showed in the diverse studies regarding lime stabilization of RE make it very difficult to draw general conclusions, so it would be necessary to carry out specific tests for particular soils and ambient conditions in order to assess the optimum lime content for the compressive strength and the maximum value of this parameter for each RE construction under consideration. If a range of UCS of LSRE should be established to have an order of magnitude, it would be from 1.00 to 2.50 MPa, a range in which the results of the present study fit.

Regarding the elastic (secant) modulus, the values obtained in the present study for the URE specimens are in agreement with those proposed by Maniatidis and Walker [59] and Bui and Morel [53]. Some other studies propose higher E values [20, 52, 57], but the enormous dispersion in the results presented in literature regarding this parameter does not allow to define a value of consensus [170, 197]. Considering the studies specifically evaluating LSRE, only Ciancio et al. [174] indicates the measurement of the stiffness, showing values between 150 MPa to 200 MPa. Again, the lack of results in literature and their variability make it very difficult to draw conclusions about this parameter.

Analyzing the variation of the stiffness when adding different lime contents, it can be observed that no relevant increases were obtained with lime contents lower than 9 %, but it significantly improved (about 25 %) when reaching that lime content. The increase in the secant stiffness modulus was even higher (over 40 %) for L12 specimens and then remained approximately constant when higher percentages of lime were added. The significance of these stiffness improvements is assessed through an ANOVA test, obtaining a p-value of 0.003, much lower than the significance level (0.05), which provides strong evidence to conclude that the population means –mean stiffness for each lime content– are significantly different. Figure 5.6 shows the evolution of the stiffness with the lime content, together with the variation of the compressive strength.

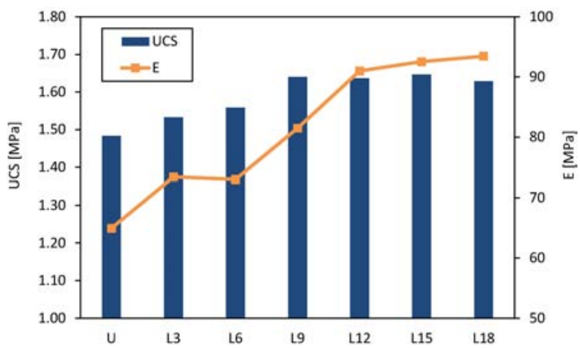


Figure 5.6: Average uniaxial compressive strength and stiffness for increasing lime contents at day 28 (Table 5.2).

In the second part of the study, UCS tests were repeated for 12 %-LSRE specimens, as it was observed that this lime content was the limit over which the improvements in the mechanical properties was almost negligible. The tests performed for the L12 specimens evaluated the strength development process for this SRE material. The results show an exponential evolution of the UCS of the specimens along time (Figure 5.7); Equation 5.4.2 is proposed as the expression that fits better the evolution of the UCS of the LSRE specimens over time, with a coefficient of determination $R^2 = 0.82$.

$$\mathrm{UCS} = 2.530\left(1 - \exp\left(-0.386\, t^{0.277}\right)\right) \tag{5.4.2}$$

whit UCS in MPa and the curing time, t, in days.

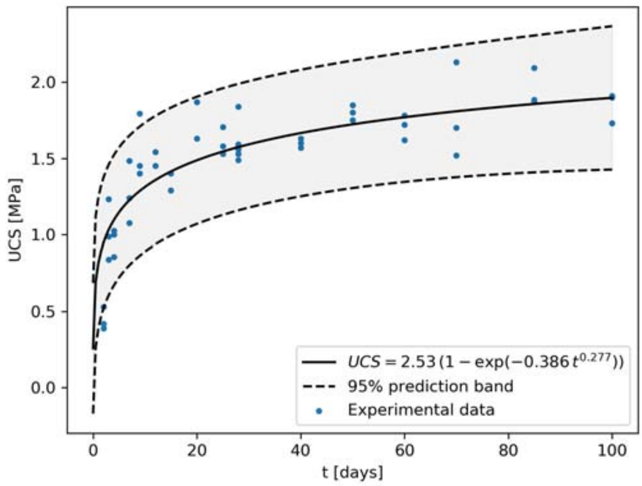


Figure 5.7: Development of the uniaxial compressive strength over time for L12 specimens.

These results and the proposed equation indicates a maximum UCS of 2.53 MPa at infinite time. Sixty five percent of this maximum strength is developed during the first 28 days of curing, and this percentage increases to 75 % if waiting until day 100. Although the UCS values obtained for 12 %-LSRE in the present study –1.64 MPa at day 28 and 1.89 MPa at day 100– are not particularly high if compared with some of the most recent results in literature that stabilize RE with diverse combinations of additives (most of them including cement), they are in agreement with most studies considering RE stabilized only or mainly with lime, as mentioned above.

Regarding the strength development process, it is common in literature to analyze the UCS of RE at relatively short periods of time (usually 28 days [174, 198, 216]), despite the fact that it is well known that the strength development of lime-stabilized earth is a long-term process [150, 152, 196]. In fact, some studies regarding LSRE [148, 158] indicate that the UCS of the material is still increasing after 100–360 days of curing. In order to reduce these long curing periods, Da Rocha et al. [158] proposed limiting the lime content and including a significant percentage of fly ash (over 25 %). There are also some examples of ancient LSRE structures constructed centuries ago that may help indicating the potential strength of this material at "infinite" time; this is the case of the Tower of Comares at the Alhambra (Granada, Spain), where cylindrical samples were extracted from its walls and tested in laboratory obtaining a compressive strength of 2.45 MPa [156, 217].

It is well known, therefore, that the strength acquisition process is slow and requires a significant amount of time to be fully developed. However, it is also possible to observe that a huge percentage of the final strength is developed during the first weeks of curing, due to the hydration reaction of lime that starts just after the lime is added to the soil in the presence of water. It was also observed that, during the first ten days of curing, the weight of the specimens significantly decreased, mainly due to the evaporation of the water present in the mixture, and then remained almost completely constant. The weight variation of the samples during their first month of curing is shown in Figure 5.8. A similar behavior of the moisture loss process was observed by Arto et al. [143] for LSRE specimens cured in natural ambient conditions. Curing conditions with higher relative humidity could reduce evaporation and extend the hydration process of lime, prolonging the time required for the strength to stabilized and allowing the material to reach higher strength values.

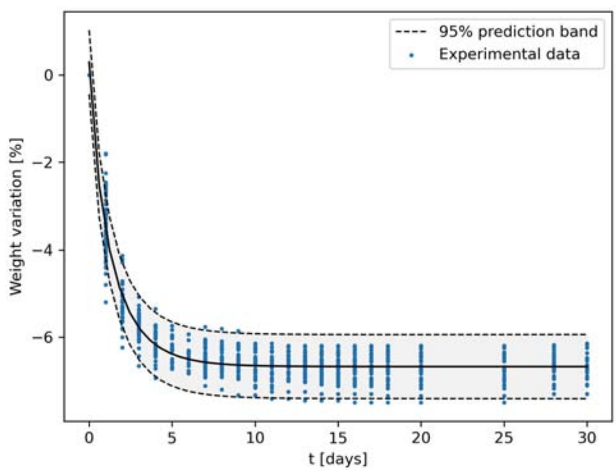


Figure 5.8: Weight variation of L12 specimens during the first 30 days of curing.

Evaluating the stiffness modulus, it is possible to observe the existence of a linear correlation between this parameter and the UCS of the LSRE specimens, where E is equal to ca. 57 times the UCS with $R^2 = 0.75$, as shown in Figure 5.9. A linear relationship between these two parameters has been noted in several previous studies regarding RE with diverse stabilizers [52, 59, 71, 167, 176]. Some relevant earth construction standards, such as NZS 4297 [44], also indicate that the stiffness can be linearly obtained from the UCS values if there is not more specific data.

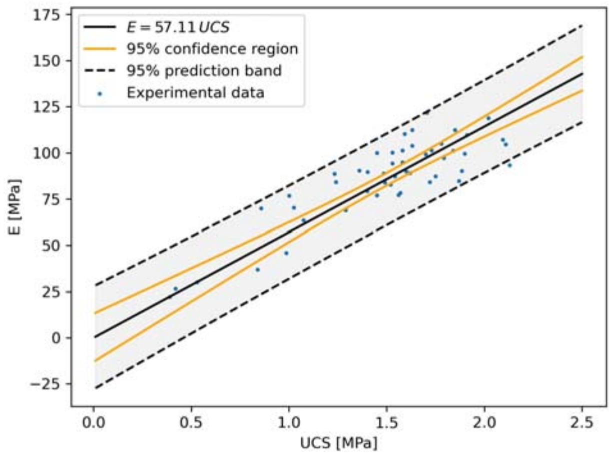


Figure 5.9: Stiffness modulus as a function of the uniaxial compressive strength.

5.4.3. Carbonation

It is also useful to evaluate the evolution of the carbonation depth in the LSRE specimens, as it is closely related to the strength development process [205]. Carbonation occurs when the lime added to the soil reacts with the CO_2 present in the air. This phenomenon should generally be avoided, as it subtracts the lime to other lime-soil reactions and hence inhibits or limits the formation of cementitious products, reducing the maximum potential strength [149, 196]. Although carbonation speed could be slowed down by limiting the CO_2 concentrations in the curing environment, this is unlikely to be possible in a real construction site, so natural ambient conditions were considered in the present study.

The carbonation depth in the specimens was measured, after the UCS tests, as the distance between the external faces of the specimen, exposed to carbon dioxide, and the carbonation front. Van Balen and Van Gemert [218] proposed the formula $c = k\sqrt{t}$ to explain the evolution the carbonation depth (c) in lime mortars, where t is the curing time and k is an experimental factor. Basing on this expression and considering the results obtained in the present study, equation 5.4.3 is proposed to describe the evolution of the carbonation depth in the 12 %-LSRE specimens, with a coefficient of determination equal to 0.93.

$$c = 4.319\, t^{\,0.430} \tag{5.4.3}$$

where c is the carbonation depth in mm and t is the curing time in days.

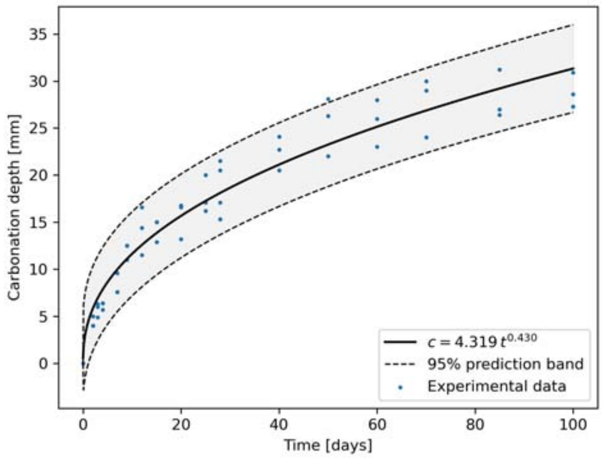


Figure 5.10: Evolution of the carbonation depth during the curing period.

Although the growth of the carbonate depth is faster during the first days of curing (Figure 5.10), as it happens with the strength acquisition or moisture loss, the carbonation process continues to develop for a much longer time. In the case of the 100 mm-side cubic specimens used in this study, the samples would be fully carbonated after ca. 300 days of curing. The carbonation speed also depends on the lime content, as it can be observed in Table 5.3, which includes the carbonation depth of the specimens for diverse lime contents at day 28, when they were subjected to the UCS tests. The carbonation depth after 28 days of curing is higher for samples with lower lime contents, probably because greater lime percentages result in a finer pore structure that impedes CO_2 permeation [149, 195, 219]. Also, as the amount of carbon dioxide in the atmosphere is controlled, a greater lime content in the material takes longer to carbonate and so a reduced carbonation rate occurs with increasing lime content.

5.4.4. Ultrasonic pulse velocity

The UPV through the RE samples was measured before destructive UCS testing in order to assess a potential relationship between this parameter and the mechanical properties of the material. In fact, the analysis of the results shows a linear correlation between the UPV and the UCS of the LSRE

Table 5.3
Carbonation depth (c) of LSRE specimens after 28 days of curing. Mean value and coefficient of variation.

	L3	L6	L9	L12	L15	L18
c [mm]	32	25	19	18	20	18
CV [%]	9.1	7.3	10.7	12.3	9.7	10.7

specimens, following Equation 5.4.4, where UCS is expressed in MPa and UPV in km/s. This relationship and its 95 % prediction band and confidence region are shown in Figure 5.11.

$$\mathrm{UCS} = -1.416 + 1.897\,\mathrm{UPV} \tag{5.4.4}$$

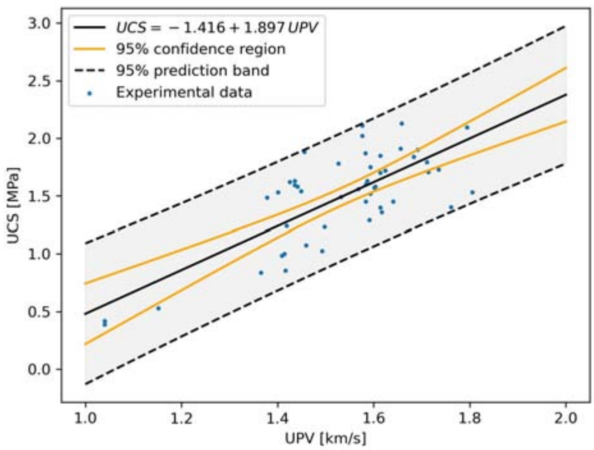


Figure 5.11: Uniaxial compressive strength as a function of the ultrasonic pulse velocity.

Although there are very few studies that use the UPV technique for RE materials, some authors have already indicated the existence of a linear correlation between compressive strength and ultrasonic pulse velocity [198, 207, 220]. Therefore, and despite the evident existing dispersion in the values of the mechanical properties of RE materials, which is partially intrinsic to the heterogeneity of the material itself [170], the existing relationship between the UCS and the UPV makes the measurement of the latter a useful method to estimate the mechanical properties without damaging the sample. This can be particularly useful for existing RE structures, especially in the case of heritage buildings where destructive testing techniques cannot be applied. Previous studies have also noted the usefulness of the UPV technique to predict the compressive behavior and to detect damage for other common construction materials, such as concrete [221, 222] or brick and stone masonry [223, 224].

For new constructions, on the other hand, UPV measurements during the curing period can be used to assess the evolution of the mechanical properties. A stabilization in the UPV values would indicate the stabilization of the UCT and stiffness, meaning that the material has already developed the majority of its strength (initial part of the strength development curve).

5.5. Conclusions

Over the last decades, the scientific research regarding RE construction has been mainly focused on unstabilized or cement-stabilized material, in addition to some other modern additives. On the other hand, very few studies have evaluated the mechanical characteristics of RE stabilized with lime, even though it is a traditional additive widely used in soil stabilization, causing an environmental impact lower than other common stabilizers such as cement, and which is present in several historic RE buildings.

In the study presented in this chapter, several RE samples with different lime contents and curing periods were evaluated in order to analyze the effect of lime stabilization on the mechanical properties of the material. The results show an increase in the UCS and stiffness when increasing the lime content, in agreement with some other previous studies, until a certain percentage of lime from which no improvement of the mechanical properties was obtained. This strength standstill is related to the lack of the aluminosilicate material in the soil, so the optimum lime content (minimum lime content for which the maximum strength is reached) may vary depending on the mineralogical characteristics of the soil, so it would be recommended to perform some UCS tests for the specific soil to be used in a construction before choosing the lime content. For the material used in this study, representative of the soils traditionally used in RE construction in Southern Spain, the optimum lime content for the compressive strength and stiffness was equal to 12 %.

The mechanical properties of the 12 %-LSRE samples were also evaluated during 100 days of curing, observing an exponential evolution of the UCT that shows that a significant percentage of the strength is developed during the first 20–30 days, but also indicating that the strength development process could last hundreds of days (about 75 % of the predicted strength was reached by day 100). Similar behavior was observed for the material stiffness, which showed a linear relationship with the UCS, although the stiffness values showed higher dispersion, also noted in previous studies.

Also carbonation of the specimens, considered detrimental to strength development, was evaluated. Carbonation was observed to develop faster in samples with low lime contents, were the coarser pore structure leads to a faster carbon dioxide permeation. This phenomenon, however, occurs in a slower way than other lime-soil reactions, following a potential evolution of the form $c = a\,t^b$.

In addition, nondestructive UPV tests were performed. This technique has proved to be a useful method to estimate the mechanical properties of the material without damaging the sample, due to its linear relation with the compressive strength of the material. UPV tests could be easily performed on RE walls in a construction site, were the stabilization in the values obtained could be used as an indicator that the mechanical parameters have also increased and reached a stable value.

Chapter 6

Constitutive models for rammed earth. Experimental campaign and numerical analysis

6.1. Introduction

Structural safety of traditional RE construction was based on geometrical relationship and qualitative rules, but more accurate design bases are needed nowadays in order to meet the high requirements established by construction standards. With this aim, several studies have been developed over the last years regarding the mechanical characterization of RE. Also, some authors have proposed constitutive models to represent the mechanical behavior and failure mechanisms of the material. The existing research, however, has been mainly focused on the compressive behavior (RE is intended to work under compression) and has been developed mostly for stabilized rammed earth (SRE), in the pursuit of finding the material with the best mechanical performance [197].

Considering the relevance of URE as a historic construction technique and its potential as a modern eco-friendly building method, the study presented in this chapter aims to develop a numerical model of RE that accurately reproduces its behavior both under compression and shear. As complex behavioral models need a significant amount of input data, experimental tests were developed: unconfined compression tests (UCT) on cylindrical specimens to analyze the compressive behavior –this kind of tests have been frequently carried out for RE characterization by diverse authors–, and diagonal compression tests (DCT) on larger prismatic samples to define the shear behavior and fracture and failure mechanisms. Despite the fact that tensile and shear behavior is one of the most relevant parameters in the analysis of RE failure (especially under extreme conditions) [57, 170], there are very few examples in literature regarding diagonal (shear) testing of RE [27, 67, 185].

In a second part of the study, a finite element model of the diagonal test was developed, defining an elastoplastic behavioral model for the material that included the mechanical properties obtained experimentally. Some other parameters that could not be assessed from the tests were obtained from literature, and their influence evaluated through a sensitivity analysis.

The experimental research included in this chapter was carried out in the Structures and Materials Laboratory (*Laboratorio di Prove Strutture e Materiali*) of the DICEA (University of Florence).

The research presented in this chapter will be published as a scientific article (currently under revision):

- F. Ávila, M. Fagone, R. Gallego, E. Puertas, G. Ranocchiai, *Experimental and Numerical Evaluation of the Compressive and Shear Behavior of Unstabilized Rammed Earth.*

6.2. Experimental campaign

6.2.1. Materials

The natural soil used in the experimental campaign of the present study comes from Seggiano (Grosseto, Italy), and can be classified, according to the European Soil Classification System (ESCS, ISO 14688-2:2018), as well-graded sand, after been passed through an 8 mm sieve in order to remove the coarser particles. The particle size distribution of the resulting earthen material contains 14 % clay, 31 % silt, 42 % sand and 13 % gravel, in agreement with several recommendations for URE source materials [51, 53, 54, 88]. The main mineralogical components of the soil are quartz (27 %) and calcite (25 %).

The consistency limits, maximum dry density (MDD) and optimum moisture content (OMC) where also evaluated. The soil had a plastic limit equal to 18 % and liquid limit equal to 38 %, leading to a plastic index of 20, according to the methodology indicated in ASTM D4318 [225]. The standard Proctor test –method C– was performed according to ASTM D698 [62], obtaining an OMC of 13 % corresponding to a MDD equal to 1.83 g/cm^3.

6.2.2. Specimen manufacturing

Two different types of unstabilized rammed earth specimens were prepared for the experimental tests: small cylinders (diameter 10.1 cm, height 11.5 cm) for the uniaxial compression tests, and large panels (50 cm × 50 cm × 10 cm) for the diagonal compression tests. The dimensions of the cylindrical samples were chosen in order to be able to use the Proctor mold [173] to manufacture the samples, which ensures that the soil receives the targeted compaction energy and makes the manufacturing process easily replicable. This is particularly useful considering the great variety of testing methodologies currently present in RE literature [170].

The prismatic samples are a scaled version of the specimens used in the standard test method for diagonal tension in masonry assemblages [83].

These reduced dimension have already been used in previous studies for the evaluation of the shear strength or RE materials [27, 175].

To prepare the specimens, the natural soil was uniformly mixed with 13 % water, reaching the water content equal to the OMC of the soil, in agreement with the recommendations of Walker et al. [51] and standard NZS-4298 [45]. This mixture was then poured into the molds and compacted. A 10.1 cm-diameter Proctor mold was used for the cylindrical specimens, compacting the soil in three uniform layers by dropping a standard Proctor rammer (2.50 kg) 25 times per layer from a height of 30.5 cm, subjecting the soil to a total compactive effort of about 600 kN m/m^3 [62].

A wooden formwork was manufactured for the prismatic samples, externally reinforced with steel bars to avoid undesired deformations (Figure 6.1). The soil was compacted in six ca. 8.33 cm-thick layers using a modified Proctor test rammer (4.54 kg) [173] dropped 123 times per layer from a height of 45.7 cm, in order to reach the same total compactive effort. Just after the final layer was compacted, the samples were carefully removed from the mold and stored for curing under constant ambient conditions –about 25 °C and 60 % relative humidity– during 28 days. A total of four cylindrical samples (C1 to C4) and three panels (P1 to P3) were manufactured. The compaction process for each sample was completed within an hour after the water was added to the soil, to avoid significant moisture losses due to evaporation [158, 174].

(a) (b)

Figure 6.1: Prismatic sample for diagonal compression tests: **(a)** compaction process and **(b)** manufactured specimen.

6.2.3. Testing methodology

The experimental part of the present study included the evaluation of the compressive and shear behavior of the URE material, through the development of uniaxial compression tests (UCT) and diagonal compression tests (DCT), respectively. The UCT were performed on the cylindrical samples by applying a homogeneously distributed load on the upper face of the specimens, in a direction perpendicular to the earth layers. In the absence of specific standards for RE testing, these UCT were performed according to ASTM standard C39/C39M "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" [226], with a displacement-controlled testing machine.

For the DCT, again there are not standards specifically designed for RE walls, so the tests were carried out according to ASTM E519 "Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages" [83]. The load was applied on the top steel loading shoe, as a monotonic displacement at a rate of 0.02 mm/s. The shortening of the diagonal parallel to the direction of applied load and the lengthening of the diagonal perpendicular to the direction of applied load were measured in both faces by means of displacement transducers with gauge length 150 mm based on electrical resistance strain gauge, mounted along the two diagonals, as close to their intersection as possible. The setup for the DCT is shown in Figure 6.2.

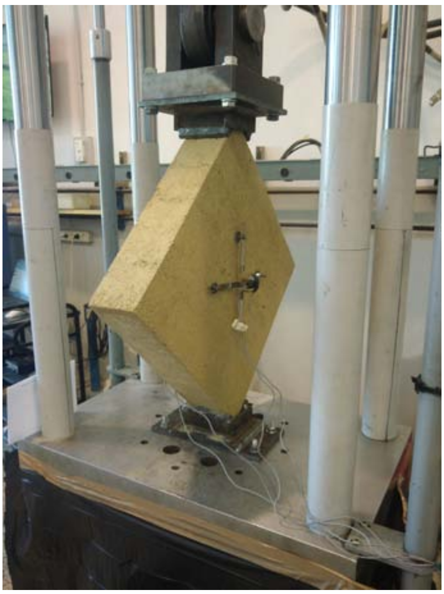


Figure 6.2: Setup for the diagonal compression tests.

6.2.4. Experimental results

From the uniaxial compression tests, the stress-strain curves were obtained (Figure 6.3); calculating the stress as the ratio between the applied load and the cross area of the sample, and the strain as the ratio between the total vertical displacement and the initial height of the specimen. It is possible to observe an initial linear branch, where the behavior of the material is mostly elastic, followed by another linear branch with lower slope, where the generation and propagation of microcracks (non recoverable, meaning a non-elastic behavior) becomes more important. A plastic non-linear behavior continues until reaching the peak strength, followed by a softening branch until failure.

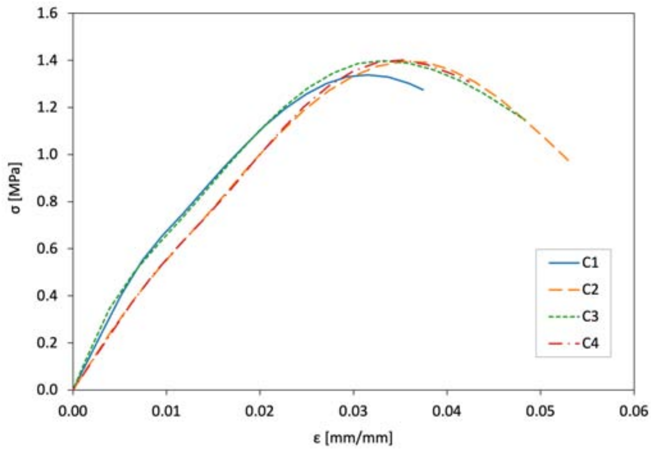


Figure 6.3: Stress-strain curves from uniaxial compression tests.

Table 6.1 shows the main parameters obtained from the UCT. The unconfined compressive strength (UCS) obtained in the tests is within the range usually indicated in the existing literature about URE, between 1.00 and 2.00 MPa [170]. Similar compressive strengths have been obtained by several authors for RE without stabilizers using both cubic and cylindrical specimens [49, 55, 66, 70]. Very small dispersion between the UCS results was observed –coefficient of variation (CV) equal to 1.8 %–, especially considering the intrinsic heterogeneity of material; which proves the effectiveness of the manufacturing and testing methodology followed in this study.

Diagonal compression tests were performed on three different prismatic specimens, loading them until failure, obtaining the cracking patterns represented in Figure 6.4. Cracks started approximately at the center of the specimens and spread following a diagonal orientation towards the loading shoes. Crack propagation was also conditioned by the presence of the interfaces between the earth layers. Smaller cracks also appeared, before reaching

Table 6.1
Results from UCT on URE cylindrical specimens. ρ_{test}: density at testing; UCS: unconfined compressive strength; ε_{ucs}: strain at maximum strength.

Sample	ρ_{test} [g/cm^3]	UCS [MPa]	ε_{ucs} [m/m]
C1	1.94	1.36	0.031
C2	1.94	1.41	0.036
C3	1.97	1.41	0.034
C4	1.98	1.41	0.036
Mean	1.95	1.40	0.034
CV	2.3 %	1.8 %	6.8 %

the peak load, near the interfaces at border of the panels.

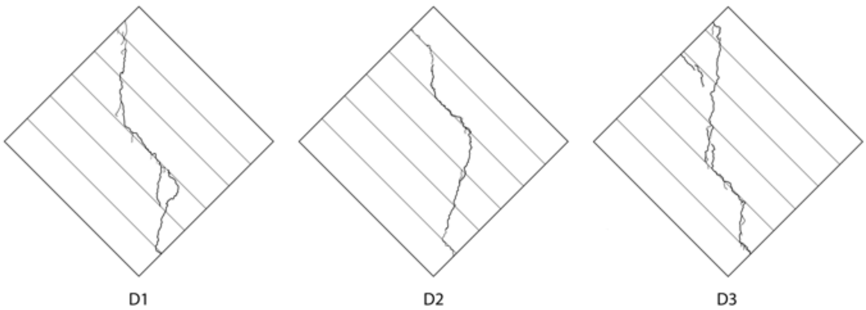


Figure 6.4: Cracking patterns at failure of the URE panels in DCT.

From the results of the DCT, the shear stress (S_s [MPa]) and shear strain (γ [mm/mm]) of the specimens were calculated, according to Equations 6.2.1 and 6.2.2, as defined in ASTM E519 [83]. The relationship between these two parameters along the test is represented in Figure 6.5. The softening branch is shorter for sample D3 because one of the gauges moved after the peak load and so further displacements could not be properly measured.

$$S_s = \frac{0.707P}{A_n} \tag{6.2.1}$$

$$\gamma = \frac{\Delta x + \Delta y}{g} \tag{6.2.2}$$

where

- P is the applied load in N;
- A_n is the net area of the sample in mm^2;

- Δx and Δy are de displacements in the direction parallel and perpendicular to loading, respectively; and
- g is the gauge length.

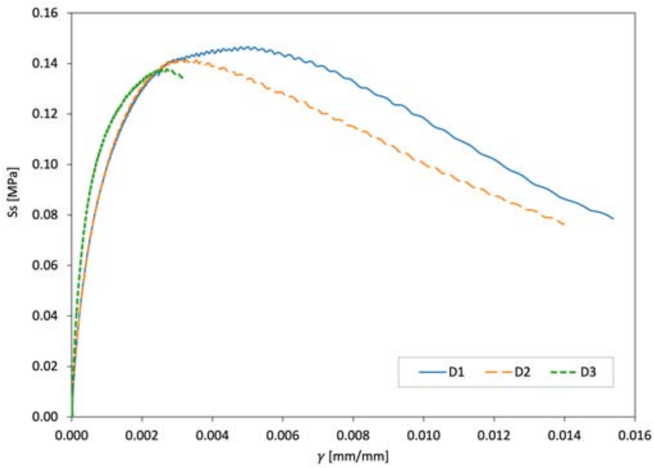


Figure 6.5: Shear stress-strain curves from diagonal compression tests.

The values obtained for these parameters in the DCT, together with the initial modulus of rigidity (G_0) –calculated as the initial slope of the shear stress–strain–, are shown in Table 6.2. As it happened with the UCT, the dispersion in the results is very low for the strength and higher for the modulus of rigidity and the strain. The average S_s obtained in this study, is similar to the values found in literature [55, 57], although there are very few studies evaluating this parameter for URE. The shear strength of the material, according to the present study, is equal to 10 % of the compressive strength. There are not relationships defined in literature between these two parameters, but several authors already indicated that the tensile strength (closely related to the shear strength) is approximately 10 % of the UCS [52, 55, 57, 66, 80].

From the initial modulus of rigidity and Poisson's ratio (ν) it is possible to estimate the elastic modulus of the material as $E = 2G(1 + \nu)$. Assuming a value of the Poisson's ratio equal to 0.27 [55, 76, 80, 170], a elastic modulus of 655 MPa is obtained. This value is within the range usually found in URE literature, frequently between 350 and 1 000 MPa [1, 20, 55, 66, 67, 69, 78, 86]. However, there is a very significant variability in the measurement techniques and dispersion in the results regarding the stiffness of RE.

Table 6.2
Results from DCT on URE panels. ρ_{test}: density at testing; S_s: shear strength; G_0: initial modulus of rigidity; γ_{ss}: shear strain at maximum strength.

Sample	ρ_{test} [g/cm^3]	S_s [MPa]	G_0 [MPa]	γ_{ss} [m/m]
D1	1.89	0.15	236.5	0.0049
D2	1.93	0.14	251.3	0.0029
D3	1.92	0.14	288.2	0.0028
Mean	1.92	0.14	258.6	0.0036
CV	1.1 %	3.2 %	10.3 %	33.2 %

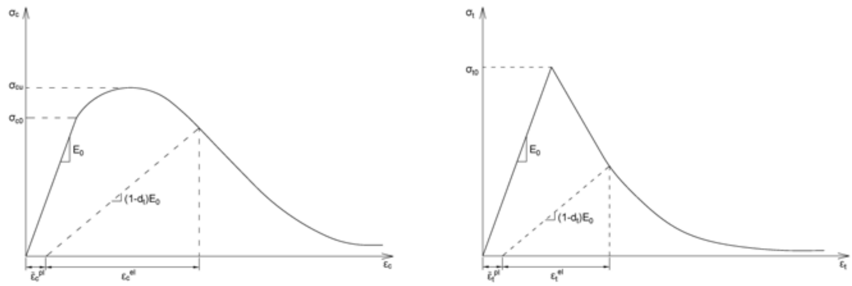
6.3. Numerical analysis

A numerical simulation of the diagonal compression test was carried out through finite element method (FEM) macro-modeling. This approach, which considers the material as continuum and homogeneous –without taking into account the existence of layers or the interaction between them–, is frequently used in RE modeling as it allows to obtain accurate results using models with lower complexity [22, 60, 76]. The numerical analysis described in the present study was carried out using FEM software Abaqus v.2022 [227].

6.3.1. Constitutive law

The continuum, plasticity-based, damage model "concrete damage plasticity" (CDP), implemented in Abaqus, was used to describe the behavior of the material. CDP is based on the constitutive model proposed by Lubliner et al. [228], with the modifications introduced by Lee and Fenves [229]. Although it was initially designed for concrete, its characteristics –such as the different yield strengths in tension and compression and the fact that it assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the material– make it particularly suitable for advanced macroscopic modeling of brittle and quasi-brittle materials [88, 230, 231]. The uniaxial stress-strain relations used in the CDP model are shown in Figure 6.6.

This behavioral model uses a Drucker-Prager surface as multidimensional strength domain, which can be modified by a factor K_c (ratio of the second stress invariant on the tensile meridian), that allows to deform the failure surface, with $K_c = 1$ meaning a circular yield surface in the deviatoric plane. Other parameters defining the CDP model are the flow potential eccentricity (ϵ), representing the rate at which the flow potential function approaches the asymptote (when the eccentricity tends to zero the function tends to a straight line); the biaxial strength ratio (σ_{b0}/σ_{c0}); the viscosity parameter



(a) (b)

Figure 6.6: Stress-strain curves in the CDP model under uniaxial loading in **(a)** compression and **(b)** tension [232].

(μ); and the dilation angle (φ). The values considered in the present study for these parameters are shown in Table 6.3 and were defined following the recommendations present in literature for RE modeling [88, 230, 231] and in Abaqus documentation [232]. For the dilation angle, it was analyzed that varying its value from 0° to 20° had a negligible effect on the stress-strain behavior of the material.

Table 6.3
Parameters used in the CDP model.

Parameter	Value
K_c	2/3
ϵ	0.1
σ_{b0}/σ_{c0}	1.16
μ	0.001
φ	10°

Together with these general parameters, Abaqus' CDP model requires the definition of the elastic properties of the material and the inelastic compressive and tensile behavior. For the RE material analyzed in the present study, an elastic modulus of 655 MPa –obtained from the experimental DCT– was considered, with a Poisson's ratio assumed equal to 0.27, according to literature, as previously indicated.

For the compressive behavior, the inelastic stress-strain data obtained in UCT was introduced. The tensile behavior of the material was defined by specifying the fracture energy and the tensile strength, assuming a linear loss of strength after cracking [89, 143].

6.3.2. Finite elements model

The FEM model for the DCT comprised three parts: a 50 cm × 50 cm × 10 cm prism with CDP behavioral model –as described in the previous section– representing the URE sample, and two L-shaped loading shoes defined as rigid solids. The contact surface between the loading shoes and the panel was defined with a "hard" contact normal behavior plus a penalty (friction) tangential behavior, with friction coefficient equal to 0.2. The loading shoes had all displacements constrained but the vertical displacement of the top shoe, where an imposed displacement of at least 5.0 mm was set. Eight-node linear brick elements were used, and a static analysis was performed. Figure 6.7 shows the geometry of the finite element model for the DCT in Abaqus.

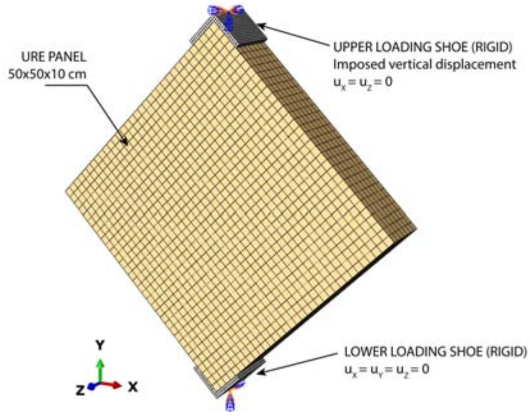


Figure 6.7: Finite elements model for diagonal compression test.

6.3.3. Calibration and results

The model was evaluated varying the two parameters that describe the tensile behavior of the CDP material model (i.e. tensile strength and fracture energy) in order to assess their effect. For the tensile strength, according to the results in literature, values between 0.14 MPa (10 % of the UCS) and 0.17 MPa were assumed [52, 55, 66, 67, 80]. For the fracture energy, there is not much information in URE literature, but some authors show results between 10 and 20 N/m [80, 86, 90]; while Abaqus recommends using typical values from 40 to 120 N/m [232] (as the model is originally designed for concrete). Considering this, the model was analyzed for fracture energy values equal to 10, 20, 30 and 40 N/m. The results (shear strength-stress curves) obtained simulating the DCT for all the possible combinations of these two parameters are shown in Figure 6.8.

It can be observed that the first part of the $S_s - \gamma$ curve, corresponding to the elastoplastic branch for increasing load, fits very well with the experimental results and does not vary when modifying the tensile parameters of the model, as the material here is mostly under compression. Before reaching the maximum load, when the behavior becomes more plastic and tension-dependent, the shape of the curves highly depends on the G_f and f_t values. Increasing the fracture energy increases the peak shear strength and the corresponding shear stress. Also, high G_f values lead to a smooth softening branch, while low values cause a fast decrease of the stress after the peak load. The tensile strength, on the other hand, does not significantly affect the post-peak behavior, but increases the maximum shear stress reached. The shear strain at which this stress is reached is also increased but not that much.

According to these results, a fracture energy in the CDP model of at least 20 N/m is required to reach the experimental peak stress, and $G_f = 40\,\mathrm{N/m}$ is needed to properly represent the post-peak behavior. At the same time, tensile strengths between 0.15 and 0.16 MPa gave the best results, reaching a good adjustment of the curve at the peak strength and for the values around this maximum.

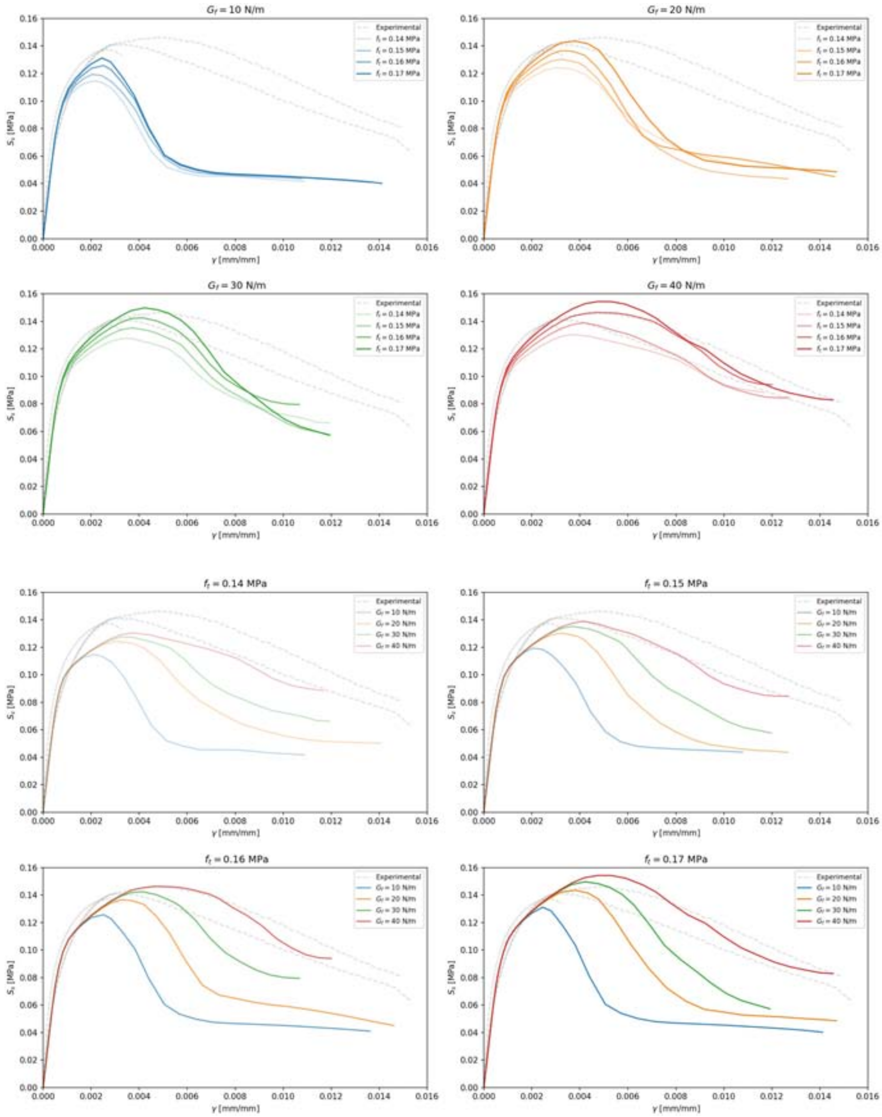
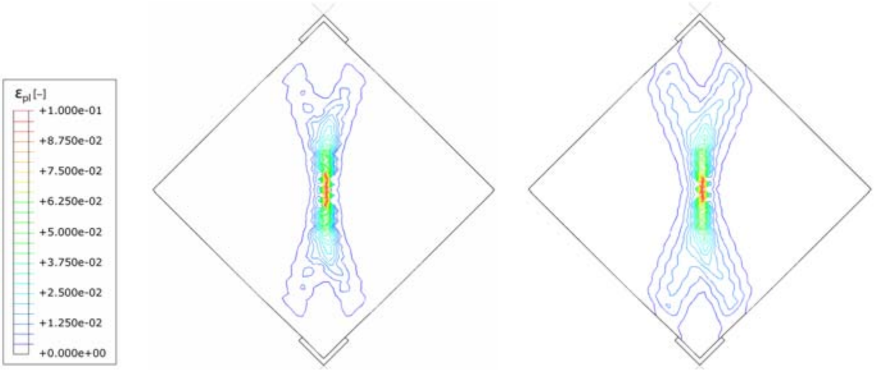


Figure 6.8: Shear stress-strain curves obtained in the FEA with varying fracture energy (G_f) and tensile strength (f_t).



(a) Tensile equivalent plastic strain

(b) Max. principal plastic strain

Figure 6.9: Isolines of tensile equivalent plastic strain **(a)** and maximum (tensile) principal plastic strain **(b)** from FEA of DCT.

The failure mode obtained with the FEA was evaluated and compared with the one observed experimentally. The "tensile equivalent plastic strain" (PEEQT in Abaqus) is a useful variable to evaluate the damage in a brittle material [232, 233]. In fact, it can be assumed that cracking initiates at points where the tensile equivalent plastic strain and the maximum principal plastic strain are greater than zero [228]. These two parameters are shown in Figure 6.9, where it can be observed that the damage in the model concentrates in central part of the sample, subjected to strong tensile stresses, and in the stress concentration zone in the contact between the URE specimen and the supports. These are the zones were the cracks were developed in the laboratory tests. This correspondence between the stresses obtained in the model and the failure in the real sample is also observed when superimposing the maximum (tensile) principal stress and the cracks obtained in the tested URE samples, as shown in Figure 6.10.

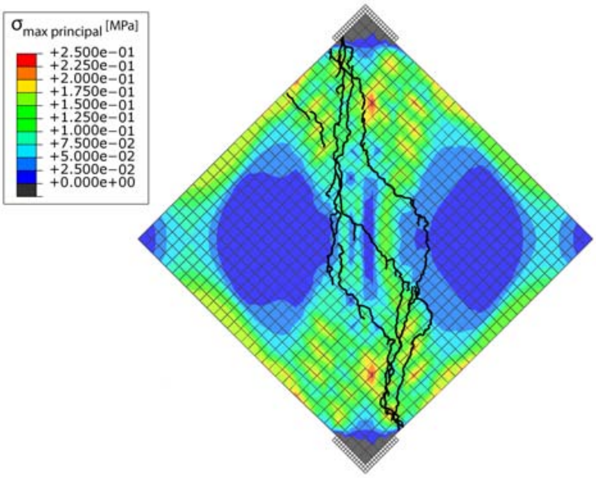


Figure 6.10: Maximum (tensile) principal stress at the end of FEM test (shear strain 0.01 m/m), and cracks from experimental tests. FE model with $G_f = 30\,\mathrm{N/m}$ and $f_t = 0.16\,\mathrm{MPa}$.

6.4. Conclusions

Understanding the mechanical behavior of unstabilized rammed earth is essential in order to introduce this environmentally sustainable building technique in new constructions, and also to properly preserve the abundant architectural heritage built with this material. In the study presented in this chapter, the compressive and shear behavior of URE were evaluated through unconfined compression tests and diagonal compression tests, and the results were used to develop a finite element model of the latter.

From the experimental tests, an average compressive strength of 1.4 MPa was obtained, similar to values frequently shown in literature for URE. A manufacturing methodology including the use of a standardized Proctor mold and the control of the compaction energy allowed to obtain a very small dispersion in the results (e.g. coefficient of variation of 1.8 % for the compressive strength), which is particularly relevant considering the high heterogeneity frequently shown by rammed earth.

The shear strength of the material, obtained from the DCT following the procedure indicated by the ASTM for masonry assemblages, was equal to 0.14 MPa, 10 % of the compressive strength. This relationship has been observed by previous authors between the compressive and the tensile strength of rammed earth. In this experiments it was also possible to observe the crack development process, following a diagonal from one support to the other, and also influenced by the interfaces between the earth layers.

In the second part of the study, the FEM model developed with the software Abaqus using the experimental data, was proved to be useful for simulating the behavior of the RE material. Concrete damage plasticity was used as the behavioral model. The experimental data was enough to define the compressive behavior of the material, but to simulate the diagonal compression test it was also necessary to define the tensile strength and fracture energy as input parameters. The sensitivity analysis performed showed that minimum fracture energy of 20 N/m was needed to reach the experimental peak stress, with tensile strengths between 0.15 and 0.16 MPa. The post-peak behavior was more accurately simulated with higher fracture energy values (30–40 N/m), although they are slightly higher than the experimental values usually obtained for earthen materials.

The numerical analysis of the diagonal tests also showed a stress distribution coherent with the experimental results and the crack propagation paths that lead to the failure of the specimen. Shear behavior is particularly relevant in the failure mechanisms of rammed earth structures under extreme loads –such as a seismic event–, so the results of this study can be a useful tool to assess structural vulnerability of rammed earth constructions and ensure their integrity.

Chapter 7

Seismic behavior of rammed earth structures

7.1. Introduction

Rammed earth constructions have some characteristics that make them potentially vulnerable to seismic events. RE walls have a very high mass, which induces significant inertial forces in the event of an earthquake, that have to be resisted by a material that works essentially in compression and with very low tensile and shear strength. However, according to several post-seismic investigations, rammed earth constructions show acceptable seismic behaviors [234], proving that a proper design and execution can provide RE structures a satisfactory seismic performance.

Seismic design of RE structures is particularly interesting considering that many of the areas where earthen constructions (RE constructions included) are usually built are areas under a significant seismic hazard, as it is shown in Figure 7.1. Tradition and building experience have led to geometrical configuration of buildings with proved good seismic performance in different regions of the world, but a thorough structural analysis with modern techniques is the only way to optimize the traditional designs; reducing material consumption, increasing the possible structural configurations and minimizing the vulnerability.

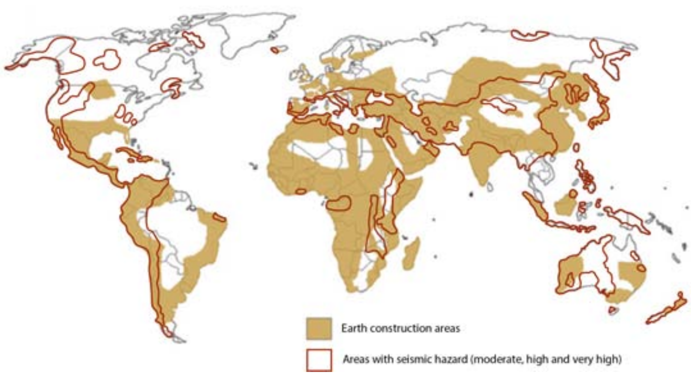


Figure 7.1: Areas of the world with tradition of earth construction and areas with seismic hazard. Data: [5, 235].

In the present chapter, the seismic behavior of rammed earth constructions is evaluated, analyzing the structural response of RE walls subjected to in-plane and out-of-plane loads and the most common failure modes of RE structures under the action of an earthquake. Reinforcement solutions to improve the seismic performance of rammed earth are also evaluated, together with general recommendations for the construction of RE buildings in areas with seismic hazard.

7.2. Behavior of rammed earth walls under seismic loads

When a RE structure is subjected to a the action of an earthquake, the walls usually have to resist both in-plane and out-of-plane loads. According to several studies, RE walls have rather acceptable in-plane seismic performance for buildings of one or two stories [230]. Under a cyclic in-plane load, RE walls typically show four limit states, representing the change of the wall behavior under the progressive increase of applied horizontal displacements [236]. The first state corresponds to the initial behavior of the wall, before cracking starts; the second one begins with the opening of the first flexural cracks at the bottom of the element; the third one takes place at the crack limit state, when the first diagonal cracks open; and the last one corresponds to the ultimate displacements, just before collapse. Crack propagation under in-plane cyclic loads typically follows a diagonal pattern, along one or both diagonals (X-shaped pattern).

Bui et al. [234] and El-Nabouch et al. [26] determined that URE walls can have satisfactory performance on seismicity zones from “very low” to “medium” –as defined in Eurocode 8 [237]– for type-A soils, and from “very low” to “moderate” for type-B soils (soil types also defined in the aforementioned standard). These studies also noted that increasing gravity loads on the walls were unfavorable for their seismic behavior, even though if they increased the compressive stress; meaning that, in practice, lower dead and live loads (as in a one-story house) offer better seismic behavior. Another study [238] indicates that two-story RE buildings can resist without significant damage in-plane seismic behaviour until ground accelerations of 0.23g, while for one-story buildings the limit is raised to 0.32g.

There are very few studies investigating the out-of-plane loading in RE structures. Indeed, current design codes for conventional materials tend to neglect the out-of-plane performance, considering that evaluating only the in-plane behavior is in the safe side [230]. However, out-of-plane behavior is worth to be investigated in RE structures, as most seismic failure modes for RE walls are related to these loads [239, 240].

Wangmo et al. (2019) [241] and Bui et al. (2020) [230] subjected FE models of U-shaped walls to out-of-plane loads. The former observed that the peak load was reached with very small deflection, and that the behavior was governed by the rocking resistance of the wall and the elastic modulus and density of the rammed earth material; while the latter focused on the relevance of modeling the interlayers and the beneficial effect of reinforcing the wall with a bond beam at the top, which was able to resist a peak ground acceleration of 0.16g.

The same kind of geometry (U-shaped wall) was used in a shake table test in recent study [242] to experimentally evaluate the out-of-plane response of RE constructions. The results from this study indicate that this type of RE sub-assemblage have a significant shear capacity, measured in terms of base shear coefficient and energy dissipation. Despite this generally positive shear behavior, severe horizontal cracking was observed in the contact –and near the contact– between the concrete foundation and the RE wall, highlighting the vulnerability of this zone and the relevance of ensuring an effective connection between these two elements.

7.3. Failure modes of RE structures under earthquake action

In order to define useful reinforcements and favorable structural configurations for RE structures, it is important to know the most common failure modes. The Colombian Association of Seismic Engineering [239] identifies the following typical failure modes for RE constructions under the action of an earthquake:

(a) Out-of-plane flexion with horizontal cracking at medium height of the wall. Typical in long walls without transversal supports.

(b) Out-of-plane flexion with main vertical cracking in the middle of the wall. Typical in short and tall wall.

(c) Out-of-plane flexion of unconfined corners (free-standing walls or connected walls with a poor execution of the corner connections).

(d) Shear failure due to high in-plane loads, with diagonal and X-shaped cracks in the walls. Frequently related to heavy slabs or roofs, worsened by the presence of openings in the walls.

(e) Collapse of the roof to the inside of the house, due to a poor execution of the supports or the existence of defects in the walls. Heavy roofs increase the probability of occurrence of this failure mode.

(f) General or partial collapse due to a poor connection between the walls of different stories. The slab between the stories breaks the main walls almost horizontally, generating instability in the second story.

These failure modes are represented in Figure 7.2. A simultaneous combination of the aforementioned failure modes is also possible.

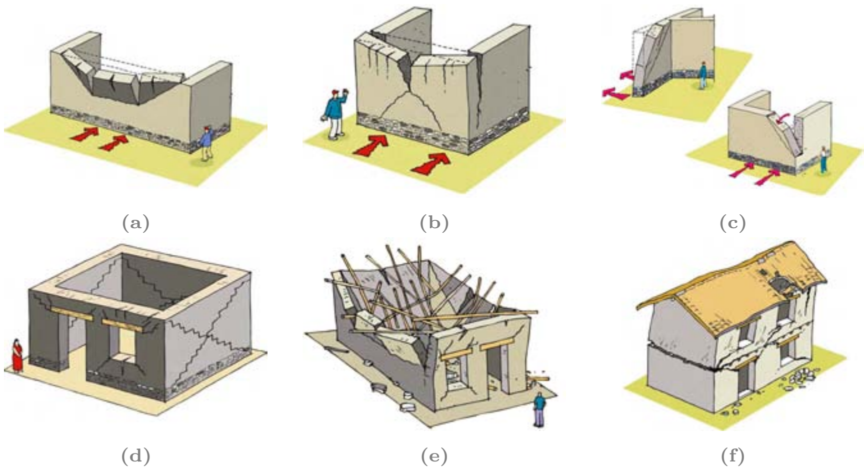


Figure 7.2: Typical failure modes of rammed earth constructions under the action of an earthquake [239].

7.4. Seismic reinforcements

Considering the well-known vulnerability of RE walls under seismic actions, several researchers have proposed different solutions to improve the seismic behavior of these structures. Generally speaking, we can distinguish between two types of reinforcements: vertical rigid elements (columns) and horizontal confining elements.

Zhou et al. [243] evaluated the effect of using different types of columns on the seismic performance of a RE wall. Three type of columns (cast-in-place concrete, square steel tube, and concrete-filled square steel tube) were constructed at both ends of three RE wall, that were subjected to an in-plane pseudo-static test. The results showed a general improvement of the wall bearing capacity to horizontal loads. The steel columns (empty and concrete-filled) showed good restraint ability, avoided the typical diagonal cracking pattern in the wall and reduced the crack width. Concrete columns also improved the seismic performance of the wall, but the horizontal load generated serious cracks on the columns and the fall of almost all the RE material around them.

A similar study was carried out by Yang et al. [244], using precast reinforced concrete columns plus a horizontal reinforcement (precast concrete tie beam or wire ties). It was found that the co-work between the columns and the wall significantly improved the energy dissipation capacity. The effect of concrete columns and horizontal tie elements on the bearing capacity was not obvious at the initial stage of loading but was significant for story drifts beyond 0.3 %. The use of concrete bond beams is a common solution to improve RE seismic behavior, either located at the top of the wall [138, 230] or at half-height [245, 246], preventing the overturning of the wall and reducing the maximum out-of-plane drift. [244] concluded, however, that the wire ties can be a practical and effective substitute of concrete tie beams. Figure 7.3a shows an example of a scaled model with concrete columns and half-height concrete bond beam.

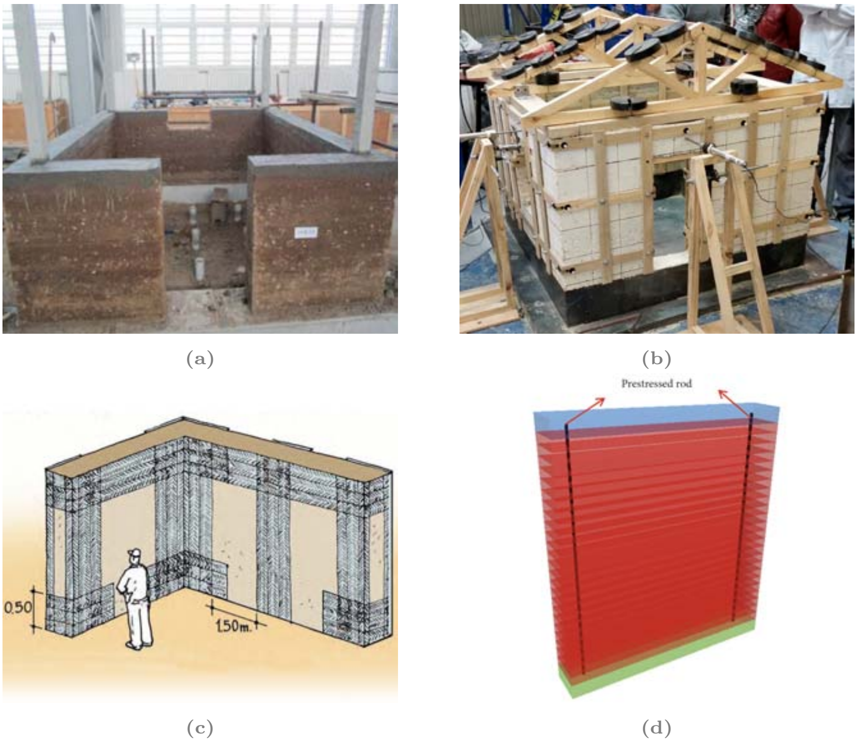


Figure 7.3: Seismic reinforcement solutions for RE buildings: **(a)** concrete columns and bond beam (scale model under construction) [245], **(b)** confining wooden elements (scale model) [138], **(c)** wire mesh (recommended layout scheme) [239], **(d)** vertical prestressed steel rods (DEM model) [81].

Another reinforcement technique consist of placing external wooden elements acting as a confining structure for the RE building (Figure 7.3b). These reinforcements help the walls to work together, reduce the maximum displacements under the seismic action and increase the energy dissipation capacity of the structure [138, 247]. The wooden elements should be placed at both sided of the wall, carefully connected with passing steel rods [239].This technique is particularly useful for the rehabilitation of existing RE buildings [67, 239, 247].

The confinement of the walls can be also done placing horizontal and vertical wire mesh strips in the critical zones of the building [67, 239], as shown in Figure 7.3c. The mesh, placed at both sides of the RE wall, is attached to the wall by wire connectors that link the strips of opposite sides. These connectors are placed in previously drilled holes which are then filled with lime an sand mortar. Once the wire mesh is placed, it is usually covered with lime and sand mortar (1:2 lime-sand ratio recommended).

Bui et al. (2019) [81] proposed reinforcing a RE wall subjected to seismic action with vertical prestressed steel rods (Figure 7.3d). The results obtained from a discrete element analysis showed that this technique increased the elastic limit and the maximum in-plane and out-of-plane horizontal force, but also reduced the ductility of the walls. However, further investigations would be required before introducing this kind of reinforcement in real constructions subjected to earthquake action.

7.5. Seismic design of rammed earth buildings

Oral transmission of knowledge has always played a very important role in rammed earth construction, as is the case with many traditional building techniques. This situation has led to the development of several codes of good practice based on geometrical relationship between the dimensions of the construction elements and recommended construction details. When subjected to severe and uncertain actions, such as an earthquake, these recommendations from building experience become even more important. Some of the existing standards and modern construction guidelines regarding seismic design of rammed earth structures have included these kind of recommendations [248]. The main requirements for building rammed earth structures in seismic zones are described below, these recommendations can be combined with the reinforcement solutions described in the previous section.

7.5.1. General configuration

In order to avoid irregular load distributions under a seismic event, it is a general recommendation that RE buildings in seismic zones should be symmetrical [36, 41, 43, 239, 249, 250] or at least not to have large differences between the main dimensions of the building (e.g. maximum ratio of 3:1 for external and internal dimensions according to [251]). It is also generally recommended that RE buildings in seismic zones should have no more than one [41, 43, 238, 250, 251] or two [32, 44, 252, 253] stories. There are several examples of traditional and historical RE structures still preserved in zones of high seismic hazard that follow these recommendations, like the traditional RE dwellings in Southern Portugal [253], the town halls of Cundinamarca (Colombia) [247], or the towers of the Alhambra of Granada (Spain) [191, 217].

7.5.2. Foundations

In contrast with the importance of foundations in the mechanical –and seismic– behavior of buildings, there are not many studies analyzing the foundations of rammed earth structures. According to the existing standards, the strip foundations of RE walls in seismic zones should have a thickness equal to the wall thickness plus 0.2–0.3 m [250, 251] and a minimum depth between 0.3 and 0.6 m [41, 43, 249, 251]. The foundation bed should be at the same level throughout the whole foundation [251]. The foundations are usually made of concrete and, according to NZS4297 [44], reinforced concrete must be used for walls wider than 30 cm (reinforced concrete masonry accepted if the thickness is lower). In traditional construction also stone masonry foundations –with or without mortar– can be found [239, 248].

Another important aspect that has not been thoroughly analyzed in the existing publications is the connection between the foundation and the RE wall. This construction detail is not so relevant when the mail actions are gravity loads, but becomes critical when there are significant horizontal loads, that generate strong shear efforts at the base of the walls. This connection can be made by means of friction between the wall and the foundation, ensuring a rough surface of the latter, or leaving reinforcement bars cast in the concrete of the foundation [248]. In this latter case, the combined behavior of the reinforcements and the earth should be evaluated and a proper compaction in the area around the bars should be ensured.

7.5.3. Walls

Walls are the main structural elements made with rammed earth technique. Standard RE walls are already quite thick –usually from 20 to 50 cm–, but some publications also define a minimum thickness in the case of seismic hazard. There is, however, a significant dispersion in these minimum values, going from 20–30 cm [34, 41, 43, 44, 249] to 40–45 cm [32, 251]. Minke (2001) [250], on the other hand, relates the minimum wall thickness with its height, in a 1:8 ratio.

There are also limitations for the wall length. A common value indicated in several standards [41, 249, 251] is a maximum length of 10 times the thickness for unsupported walls; while the Australian Handbook [43] recommends a maximum of 15 times the thickness, and the New Zealand standard fix the maximum length at 12 m. These differences can be relevant in some cases, for examples for a 40 cm-thick wall we would have maximum lengths from 4.0 m to 12 m. Wall length is limited by trasversal walls, bracing walls or buttresses [248].

Some guidelines also define a maximum height for the walls, in most cases equal to 8 times the wall thickness [34, 36, 41, 250, 251] (10 times according to the Australian standard [43]). These limit would lead to 3.2 m-tall walls for a common thickness of 40 cm, which is in agreement with the maximum heights established by the New Mexican code [32] (3.0 to 3.6 m) and is higher than the limitation of 2.5 m defined by the Nepalese standard [251].

Not only the wall dimensions define their seismic performance but also the presence of openings for windows and doors, and so this is an aspect also considered by the existing standards. Some publications [36, 41, 43, 249, 250] define the the maximum percentage of wall area that can be occupied by an opening, with values from 20 % to 33 %. Also a maximum size of the openings of 1.2 m is indicated in several standards [36, 41, 249–251]. In addition, the distance between the corner of the building and the first opening is fixed in diverse publications [32, 41, 43, 249–251] with values between 0.75 m and 1.20 m.

7.5.4. Roofs

Proper roof construction is essential, as it could transmit horizontal forces into the walls that may lead to leaning or cracking and compromise the structural integrity of the construction under seismic action [248]. As a general rule, most standards [32, 41, 43, 44, 239, 250, 251] indicate that roof must be as light as possible, recommending timber or bamboo as the construction material.

7.6. Conclusions

The seismic performance of rammed earth constructions is a matter of concern for builders and researchers, due to the large number of these buildings placed in zones with a significant seismic hazard and to the fact that RE elements are particularly vulnerable to the action of an earthquake because of their low tensile strength and high weight.

The seismic action induce horizontal in-plane and out-of-plain loads on the RE walls, being the latter particularly critical for the integrity of these structures, although there are still few studies in literature analyzing their effect. However, in the event of an earthquake, the two aforementioned kind of loads can generate damage in the walls that may lead to the collapse of the structure, more likely if some good practice rules are not followed.

The building experience over the years has allowed the development of standards and constructions guidelines with recommendations for RE constructions in seismic zones, establishing minimum and maximum dimensions for walls and foundations. As a general recommendation, it is possible to conclude that RE buildings potentially subjected to an earthquake should be as symmetrical as possible and with no more than two stories, with thick walls with a maximum free length from 10 to 15 times the thickness and a maximum height of ca. 8 times the thickness, and with a light roof.

In addition, the seismic performance of RE constructions can be enhanced by different types of reinforcements. A common way to improve the seismic behavior is by introducing concrete columns at the corners, usually combined with one or more concrete bond beams at the top and/or at half-height of the wall. Some other techniques, particularly useful for rehabilitation of RE building, is the placement of confining elements at both sides of the walls, in the form of wooden frames or wire mesh strips.

Chapter 8 Overall results and conclusions and future work

8.1. Overall results and conclusions

The research carried out during the development of the present doctoral thesis has made it possible to deepen the knowledge about the mechanical, structural and seismic behavior of rammed earth constructions.

The analysis of the existing constructions built with earth, presented in Chapter 2, allows to understand the relevance of this kind of structures over time in several regions all over the world; existing many different techniques such as adobe, rammed earth, cob or wattle and daub. The combination between the good mechanical behavior provided by earthen structures and their capacity to increase environmental sustainability in constructions, has made these techniques a great alternative to the common current building techniques, attracting the interest of researchers and companies in the construction sector. Despite these advantages, there are still very few standards regulating earth construction, and most of them are not based on a real structural knowledge of the behavior of the material.

From the review of the state of the art of research about unstabilized and stabilized rammed earth, presented in chapter 3 and 4, it is possible to conclude that most studies are focused on the compressive behavior of the material, with strength values between 1.0 MPa and 2.5 MPa for URE, and which can be improved through stabilization. The most common stabilizers to enhance the compressive behavior of rammed earth are cement –the most used by far– and lime, sometimes combined with other additives such as fly and bottom ash. Rammed earth presents very low tensile and shear strength (ca. 10 % of the compressive strength), but that can be critical for the vulnerability of the RE structures, reason why some authors have tried to improve it by the use of natural or synthetic fibers.

Rammed earth constructions offer high thermal and acoustic insulation. Thermal insulation can be improved using thermal energy storage additives (e.g. EPS or PCM), but significantly worsening the mechanical performance of the material. The enhancement of the acoustic properties of RE, on the other hand, has not be thoroughly studied yet.

It has to be noted that the use of stabilizers significantly increases the environmental and economic cost of RE construction, due to the manufacturing processes and transportation distances. This impacts can be reduced by replacing industrial stabilizers, such as cement, by industrial by-products or natural additives. An alternative to cement, with less environmental impact, is lime, a well-known stabilizer for soils which has been traditionally used in RE construction. The research presented in Chapter 5 shows the ability of lime to increase RE compressive strength and stiffness, with 12 %-LSRE showing the best compressive behavior. A long curing process (over 100 days) was observed to be required to develop full strength. The conventional tests were combined with nondestructive ultrasonic pulse velocity tests, proving the latter to be a useful method to estimate the mechanical properties of the material without damaging the sample. UPV tests could be easily performed on RE walls in a construction site, were the stabilization in the values obtained could be used as an indicator that the mechanical parameters have also increased and reached a stable value.

The next step to understand, and also to predict, the behavior of rammed earth structures is the development of numerical models that properly represent the material behavior. An elastoplastic model based on the concrete damage plasticity Abaqus model is proposed in Chapter 6, using the experimental material data obtained from uniaxial and diagonal compression tests carried out for URE, and obtaining very accurate results when replicating the diagonal test with a finite element model.

The development of this kind of numerical models is essential to assess the vulnerability of rammed earth structures, under normal conditions or extreme loads, as in the case of an earthquake. In fact, the seismic performance of rammed earth constructions is a matter of concern for builders and researchers, due to the large number of these buildings placed in zones with a significant seismic hazard and to the fact that RE elements are particularly vulnerable to the action of an earthquake because of their low tensile strength and high weight. As it is described in Chapter 7, the horizontal in-plane and out-of-plain loads induced by a seism can generate severe damage in the RE walls that may lead to the collapse of the structure, being the out-of-plain loads particularly critical for the integrity of these structures. In order to prevent or minimize seismic damage in RE buildings, standards and guidelines recommend building structures as symmetrical as possible, with no more than two stories, covered with a light roof, and with thick walls with a maximum free length from 10 to 15 times the wall thickness and a maximum height of ca. 8 times the wall thickness.

8.2. Future work

Based on the results obtained in the present doctoral thesis, the following research lines are open to be developed in future studies:

- Analyzing the strength development process of lime-stabilized rammed earth at very long curing times (over 100 days).

- Evaluating potential combinations between lime and other additives (stabilizers and/or reinforcement fibers) to enhance even more the mechanical behavior of rammed earth structures.
- Carrying out large-scale laboratory tests of rammed earth assemblies subjected to seismic actions.
- Using the numerical model for rammed earth developed in this study to assess the vulnerability of whole structures, introducing damage parameters. This assessment is particularly useful to evaluate seismic response and failure mechanisms of rammed earth buildings, and to optimize the geometry and define structural and seismic reinforcements.
- Studying possible options to introduce prefabrication in rammed earth construction, as a way to reduce costs and improve reliability.

8.3. Resultados y conclusiones generales

La investigación llevada a cabo durante el desarrollo de la presente tesis doctoral ha hecho posible profundizar en el conocimiento sobre el comportamiento mecánico, estructural y sísmico de las estructuras construidas con la técnica del tapial.

El análisis de las construcciones existentes construidas con tierra, mostrada en el Capítulo 2, ayuda a comprender la relevancia que han tenido este tipo de construcciones a lo largo del tiempo en numerosas regiones de todo el mundo; habiéndose desarrollado un gran número de técnicas diferentes, como el adobe, el tapial, el cob o la quincha. La combinación entre el buen comportamiento mecánico proporcionado por las estructuras de tierra y su capacidad para aumentar la sostenibilidad medioambiental en la construcción, han convertido a estas técnicas en una gran alternativa a las técnicas de construcción modernas habituales, atrayendo el interés de investigadores y empresas del sectores de la construcción. Sin embargo, pese a estas ventajas, aún existen pocas normativas regulando la construcción con tierra cruda, y la mayor parte de ellas sin una base en un conocimiento estructural real y profundo del comportamiento de este material.

A partir de la información recogida en el análisis del estado del arte de la investigación sobre tapia sin estabilizar y estabilizada, mostrada en los capítulos 3 and 4, es posible concluir que la mayoría de los estudios existentes se centran en el comportamiento a compresión del material, con valores de resistencia entre 1.0 MPa y 2.5 MPapara tapia sin aditivar, y que pueden ser mejorados mediante la estabilización. Los aditivos más comunes para mejorar las propiedades a compresión de la tapia son el cemento –el más utilizado con diferencia– y la cal, a veces combinados con otros aditivos como cenizas volantes o escorias. La tapia presenta una muy baja resistencia a tracción y cortante (aprox. 10 % de la resistencia a compresión), pero estas pueden ser cruciales la su vulnerabilidad de estas estructuras, motivo por el cual algunos autores han intentado mejorar su valor mediante el uso de fibras naturales o artificiales.

Las construcciones con tapial normalmente ofrecen un buen aislamiento térmico y acústico. El aislamiento térmico puede mejorarse mediante el uso de aditivos con alta capacidad de almacenamiento térmico (como EPS o PCM), pero que empeoran notablemente el comportamiento mecánico del material. La mejora de las propiedades acústicas de la tapia, por su parte, todavía no ha sido estudiada en profundidad.

Se debe destacar que el uso de aditivos aumenta significativamente el coste medioambiental y económico del tapial, debido al aumento de los procesos industriales y las distancias de transporte. Este impacto puede mitigarse sustituyendo total o parcialmente los aditivos industriales, como el cemento, por subproductos de la industria o aditivos naturales. Una alternativa al cemento, con menor impacto ambiental, es la cal, un aditivo habitual en estabilización de suelos y que se ha empleado tradicionalmente en la construcción con tapial. La investigación descrita en el Capítulo 5 muestra la capacidad de la cal para aumentar la resistencia a compresión y el módulo de rigidez de la tapia, siendo un 12 % el contenido de cal que ofreció mejores resultados. Se observó además la necesidad de un largo proceso de curado (más de 100 días) para que el material desarrollara toda su resistencia. Los ensayos convencionales se combinaron con ensayos no destructivos de velocidad de ultrasonidos, mostrándose estos últimos como un método eficaz para estimar las propiedades mecánicas del material sin dañar la muestra. Los tests de ultrasonidos se pueden realizar fácilmente sobre los muros en obra, donde la estabilización en los valores medidos puede usarse como indicador de que las propiedades mecánicas del material se han desarrollado y alcanzado un valor estable.

El siguiente paso para entender, y también predecir, el comportamiento de las estructuras de tapia es el desarrollo de modelos numéricos que repliquen adecuadamente el comportamiento del material. En el Capítulo 6 se propone un modelo elastoplástico basado en el modelo *concrete damage plasticity* de Abaqus, empleando para su desarrollo los datos experimentales sobre el material obtenido de los ensayos a compresión uniaxial y diagonal llevados a cabo en laboratorio para tapial sin estabilizar. Se obtienen resultados muy adecuados al replicar los ensayos de compresión diagonal mediante el modelo de elementos finitos desarrollado.

El desarrollo de este tipo de modelos numéricos es esencial para evaluar la vulnerabilidad de las estructuras de tapia, en condiciones normales de carga o en situaciones extremas, como en el caso de un sismo. De hecho, el comportamiento sísmico de las estructuras de tapia es un tema que preocupa a constructores e investigadores, debido al gran número de este tipo de construcciones situadas en zonas con riesgo sísmico elevado, y al hecho de que los elementos de tapia son particularmente vulnerables a la acción sísmica debido a su baja resistencia a tracción y su elevado peso. Como se describe en el Capítulo 7, las acciones horizontales en el plano y fuera del plano producidas por un terremoto pueden generar graves daños en los muros de tapia, pudiendo llevar al colapso de la estructura, siendo las cargas fuera de plano particularmente críticas para este tipo de estructuras. Para prevenir o minimizar el daño sísmico en estructuras de tapia, las normas y guías existentes recomiendan construir edificios lo más simétricos posibles, con no más de dos plantas, con una cubierta ligera, y con muros gruesos de longitud libre máxima entre 10 y 15 veces el espesor y altura máxima de unas 8 veces el espesor.

8.4. Risultati e conclusioni generali

La ricerca svolta durante lo sviluppo della presente tesi di dottorato ha permesso di approfondire le conoscenze sul comportamento meccanico, strutturale e sismico delle costruzioni in terra battuta.

L'analisi delle costruzioni in terra esistenti, presentata nel capitolo 2, permette di comprendere la rilevanza storica di questo tipo di strutture in diverse regioni del mondo; con molte tecniche diverse sviluppate, come adobe, terra battuta, cob o *wattle and daub*. La combinazione tra il buon comportamento meccanico fornito dalle strutture in terra e la loro capacità di contribuire alla sostenibilità ambientale delle costruzioni, ha reso queste tecniche un'ottima alternativa alle tecniche costruttive abituali nell'attualità, attirando l'interesse di ricercatori e aziende del settore edile. Nonostante questi vantaggi, sono ancora poche le norme che regolano le costruzioni in terra, e la maggior parte di esse non si basa su una reale conoscenza strutturale del comportamento del materiale.

Dalla revisione dello stato dell'arte della ricerca sulla terra battuta non stabilizzata e stabilizzata, presentata nei capitoli 3 e 4, è possibile concludere che la maggior parte degli studi si concentra sul comportamento a compressione del materiale, con valori di resistenza compresi tra 1.0 MPa e 2.5 MPa per il pisé non additivato, che possono essere migliorati attraverso la stabilizzazione. Gli additivi più comuni per migliorare il comportamento a compressione della terra battuta sono il cemento – il più usato in assoluto– e la calce, talvolta combinati con altri additivi come ceneri volanti e di fondo. La terra battuta presenta una resistenza a trazione e a taglio molto bassa (circa il 10 % della resistenza a compressione), ma che può essere critica per la vulnerabilità delle strutture in terra battuta, motivo per cui alcuni autori hanno cercato di migliorarla con l'uso di fibre naturali o sintetiche.

Le costruzioni in terra battuta offrono un elevato isolamento termico e acustico. L'isolamento termico può essere migliorato utilizzando additivi con alto accumulo di energia termica (ad esempio EPS o PCM), ma che peggiorano significativamente le prestazioni meccaniche del materiale. Il miglioramento delle proprietà acustiche del pisé, invece, non è ancora stato studiato a fondo.

Va notato che l'uso di stabilizzanti aumenta significativamente il costo ambientale ed economico delle costruzioni in terra battuta, a causa dei processi di produzione industriali e delle distanze di trasporto. Questo impatto può essere ridotto sostituendo gli additivi industriali, come il cemento, con sottoprodotti industriali o additivi naturali. Un'alternativa al cemento, con un minore impatto ambientale, è la calce, ben nota come stabilizzatore per terreni e che è stata tradizionalmente utilizzata nel pisé. La ricerca presentata nel Capitolo 5 mostra la capacità della calce di aumentare la resistenza a compressione e la rigidezza della terra battuta, ottenendo il miglior comportamento a compressione con un contenuto in calce pari al 12 %. Si osserva anche che è necessario un lungo processo di stagionatura (oltre 100 giorni) per lo sviluppo completo della resistenza. I test convenzionali sono stati combinati con prove non distruttive di velocità degli impulsi di ultrasuoni, dimostrando che quest'ultimo è un metodo utile per stimare le proprietà meccaniche del materiale senza danneggiare il campione. I test di ultrasuoni potrebbero essere facilmente eseguiti su muri di pisé in cantiere, dove la stabilizzazione dei valori misurati potrebbe essere utilizzata come indicatore che anche i parametri meccanici sono aumentati e hanno raggiunto un valore stabile.

Il passo successivo per capire e prevedere il comportamento delle strutture in terra battuta è lo sviluppo di modelli numerici che rappresentino correttamente il comportamento del materiale. Nel Capitolo 1.0 MPa si propone un modello elastoplastico basato sul modello *concrete damage plasticity* di Abaqus, utilizzando i dati sperimentali del materiale ottenuti da prove di compressione uniassiale e diagonale eseguite per pisé senza stabilizzare. I risultati ottenuti sono molto accurati quando si replica la prova diagonale con un modello a elementi finiti.

Lo sviluppo di questo tipo di modelli numerici è essenziale per valutare la vulnerabilità delle strutture in terra battuta, in condizioni normali o sotto carichi estremi, come nel caso di un terremoto. Infatti, le prestazioni sismiche delle costruzioni in terra battuta sono una questione di preoccupazione per i costruttori e i ricercatori, a causa del gran numero di questi edifici presenti in zone con una significativa pericolosità sismica e del fatto che gli elementi in terra battuta sono particolarmente vulnerabili all'azione di un terremoto, a causa della loro bassa resistenza a trazione e del loro peso elevato. Come descritto nel Capitolo 7, i carichi orizzontali in piano e fuori piano indotti da un sisma possono generare gravi danni nei muri di terra battuta, e possono portare al collasso della struttura, essendo i carichi fuori piano particolarmente critici per l'integrità di queste costruzioni. Al fine di prevenire o minimizzare i danni sismici negli edifici in pisé, le norme e le linee guida raccomandano di costruire strutture il più possibile simmetriche, con non più di due piani, coperte da un tetto leggero, e con muri di grande spessore con una lunghezza libera massima pari a circa 10–15 volte lo spessore del muro e un'altezza massima pari a circa 8 volte questo spessore.

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Appendix A

Glossary and acronym list

γ	shear strain, as defined in ASTM E519 [83]
ε	normal strain
λ	thermal conductivity
ν	Poisson's ratio
ρ	density
φ	internal friction angle
ψ	dilation angle
AET	accelerated erosion test
BA	bottom ash
c [kPa]	cohesion
c [mm]	carbonation depth
CCR	calcium carbide residue
CDP	concrete damage plasticity
CEB	compressed earth blocks
CSRE	cement-stabilized rammed earth
CV	coefficient of variation
DCT	diagonal compression test
DEM	discrete element method
E	elastic modulus
EPS	expanded polystyrene
f_c	compressive strength
f_s	shear strength
f_t	tensile strength
FA	fly ash
FE	finite elements
FEA	finite element analysis
FEM	finite element method
G	modulus of rigidity
G_c	compressive fracture energy

G_f	tensile fracture energy
LSRE	lime-stabilized rammed earth
LVDT	linear variable differential transformer
MC	moisture content
MDD	maximum dry density
MBV	moisture buffer value
NHL	natural hydraulic lime
OMC	optimum moisture content
PCM	phase-change materials
PU	polyurethane
PSD	particle size distribution
$R\,[\mathrm{m^2K/W}]$	thermal resistance
$R\,[\mathrm{dB}]$	sound reduction index
RE	rammed earth
RH	relative humidity
S_s	shear strength, as defined in ASTM E519 [83]
SRE	stabilized rammed earth
STC	Sound Transmission Class
UCS	unconfined compressive strength
UCT	uniaxial compression test
UPV	ultrasonic pulse velocity
URE	unstabilized rammed earth
WBT	wire brush test
WTTF	waste tire textile fibers
XPS	extruded polystyrene

Appendix B
Scientific publications

This appendix includes the three scientific articles published with the results of the research developed in the present doctoral thesis. The articles are as follows:

- F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of unstabilized rammed earth: A review.* Construction and Building Materials. 270 (2021) 121435.
  doi: 10.1016/j.conbuildmat.2020.121435.

  Quality indicators:

  – Journal Impact Factor JCR (2021): 7.693
  – Rank by category, JCR (2021):
    "Engineering, Civil" – 5/138 (Q1, 1st decile)
    "Construction & Building Technology" – 6/68 (Q1, 1st decile)
  – Citations (14/12/22): WoS–28; Scopus–31; Google Scholar–43

- F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of stabilized rammed earth: A review.* Construction and Building Materials. 325 (2022) 126693.
  doi: 10.1016/j.conbuildmat.2022.126693.

  Quality indicators:

  – Journal Impact Factor JCR (2021): 7.693
  – Rank by category, JCR (2021):
    "Engineering, Civil" – 5/138 (Q1, 1st decile)
    "Construction & Building Technology" – 6/68 (Q1, 1st decile)
  – Citations (14/12/22): WoS–7; Scopus–8; Google Scholar–9

- F. Ávila, E. Puertas, R. Gallego, *Mechanical characterization of lime-stabilized rammed earth: Lime content and strength development.* Construction and Building Materials. 350 (2022) 128871.
  doi: 10.1016/j.conbuildmat.2022.128871.

  Quality indicators:

  – Journal Impact Factor JCR (2021): 7.693

- Rank by category, JCR (2021):
  "Engineering, Civil" – 5/138 (Q1, 1st decile)
  "Construction & Building Technology" – 6/68 (Q1, 1st decile)
- Citations (14/12/22): WoS–1; Scopus–1; Google Scholar–1

Note: The attached documents are the original manuscripts (preprints) of the articles, for the final published versions please refer to the provided URL of the DOI of each article.

F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of unstabilized rammed earth: A review*. Construction and Building Materials. 270 (2021) 121435. doi: 10.1016/j.conbuildmat.2020.121435.

Characterization of the Mechanical and Physical Properties of Unstabilized Rammed Earth: A Review

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Abstract

Sustainable development is becoming increasingly important in the construction sector. Therefore, building techniques that reduce environmental impacts by minimizing industrial processes and using locally available materials, such as earth, are receiving a new impetus. This paper presents a review of the state-of-the-art of research on characterization of unstabilized rammed earth, as understanding its behavior is essential for its use in modern construction. The results indicate that compressive strength is considered as the most representative parameter, but there is a significant dispersion in its values. Tensile and shear strength are known to be low, but further investigations are needed to assess their real magnitude. Several experiences show good thermal and acoustic properties, although more studies are also required to support these conclusions.

Keywords: rammed earth, mechanical properties, characterization, review.

1. Introduction

1.1. Background

From the very beginning, the human being has used earth as a construction material. Its availability at little or no cost, its versatility and its mechanical and insulating properties have turned it into an excellent constructive solution throughout History [1, 2]. Earth construction is worldwide extended (Figure 1), mainly in warm and arid climate zones.

There exist several earth construction techniques, among which rammed earth (RE) stands out as one of the most relevant ones, in both historical and geographical contexts. RE has been used since historical times in many countries all over the world [1, 4, 5] and is receiving a new impetus in recent years due to the heightened concern over environmental sustainability of building materials and procedures [6, 7].

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Figure 1: Areas with tradition of earth construction in the world and UNESCO World Heritage Sites. Adapted from [3].

RE technique consists of compacting layers of soil between temporary formworks up to the desired level, creating walls with a thickness of 30 cm to 60 cm [8–10]. The earth mixture is compacted into layers of about 7.5 cm to 15 cm [6, 11–13] by the use of a rammer, adding a new formwork above when one is filled, until achieving the required height; then the formworks can be removed.

The compaction is usually done up to approximately the optimum moisture content (OMC) [7, 14, 15], defined as the water content at which a soil can be compacted to a maximum dry density (MDD) by a given compactive effort [16]. The OMC and MDD can be determined via standard [17] or modified [18] Proctor compaction tests.

Although the RE construction technique has not substantially changed from the traditional one, there are some studies introducing novel RE manufacturing techniques. Noteworthy among them is pre-formed RE, consisting of the prefabrication of RE wall blocks in factory conditions for their transportation to the construction site; which might increase the manufacturing and transportation cost but reduces the building time and labor and allows a better manufacturing control, leading to a higher-quality material [7, 19–21]. Another innovative earth-based building technique is 3D printing, in which a robot deposit an earth-based mixture on a controlled path, superposing layers until reaching the desired height of the wall [22–24]. However, as the earth is not compacted, it cannot be considered as an actual RE technique.

RE source materials are a mixture of clay, silt, sand, gravel and sometimes stones with a diameter of a few centimeters. When clay is used as the only binder, it is referred to as unstabilized rammed earth (URE); and when other additives are included in order to improve RE properties, such as its strength or durability, it is referred to as stabilized rammed earth (SRE). Lime or cement are two of the most common additives used in SRE, but also fly and bottom ashes [25–28] and natural or synthetic fibers [15, 29, 30] have been added to the earth mixture in some studies.

1.2. Problem

The RE construction has historically been bound to the oral transmission of knowledge from generation to generation, with few structural notions mostly based on geometric relations between the elements dimensions. In the same way, RE codes and standards [31–34] have tend to put in writing these geometric relations, without thoroughly studying the mechanical behavior of the material.

However, considering RE as a building technique comparable to the other ones used in contemporary construction, implies that this material has to be considered and analyzed with the same rigor as any other construction material, and this means understanding its behavior and characterizing its properties. In this regard, several studies have carried out experiments in order to describe the mechanical properties of RE, with particular focus on the unconfined compressive strength (UCS). Nevertheless, and despite the increasing interest in RE construction, some of the material properties have not yet been exhaustively analyzed, and there is a very significant dispersion in the values obtain for those which have been more deeply studied and that are essential to characterize the behavior of this material.

1.3. Focus and research questions

Therefore, the aim of this paper is to critically review the existing literature in URE characterization, considering the tests and experiments carried out by several authors and compiling and analyzing the results obtained and their variability; with the final purpose of identifying relevant values and possible relationships between them.

The first section of this paper analyses the requirements (such as particle size distribution, moisture content or density) that soils must meet in order to be considered acceptable for URE construction. The second part deals in detail with the test results of the main mechanical properties (compressive, tensile and shear strength, Young modulus, Poisson's ratio, cohesion, friction angle and fracture energy) of URE. The third section evaluates the thermal, acoustic and humidity insulating properties of the material. The four section focuses on the durability of RE and the impact of aggressive environments. Finally, the last section analyzes the environmental benefits and economic impact that have been measured in diverse studies for URE constructions, comparing the results with other common construction materials.

2. Source material

2.1. Particle size distribution

Earth, as the source material for RE construction, must meet certain characteristics in order to be considered acceptable. On the one hand, it is true that traditionally the soil used has simply been the one easily available near the construction site, and there are various studies [35, 36] indicating that particle size distribution (PSD) should not be considered as a discriminating parameter when selecting the suitability of a soil for RE construction.

On the other hand, however, it is equally certain that a soil mixture with heterogeneous PSD, including both fine and coarse particles, is generally recommended for earth construction [7, 25, 37, 38]. Houben et al. [38] propose one of the most well-known and recommended envelopes for the PSD of soils that might be suitable for RE walls. Figure 2 shows the aforementioned envelope together with the PSD used by several authors in recent studies. It can be noticed that most of the PSD present in literature are included within the recommended envelope; with the only significant exceptions of El Nabouch [10], using a soil with a great silt and clay content, and Toufigh and Kianfar [15], that utilize a mixture containing a limited amount of fine particles, even though additional clay was added to the original soil in that study.

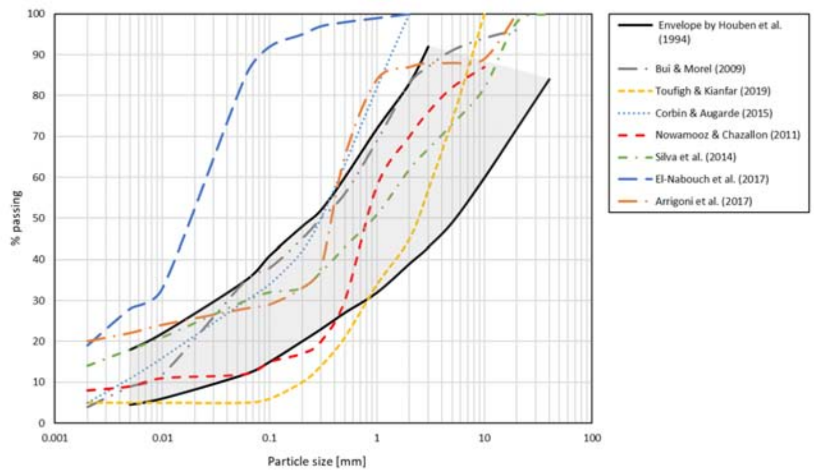

Figure 2: Particle size distribution for URE constructions: envelope recommended by Houben et al. [38] and values used by Bui & Morel [6], Toufigh & Kianfar [15], Corbin & Augarde [39], Nowamooz & Chazallon [12], Silva et al. [40], El Nabouch et al. [10] and Arrigoni et al. [25].

A relevant aspect to be considered with regard to PSD is clay content. Due to its small particle size (< 0.002 mm), clay provides cohesion to the mixture, acting as the only binder between soil particles in URE [15, 41]. The optimum clay value, according to the soil mixtures used in literature (Table 1), is between 8 % and 14 % by mass [12, 14, 40, 42–44]; although there can be found some studies that select a coarser soil with only about a 5 % of clay [6, 15, 39] and few exceptions with a clay content near 20 % [10, 25]. According to Maniatidis and Walker [45], the percentage of fine particles (clay and silt combined) should be between 20 % and 35 %, and the percentage of sand between 50 % and 75 %. These ranges are in agreement with the envelopes recommended by Houben et al. [38] and with the soil mixtures used by most authors in URE literature [6, 14, 25, 39, 40, 44].

Therefore, it is possible to conclude that, even though almost any type of local soil can be used as a source material for URE, controlling the PSD of the

Ref.	Clay	Silt	Sand	Gravel
[6]	4	31	48	17
[15]	5	0	40	55
[42]	8	34	8	50
[12]	8	4	60	28
[43]	10	–	–	–
[44, 46]	11	25	65	
[14]	12	13	45	30
[40]	14	16	32	38
[25]	20	8	59	13
[47]	20	65	15	0

Table 1: Particle Size Distribution [%wt] for URE source material.

earth material is important in order to reach a better mechanical behavior. In this regard, as shown in Table 1, a PSD with about 30 % fine particles and 70 % coarse particles seems to be recommended. It has to be considered, however, that the use of non-local materials in order to improve the PSD of the soil may lead to an increase in the environmental and economic costs.

2.2. Optimum moisture content and dry density

Soil moisture content is another key aspect that affects the mechanical behavior of the RE constructions [7]. In contrast to other parameters related to RE, there is quite a good agreement on the water content that RE source materials should have. Walker et al. [7] recommend using the soil OMC ± 1 to 2 %. This OMC is generally obtained via standard or modified Proctor compaction test, and leads to moisture values from 8 % to 12 % by weight in almost all the studies present in literature [6, 10–12, 14, 15, 25, 39, 40, 42, 44].

Nevertheless, it is important to understand that the Proctor compaction tests do not apply the same energy as the one used in earth construction, which means that they lead to a OMC that could be excessively high [7, 48]. In addition, results of a standard Proctor test, which implies lower compaction energy, could be more accurate when a manual rammer is used for the construction [41]; while modified Proctor test results could fit better in cases where a pneumatic rammer is used. Despite all these facts, Proctor compaction tests are still a useful and reliable method to assess the appropriate manufacturing water content for RE structures [47].

Depending on the water content during the compaction of the material, and also on the compaction energy applied, a different dry density is obtained. As moisture values close to the OMC are used for RE, the soil reaches almost its maximum dry density (MDM), which is an indicator of the compressive strength of the earth material [47, 49]. A wide range of dry density values are quoted for URE, varying from 1 750 kg/m^3 to 2 200 kg/m^3, as shown in Figure 3.

Studies analyzing the influence of compaction energy on the mechanical properties of earth materials [48–51] indicate that a higher compaction energy increases the MDD of the mixture and thus its compressive strength. Also, when increasing the compaction energy, the OMC at which MDD is reached becomes lower [48].

3. Mechanical properties

3.1. Unconfined compressive strength

As is the case with most brittle materials, especially those with low cohesion, unconfined compressive strength (UCS) becomes the main parameter to characterize the mechanical behavior, and so happens with RE. Several studies have been carried out in the last years to determine URE compressive strength (Table 2), most of them using small-size samples with different shapes and only a few [14, 52, 53] with constructive-scale samples. Although there is a significant dispersion in the results, it is possible to observe that these are in a range from 1.0 MPa to 2.5 MPa, excluding some few exceptions.

Ref.	Sample [cm]	ρ [kg/m^3]	MC [%wt]	f_c [MPa]	E [MPa]
[14][a]	$30 \times 30 \times 60$	1920	13	0.81	65
[42]	$40 \times 40 \times 65$	1900	11	1.00	100
[54][a]	$\varnothing 4,\ h = 8$	1649	21	1.04	103
[55]	$10 \times 10 \times 10$	1660	–	1.10	1050
[47]	$25 \times 25 \times 50$	1878	12	1.15	365
[40]	$55 \times 55 \times 20$	2100	10	1.26	1034
[52]	$100 \times 100 \times 100$	2000	–	1.30	500
[25]	$\varnothing 10,\ h = 20$	2080	8	1.40	–
[56][a]	$\varnothing 7.5,\ h = 15$	2043	12	1.77	–
[57]	$\varnothing 7.5,\ h = 15$	2143	7	1.85	34
[14]	$\varnothing 30,\ h = 60$	1850	13	1.90	–
[58]	$15 \times 15 \times 15$	2020	–	1.90	–
[47]	$\varnothing 10,\ h = 20$	1790	12	2.00	763
[15]	$\varnothing 7.5,\ h = 15$	1946	12	2.23	143
[14]	$\varnothing 10,\ h = 20$	1850	13	2.46	160
Mean		1942	12	1.55	392
CV		0.084	0.282	0.324	0.992

Table 2: Density (ρ), moisture content (MC), compressive strength (f_c) and Young modulus (E) of URE.
[a]Mean values for URE samples.

The test procedure followed to obtain UCS of the earthen material is in most cases the conduction of uniaxial compression tests. Since there are no ASTM standards specifically for testing UCS of RE samples, authors have followed ASTM D1633 [59] standard for compressive strength of soil-cement cylinders [60] or proposed specific procedures derived from ASTM standards for cement mortars [61] and from masonry design rules [14]. Although the dispersion in the UCS results of RE in literature is partly due to the heterogeneity of the material itself, a standardized test procedure would be necessary in order to actually make the results obtained by the diverse studies comparable.

It is well known that UCS is influenced by the manufacturing conditions (moisture content, compaction energy and sample size) [47, 62], but the relation between these parameters and the UCS of RE is still unclear. Figure 3 shows that an increase in the material density leads to a greater UCS, although there is a very significant dispersion. Maniatidis and Walker [14] conducted compression tests on samples with different sizes and shapes, concluding that there was a considerable variation in soil performance between small-scale cylinders (⌀10 cm, $h = 20$ cm) and full-scale prisms ($30 \times 30 \times 60\,\mathrm{cm}^3$) and columns (⌀30 cm, $h = 60$ cm) made of the same material. That reduction in the UCS of the full-scale samples was attributed to the variation in material grading, which included aggregates greater than 20 mm. Also Bui et al. [63] performed tests with specimens of different scales, indicating that the UCS obtained for small samples was higher than the one calculated for the bigger ones, which might be more representative of the behavior of a real RE wall.

Not only size but also shape affects the UCS of the RE specimens. Studies present in literature [10, 14, 63] have reported substantial differences in the results for prismatic and cylindrical samples. One of the reasons can be that the friction between the earth and the formwork during ramming is greater in the prismatic specimens (especially in the corners), so the cylindrical specimens can be compacted better and thus have better mechanical behavior. Also the differences in load distribution patterns between the prismatic and cylindrical specimens might be the reason for such variances in the results.

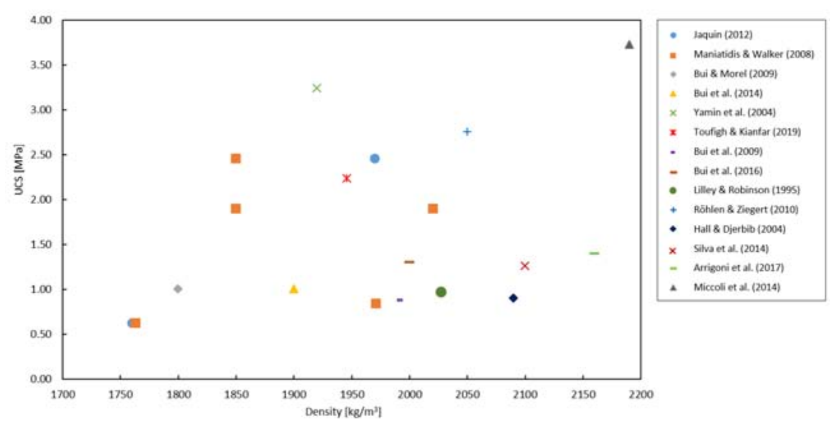

Figure 3: Unconfined compressive strength (UCS) as a function of density: values obtained by Jaquin [43], Maniatidis & Walker [14], Bui & Morel [6], Bui et al. (2014)[42], Yamin et al. [53], Toufigh & Kianfar [15], Bui et al. (2009) [63], Bui et al. (2016) [52], Lilley & Robinson [58], Röhlen & Ziegert [64], Hall & Djerbib (2004) [37], Silva et al. [40], Arrigoni et al. [25] and Miccoli et al. [44].

Almost all the studies on RE compressive strength have applied the load perpendicular to the direction of the earth layers, which is a reasonable criteria as this is the normal loading direction of real RE walls. However, and despite the expected anisotropy of the material, a study carried out by Bui et al. [42] tested the bearing capacity of RE in a direction parallel to the earth layers, concluding that the layer separation that occurs does not seem to affect the mechanical properties of the sample.

To summarize, the studies regarding the UCS of RE show that there is a wide range of parameters affecting this mechanical property: sample size and shape, compaction, density, moisture content and testing procedure. The wide range of combinations between these parameters makes it difficult to assess clear relationship between them and the UCS. However, and despite this fact, it is possible to establish the UCS of URE within the range from 1 MPa to 2.5 MPa.

3.2. Young modulus and Poisson's ratio

Most studies calculating the UCS of RE have also measured its Young Modulus (E), traditionally obtained as the slope of the tangent line with the elastic part of the stress-strain curve. An enormous dispersion is noted in the Young modulus of URE (Table 2), with values from about 60 MPa to 1 000 MPa.

Such a significant dispersion is related to factors associated with sample manufacturing (source material, moisture content and sample size) [14, 42, 47] and also to the testing procedure and varying definitions of elastic modulus. According to Alós Shepherd et al. [65], the elastic modulus determined following concrete testing standards is higher than the one obtained from geotechnical testing standards, due to the techniques used measure deformation (concrete standards measure specimen deformation with strain gauges or similar, while geotechnical standards commonly use the machine displacement).

Similarly to concrete or other brittle materials, the Young modulus of RE is expected to increase with increasing UCS. However, the above-mentioned dispersion of results depending on the sample manufacturing and test procedures, does not allow to define a clear correlation between these two parameters, in the way it is done for concrete. Despite this, the direct relationship between Young modulus and UCS is proved by some studies [10, 14, 43] that have carried out several uniaxial compression test on RE samples with homogeneous characteristics. These studies have obtained increasing values of the Young modulus when the UCS was higher. Figure 4 shows the relation between Young modulus and UCS for URE in literature.

Fewer reports of RE Poisson's ratio (ν) are noted in literature. The studies that did calculate it show values from 0.22 to 0.30 [42, 44, 47]. Poisson's ratio is obtained via uniaxial compression test of RE samples by measuring vertical and lateral displacements with extensometers [42] or LVDT sensors [14, 15, 42, 44].

3.3. Tensile strength

As happens with any other type of earth construction, RE has very low strength in tension and shear, especially when moist [45], meaning that RE elements should not be designed for pure tension.

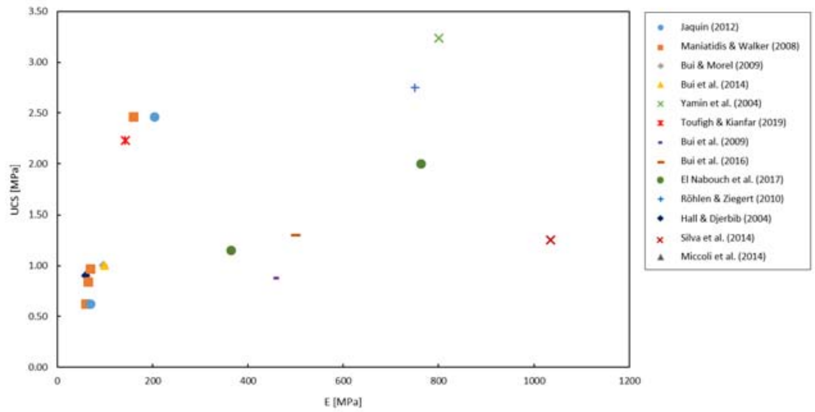

Figure 4: Unconfined compressive strength (UCS) as a function of Young modulus (E): values obtained by Jaquin [43], Maniatidis & Walker [14], Bui & Morel [6], Bui et al. (2014)[42], Yamin et al. [53], Toufigh & Kianfar [15], Bui et al. (2009) [63], Bui et al. (2016) [52], El Nabouch et al. [10], Röhlen & Ziegert [64], Hall & Djerbib (2004) [37], Silva et al. [40] and Miccoli et al. [44].

Although the tensile strength is one of the most relevant parameters in the analyses of RE failure, particularly in extreme conditions (e.g. seismic) [42, 66], it is often neglected in design and has not been yet thoroughly studied. Authors studying this parameter have carried out Brazilian tests [15, 42] or pull-off tests [44] on RE specimens, concluding that the tensile strength of the material can be considered equal to approximately 10 % of its compressive strength. This criteria leads to values of the tensile strength between 0.10 MPa and 0.35 MPa, which are in accordance with the values found in literature [1, 40, 53, 67, 68].

Bui et al. [42] suggested the need to distinguish between the tensile strength in an earth layer and the tensile strength at the interfaces between layers. The result of that study, however, showed that the tensile strength at layer interfaces was similar to the one measured within the layers, leading to the conclusion that it might be acceptable to consider RE as an isotropic material in tension.

3.4. Shear strength and cohesion

Shear strength of URE is also very limited, so its design values are considered close or equal to zero (e.g. 0.035 MPa in the New Zealand code [33] or zero in Australian Handbook [69]) in the absence of direct experimental data. Despite this fact, the few studies that have assessed the shear strength of RE have obtained results that, although small, are well above the ones recommended by the standards. These values, as shown in Table 3, are between 0.15 MPa and 0.85 MPa.

Two different test procedures are used to assess the shear behavior of RE: diagonal compression tests [40, 44, 53] or direct shear tests [44, 47]. Authors have used full-scale samples to perform the diagonal compression tests, which

Ref.	Sample [cm]	ρ [kg/m^3]	f_s [MPa]	c [kPa]	φ [°]
[40]	$55 \times 55 \times 20$	2100	0.15	189	37
[42]	$40 \times 40 \times 65$	1900	0.18	170	51
[53]	$250 \times 250 \times 50$	1920	0.37	–	–
[44]	$50 \times 50 \times 11$	2190	0.65 – 0.85	–	39
[12]	⌀7.6, $h = 14.7$	2000	–	13	41
[47]	$49 \times 49 \times 36$	–	–	30	35
[57]	$15 \times 15 \times 18$	2143	–	50	65
[39]	$6 \times 6 \times 2$	2131	–	68	44
[52]	$100 \times 100 \times 30$	2000	–	130	45
[47]	$10 \times 10 \times 3.5$	–	–	135 – 260	45
[46]	$50 \times 50 \times 12$	2190	–	561	37

Table 3: Density (ρ), shear strength (f_s), cohesion (c) and friction angle (φ) of URE.

have been carried out in accordance with ASTM E519 [70]. Silva et al. [40] noted that the shear strain-stress curves are characterized by an early peak shear stress, related to the cohesion generated by the binder effect of clay, followed by a significant reduction of stiffness when the contribution of cohesion diminishes and the shear behavior relies on friction and interlocking.

A key factor affecting URE shear strength is the moisture content at the testing time [45, 47, 71]. Narayanaswamy [71] performed compression tests on inclined RE samples varying the moisture content in order to assess the variation of shear strength, concluding that there is a significant decrease in the shear strength when increasing the moisture content (about a 75 % when increasing moisture from 0.0 % to 4.2 %).

According to Mohr-Coulomb theory, shear strength depends on cohesion, friction angle and normal stress. It is, therefore, possible to determine cohesion and friction angle of RE from the relationship between shear and normal stresses, which can be obtained by either a shear box test [47, 72] or a triaxial compression test [12]. Another option, commonly found in literature, to obtain these two parameters is by calibration in a numerical discrete elements model (DEM) of finite elements model (FEM) [40, 42, 44, 52]. For URE cohesion, some authors suggest a direct relation with compressive strength of the form $c = (0.10{-}0.14) f_c$ [42, 52], or with tensile strength of the form $c \approx 1.5 f_t$ [40, 66], but further investigation is needed to confirm the validity range of these relations.

As shown in Table 3, there is a significant dispersion in URE cohesion values, varying from 30 kPa to 560 kPa; while friction angle shows a bit more homogeneous values, mainly in between 35° and 45°. El Nabouch [47] used a shear box to test large-scale RE specimens with different densities, and arrived to the conclusion that a higher density significantly increases cohesion but does not affect the friction angle. In that study, also small-scale samples were tested, obtaining higher values for both cohesion and friction angle.

Another parameter related to the shear behavior of URE that has not been yet studied in depth is the dilation an gle (ψ). In a recent study, Bui et al. [73] analyzed the effects of the dilation angle on the behavior of RE walls using a FEM model, noting that this parameter only influences the ultimate displacements, and that a value of $\psi = 30°$ provided a good agreement between numerical and experimental results. However, a previous study [52] indicated a value of 12°, and Miccoli et al. [66] considered it equal to zero; which shows that there are still not enough investigations to establish an acceptable value for RE dilation angle.

Regarding shear behavior of RE, Kosarimovahhed and Toufigh [57] also proposed the dissipated energy in shear (U_f) as a useful parameter to represent the deformability capacity of RE materials under shear loading. U_f is calculated as the area under the shear force - shear displacement curve until the failure point, and a value of 15 J was obtained for the URE samples.

3.5. Fracture energy

The tensile fracture energy (G_f), along with the compressive and tensile strength and the Poisson's ratio, is one of the most relevant parameters in the characterization of the mechanical behavior of RE [66, 74, 75], having a great influence on its maximum shear stress [46]. However, there are very few studies concerning the determination of both the tensile and compressive fracture energy of RE.

There are two main procedures for obtaining the fracture energy of a sample: the three-point bending test [76] and the wedge splitting test [74, 77]. The latter has the advantage of using much smaller specimens, so they are easier to manufacture and transport, and their shape and size eliminate any effects of the sample self-weight [74].

Miccoli et al. [66] proposed a relation between the fracture energy and the strength of the RE material, estimating the mode-I tensile fracture energy as $0.029 f_t$ and the compressive fracture energy (G_c) as $1.6 f_c$; this relationship was also used by Silva et al. [40]. Bui et al. [73] proposed to calculate the G_f according to CEB-FIP Model Code 90 [78].

The values obtained in literature for the tensile and compressive fracture energy are shown in Table 4. There is a relevant dispersion in the G_f values, which are between 0.002 N/mm and 0.020 N/mm, and very few data about G_c to draw conclusions. Therefore, further investigation is needed to assess the values of the URE fracture energy.

Ref.	G_f **[N/mm]**	G_c **[N/mm]**
[74]	0.002	–
[40]	0.004	–
[66]	0.011	6
[73]	0.012	10 – 25
[77]	0.020	–

Table 4: Tensile (G_f) and compressive (G_c) fracture energy of URE.

4. Insulating properties

4.1. Thermal insulation

Although most studies regarding RE characterization have focused on its mechanical properties, to a lesser extent there are also some investigations oriented to the assessment of the insulating properties (thermal and acoustic) of this material.

One of the main parameters which define the thermal insulation capacity of a material is its thermal conductivity (λ [$\mathrm{Wm^{-1}K^{-1}}$]) [1]; so the lower is the thermal conductivity, the higher the insulation will be.

There is a relevant relationship between the density of the earth material and its thermal conductivity, as shown in Figure 5, so when density increases, the thermal insulating capacity of RE decreases. As well as density, the influence of water content is also important in the thermal behavior of RE, as an increase in the material moisture content leads to a significant reduction of the thermal insulation [1, 79]. Soudani [80] measured that the thermal conductivity increased by 30 % between dry conditions and a moisture content of 2 % and by 70 % if the moisture content reached the 5 %.

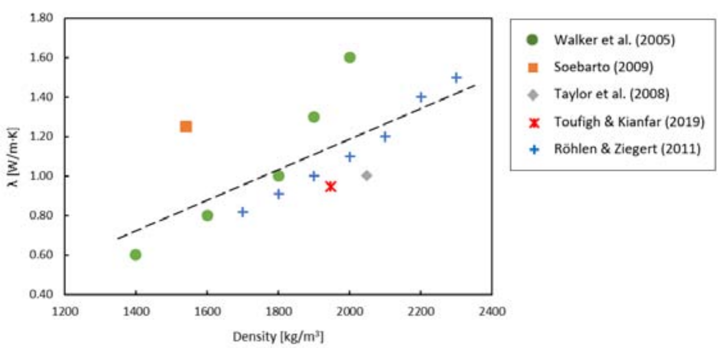

Figure 5: Thermal conductivity (λ) as a function of density: values obtained by Walker et al. [7], Soebarto [81], Taylor et al. [82], Toufigh & Kianfar [15] and Röhlen & Ziegert [64].

The values found in literature for the thermal conductivity of RE with a normal density are between 1.0 and 1.4 $\mathrm{Wm^{-1}K^{-1}}$ (Figure 5), which means they offer similar insulation to a traditional ceramic brick [1, 83] and better than other common construction materials such as concrete (1.5 to 2.5 $\mathrm{Wm^{-1}K^{-1}}$) or stone (1.1 to 3.5 $\mathrm{Wm^{-1}K^{-1}}$) [83]. Also, recent studies [84] show that stabilized RE materials provide a satisfactory thermal performance in comparison to masonry materials, and conclude that the application of acrylic insulators have a great influence on RE thermal behavior while their effect on masonry is quite low.

Not only the material properties are relevant when measuring thermal insulation, but also the wall thickness. In this regard, thermal resistance (R [$\mathrm{m^2K/W}$]) is defined as the ratio between the thickness of the element and its thermal conductivity. Considering the aforementioned λ-values and usual URE wall thickness between 30 cm and 60 cm, the thermal resistance of an URE wall will be approx. between 0.2 and 0.6 m^2K/W, which is in accordance with the order of magnitude indicated by various authors [79, 80, 84, 85]. This range is lower than the minimum values established in earth standards (e.g. 1.3 m^2K/W in the Australian standard [69]), which goes against the global opinion on the thermal comfort experienced in existing RE buildings, leading to the conclusion that *R*-value might not be representative enough to characterize the URE thermal behavior [80].

However, in order to solve these shortcomings, it is easy to include additional insulating elements to the RE walls with the aim of significantly increasing their thermal properties. In this respect, not only traditional acrylic insulating materials such as extruded polystyrene (XPS) [84, 86], polyurethane (PU) [86] or expanded polystyrene (EPS) [56] have provided good results, but also more eco-friendly solutions such as wood panels have shown an excellent thermal behavior when combined with RE [86, 87].

Another important aspect regarding earth thermal performance, which is well-known since the beginnings of earth construction, is its capacity to reduce the thermal amplitude inside the building, keeping the interior fresh during the day and warm at night [11, 88]. Recent studies [86, 89] have measured this thermal behavior, concluding that the reduction of thermal amplitude provided by RE is between 70 % and 77 % for 29 cm-thick walls and up to 75 % to 80 % for 50 cm-thick walls, which means that the temperature inside the building remains almost constant during the whole day [89]. The capacity of RE to buffer temperature variations is related to its ability to store heat (thermal mass), and can have a greater impact on thermal comfort than the insulation and thus counterbalance a low thermal resistance, especially in temperate climates with warm days and cold nights [90–92]. A case of study developed in Southern Portugal [88] proved that RE can provide satisfactory indoor thermal comfort during almost the whole year, although a heating system could be necessary to overcome some periods of thermal discomfort during winter.

Some studies [30, 56] have evaluated the impact of adding thermal energy storage materials such as expanded polystyrene (EPS) and phase-change materials (PCM) to the earth mixture, concluding that they enhance the thermal behavior of RE. However, their use entails a significant increase in manufacturing costs, especially in the case of PCM, and their effect on the UCS of the RE material is still unclear.

The thermal behavior of RE described in this section has been mainly studied by the diverse authors via laboratory tests and cases of study, but there are some few attempts to develop numerical models to predict the hygrothermal performance of RE materials. Soudani [80] proposed a coupled model based on heat and mass balances which considers separately the kinematics of each phase in interaction with each other, obtaining a good concordance between the numerical results and the experimental data. Another recent study [93] carried out numerical simulations of a RE wall with and without a moisture barrier using a numerical model driven by temperature and relative humidity, on the basis of the theory of heat and mass transfer in porous media. The results from a small-scale experiment where used by the authors to verify the validity and accuracy of the numerical model.

4.2. Acoustic performance

Acoustic insulation provided by RE elements is another relevant property for the functional behavior of the material that has not been thoroughly studied in literature. This parameter can be measured using the sound reduction index (R [dB]), defined as ten times the decimal logarithm of the ratio between the incident acoustic power on an element and the acoustic power radiated by the other side of that same element [94]. In some countries it is also common to measure acoustic insulation via the Sound Transmission Class (STC [dB]) [95, 96]. Both parameters indicate the decibel reduction of noise that a partition can provide; although there are some systematic differences in their calculation procedures, the sound reduction index is normally similar or slightly lower number than the STC rating value [97, 98].

Table 5 shows the values of R and STC found in literature. According to these results, it seems acceptable to consider 57 dB as a value of consensus. Taking into account that STC-50 means that loud speech is not audible and STC-60 that even amplified sounds are barely audible [99, 100], it is possible to conclude that RE has have a good acoustic behavior. Regarding the relation between the acoustic insulation and the material density (ρ) and wall thickness (t), several authors [7, 101–103] propose to use the expression suggested by the British Standard 8233 [104] for ordinary masonry walls (Equation 1).

$$R = 21.65 \log_{10}(\rho \cdot t) - 2.3 \quad (1)$$

Ref.	ρ [kg/m^3]	t [cm]	R [dB]	STC [dB]
[96]	–	25 – 30	–	50.0 – 57.0
[105]	–	30	–	57.0
[64]	1900	50	57.0	–
[7]	2000	30	57.9	–
[103]	2100	30	58.3	–

Table 5: Sound reduction index (R) and Sound Transmission Class (STC) of URE depending on its density (ρ) and the wall thickness (t).

One more parameter that defines the acoustic performance of a material is the reverberation time. There are not yet enough studies on this regard to assess a value for this parameter of RE, but some authors [101, 103, 106, 107] indicate that, due to its porosity, RE has excellent sound reverberation properties, generating far fewer harsh echoes than conventional wall materials.

4.3. Air humidity balance

Earth has the ability to absorb and desorb humidity faster and to a greater extent than any other conventional construction material, enabling it to balance indoor climate [1]. Measurements taken in a house of new construction in Germany with all its walls made of earth, and reported by Minke [1], showed that the relative humidity inside the house fluctuated by only 5 % to 10 % throughout the year.

Rode et al. [108] proposed the Moisture Buffer Value (MBV) as an appropriate parameter to measure the capacity of building materials to absorb and desorb humidity, and thus to balance it inside a building. MBV is measured in mass of water per open surface area and per relative humidity variation (%). According to Arrigoni et al. [109], diverse studies have measure a MBV for URE between 1.0 and $3.7\,\mathrm{g/(m^2 \cdot \%RH)}$, which can be considered within the categories *good* and *excellent* defined in [108]. Although there is a significant dispersion in MBV for URE, all the values within the range are considerably better than the ones reported for other common constructions materials such as concrete, baked bricks or gypsum boards, whose MBV are always lower than $0.7\,\mathrm{g/(m^2 \cdot \%RH)}$ [109].

Although there are some studies regarding the numerical modeling of the hygrothermal behavior of earthen materials and the effect of moisture in their thermal performance, there are not yet numerical models specifically design to describe RE moisture buffering capacity. In [110], a coupled model is develop to simulate the heat and mass transport considering the effects of the phase change of water inside the earthen walls. Abahri et al. [111] proposed a one-dimensional model for evaluating coupled heat and moisture transfer in porous building materials, concluding that the thermal diffusion affects strongly the moisture migration in the walls. A study regarding the numerical assessment of earth materials buffering potential [112] concluded that earth mixtures can be advantageously used in buildings due to their capacity to lower heat transfer and moderate indoor humidity variations, although the material analyzed was not RE but a straw-clay mixture. A numerical model recently proposed by Jiang et al. [93] showed that the addition of a moisture barrier is beneficial in protecting a RE wall, but it reduces its moisture buffering capacity.

5. Durability

The durability of RE materials and the effect of harsh environments on their properties is also a relevant aspect that should be taken into consideration, as it has always been one of the main concerns for designers and consumers [113, 114]. Several authors have evaluated RE durability using laboratory tests such as the accelerated erosion tests (AET) [9, 115, 116] or the wire brush test (WBT) [115, 117] presented by ASTM D559 [118] for compacted soil-cement mixtures. The results from these tests show that RE materials may need protection against rain (waterproofing agents or sloping roofs) or the addition of a stabilizer such as cement or lime to reduce erosion and so avoid excessive maintenance. However, Bui et al. [119] measured the real erosion of different RE walls exposed for 20 years to natural weathering and found much lower erosion than the one obtained via AET, assessing a potential lifetime for URE walls greater than 60 years (precipitation about 1 000 mm/year).

To date, few studies have analyzed the durability of RE in aggressive environments. A recent study developed by Ghasemalizadeh and Toufigh [113] evaluated the effect of different aggressive environments on the durability of cement-stabilized RE, observing that the specimens with low cement content disintegrated between 6 and 9 months of exposure in sulfate, alkaline and acidic environments. Luo et al. [120] carried out drip tests and rainfall simulation tests to investigate the degradation of RE under wind-driven rain, and obtained that a the critical rain direction was between 30° and 45° in drip tests and between 15° and 30° in rainfall simulation tests. The authors attribute this variation in the results to the formation of a water film that lowers the influence of the increase of kinetic energy. This study also concluded that a lower water content and higher clay content reduces the erosion due to wind-driven rain.

6. Environmental and economic benefits

6.1. Environmental benefits

Sustainable development and respect for the environment are two aspects that are becoming increasingly important in the field of construction, and this is precisely one of the strong points of earth construction, which helps to save energy and reduce environmental pollution [1, 7, 121]. As a wide variety of soils are acceptable for RE construction without a significant industrial manipulation, these can be easily found near the construction area, so the production and transportation costs (both economic and environmental) are significantly reduced. According to Minke [1], the process of preparation, transport and handling of earth for construction requires only ca. 1 % of the energy needed for the same process for baked bricks or reinforced concrete.

Therefore, if one looks at CO_2 emissions as a key indicator of the material environmental performance, it is possible to observe (Table 6) that URE generates lower emissions than any other building material or technique.

Material	kg CO_2/kg	kg CO_2/m^3	kg CO_2/(m^{3}MPa)
URE	0.004	9	4 – 9
7.5 % fly ash SRE [57]	0.045	106	12 – 22
7.5 % cement SRE [57]	0.06	127	13 – 43
Adobe	0.06	72	36 – 144
Hollow brick	0.14	94	19
Mass concrete	0.14	330	9 – 17
Reinforced concrete	0.18	450	9 – 18
Solid brick	0.19	304	30

Table 6: CO_2 emissions of main building materials. Emissions per weight, per volume and per volume and compressive strength. Adapted from [121].

Taking into account that between 20 % and 40 % of solid waste generated in developed countries comes from the construction and demolition sector [122–124], it is clear why minimizing waste generation is becoming a priority for the building industry. URE construction could help reducing demolition waste, which represents a significant percentage of the total waste, as unbaked earth can be reused an indefinite number of times, never becoming a waste material harmful to the environment [1, 121].

6.2. Economic impact

Building with earth has a significant impact on the reduction of the construction costs, due to the low price of the source materials and the reduction of the transportation costs when using local soils [1]. This economic advantages make RE an excellent choice for lower-income countries and regions [63, 125, 126], where costs can be reduced from 30 % to 60 % compared to conventional concrete-based construction [125]. In addition, the predominant use of manual labor contributes to the creation of local jobs [68]. In countries where labor costs are high, the industrialization of the process (e.g. prefabricated RE) may help to reduce the overall costs [1, 19, 20].

Nevertheless, it is worth to mention that when better mechanical properties are needed due to building requirements, the local soil might not be acceptable without a previous modification. This means that non-local material would have to be used in order to improve the PSD of the soil, leading to higher material and transportation costs. Another way to improve the RE material properties is the use of additives, although it also increases the manufacturing costs, as shown in Table 7.

Material	Cost [$/t]
URE	3.54[a]
RE with 7.5 % cement	5.46[a] – 11.25[b]
RE with 7.5 % fly ash	9.55[b]
RE with 15 % EPS	4.54[a]
RE with 10 % PCM	653[a]

Table 7: Material cost of RE mixtures. Source: [a][56], [b][57].

7. Conclusions

Sustainable development and waste reduction are becoming increasingly important in the construction sector. This heightened concern over environmental sustainability is attracting the attention of researchers to earth as an available building material with a low environmental impact. The review presented in this paper shows and analyses the state-of-the-art of URE characterization, as one of the earth construction techniques with more tradition and future projection, and whose understanding is essential for its use in modern construction. The following conclusions can be reached based on this review.

The first aspect to be considered when constructing an URE wall are the characteristics of the source materials. In this regard, the PSD of the soil should not be considered as a discriminating parameter, but heterogeneous distributions are recommended. In fact, most studies are in accordance with the PSD envelopes proposed by Houben et al. [38]. Clay content is also a relevant aspect, as it acts as the only binder in URE, normally lying between 8 % and 14 % by mass.

URE is compacted up to approx. its OMC, which is between 8 % and 12 % by mass, reaching a MDD from 1 750 kg/m^3 to 2 200 kg/m^3. Moisture content and dry density are proved to be very relevant for determining the mechanical, thermal and acoustic behavior of RE.

Most studies on RE are focused on calculating the UCS of the material, which is traditionally considered as the main parameter to characterize the mechanical behavior of brittle materials. There is a significant dispersion in the compressive strength of URE measured in diverse studies, but the values are generally in range from 1.0 MPa to 2.5 MPa. This dispersion is due to the heterogeneity of the material and also to the manufacturing and testing conditions, been necessary to establish standardized test procedures to make the results actually comparable. The material Young modulus has also been measured in several studies, but the dispersion is even greater, with values from 60 MPa to 1 000 MPa. There is expected to exist a direct relation between density, UCS and Young modulus, but a clear correlation between these parameters has not yet been defined.

URE tensile and shear strength are known to be very low, so they are frequently neglected in design. However, they are essential to characterize the material failure, so further investigations are needed on this topic. The studies present in literature give values between 0.10 MPa and 0.35 MPa for the tensile strength (approx. 10 % of the UCS) and between 0.15 MPa and 0.85 MPa for the shear strength.

The shear behavior of URE is related to the cohesion and friction angle of the earthen material. Some authors [40, 42, 52, 66] suggest a relationship between cohesion and compressive strength, $c = (0.10 - 0.14) f_c$, or between cohesion and tensile strength, $c \approx 1.5 f_t$; but the accurate value of this parameter is not yet defined if one looks at the wide range that it adopts in literature (from 30 to 560 kPa).

Another parameter for which a deeper investigation is needed is the fracture energy, especially in tension, as it has a great influence in the RE mechanical behavior [46, 66] and only few studies have carried out tests to calculate its value. The results obtained are between 0.002 N/mm and 0.020 N/mm.

Several experiences in earth construction have proved that RE elements provide excellent thermal and acoustic behavior, but more studies are also required to support these considerations. The thermal conductivity of URE (between 1.0 and 1.4 Wm^{-1}K^{-1}) is better than the one measured for other construction materials, but still not enough to reach the values required in most standards. However, its capacity to dump temperature variations, and thus to reduce the thermal amplitude inside the buildings (about 75 %), can counterbalance the low thermal resistance and have a considerable impact on thermal comfort [90–92].

Not only temperature, but also air humidity inside an URE building is well balanced and buffered, due to the ability of earth to absorb and desorb humidity in a very fast way. This feature has been measured in literature using the MBV, and better values have been obtained for URE than for any other common construction material.

The acoustic insulation provided by RE walls has been calculated only in some few studies, using the Sound Reduction Index or the Sound Transmission Class. In this case the results have been quite homogeneous, with values equal to ca. 57 dB, which proves a good acoustic behavior of the material [99, 100].

The durability of RE is one of the main concerns for designers and customers. The studies in literature highlight the importance of protecting RE against rain, using physical protections or stabilizers such as cement or lime.

Finally, some of the environmental benefits of URE construction measured in literature are analyzed; regarding the reduction of energy consumption, CO_2 emissions and waste generation. Despite the fact that it is clear that earth construction is a low-impact building technique which helps protecting the environment, further investigations would be needed in order to quantify the real magnitude of these benefits. Also some economic benefits have been found, especially when using local soil and in countries where labor costs are low.

In conclusion, URE construction seems to meet the requirements to be considered as a useful eco-friendly building solution, so a greater effort is needed to further understand its behavior and thus to be able to extend the use of this technique for modern constructions.

Acknowledgements

This research was supported by the Spanish Ministry of Universities via a doctoral grant to Fernando Ávila (FPU18/03607).

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F. Ávila, E. Puertas, R. Gallego, *Characterization of the mechanical and physical properties of stabilized rammed earth: A review*. Construction and Building Materials. 325 (2022) 126693. doi: 10.1016/j.conbuildmat.2022.126693.

Characterization of the Mechanical and Physical Properties of Stabilized Rammed Earth: A Review

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Abstract

Rammed earth is a traditional construction technique that is attracting the interest of the building sector due to its limited cost and very low environmental impact. The use of rammed earth in modern construction, however, often requires an improvement of its properties in order to reach the performance levels fixed by the diverse national and international standards; so rammed earth is frequently improved by the use of different types of additives and stabilizers that, on the other hand, may reduce its environmental and economic benefits. The present study analyzes the alternatives available to enhance rammed earth behavior by reviewing how the existing scientific studies have tried to improve the most relevant mechanical, thermal and acoustic properties.

Keywords: stabilized rammed earth, characterization, mechanical properties, insulating properties, durability, sustainability, review.

1. Introduction

1.1. Background

Earth has been a very relevant construction material since the beginning of human history, due to its availability at little or no cost, its versatility and its mechanical behavior and insulating properties, both thermal and acoustic [1, 2].

Diverse cultures and societies all over the world have developed along time different techniques to use earth for construction: cob, adobe, wattle and daub, etc. One of such techniques with a greater historical and geographical presence is rammed earth (RE) [1, 3–5], which consists of compacting a mixture of soil and water in 7.5 to 15 cm-thick layers of [6–9], using temporary formworks, until reaching the desired wall height. These RE walls usually have a thickness between 30 and 60 cm [10–12]. This traditional technique, which only uses soil and water as the source material, with clay acting as the only binder of the mixture, is called unstabilized rammed earth (URE).

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The relevance of RE, however, is not a thing of the past. Nowadays, earth construction is attracting the attention of a great number of builders and researchers that are looking for alternative sustainable construction techniques, in the framework of a growing environmental awareness in the construction sector [6, 13–15].

However, when rammed earth technique is to be applied in new constructions, its mechanical performance is frequently not good enough to reach the values defined by the building standards. To improve these mechanical properties, and also some other aspects such as the thermal and acoustic behavior, diverse additives can be added to the earth and water mixture, leading to the so-called stabilized rammed earth (SRE). There exist diverse additives or stabilizers that improve the behavior of RE by physical and chemical interactions with the soil particles and the water present in the mixture; some of these additives have been used since antiquity (e.g. lime or natural fiber [3, 16, 17]) and some others have been introduced in the last decades or years (e.g. cement, coal combustion residuals, artificial fibers or advanced materials) [2, 5, 18].

The use of stabilizers in RE is becoming more and more frequent, improving its properties and allowing to use this technique in a wider range of constructions. However, if additivation is used systematically and without taking enough care about which are the requirements that URE cannot fulfill, there is the risk that RE constructions lose some of the most important properties (i.e. low cost and low environmental impact) that make this technique interesting and useful nowadays [19–21].

1.2. Focus and research questions

Considering the above, this document analyzes the state of the art of SRE, aiming to present the different options for RE stabilization, from the point of view of the property that needs to be improved, in order to make it easier for researchers and builders to choose the best alternative and to understand the consequences (mechanical, environmental and economical) derived from the stabilization.

To reach this goal, this study is divided in five parts, including the mains aspects to be considered when choosing a construction technique or material. The first one presents the main stabilizers that have been commonly used in rammed earth construction, their characteristics and the characteristics of the soil to be used for stabilization. The second and third parts regard the mechanical behavior and insulating properties of SRE, focusing on how each kind of stabilizer is used to enhance each parameter. Then the durability is analyzed, as one of the greatest concerns about rammed earth structures. Finally, the last sections evaluates the environmental and economic impact of this building technique, focusing on how the use of stabilizers could affect some of the main benefits of traditional RE construction.

2. Materials

2.1. Stabilizers, additives and reinforcements

As mentioned above, natural soil can be directly used to build RE structures, but when higher strength or durability are required it is common to add different kinds of additives to the mixture. The growing interest in the use of additives and reinforcements to improve the mechanical and physical behavior of RE can be noted observing the increasing number of scientific publications regarding RE construction, and their citations, that refer to stabilization (Figure 1).

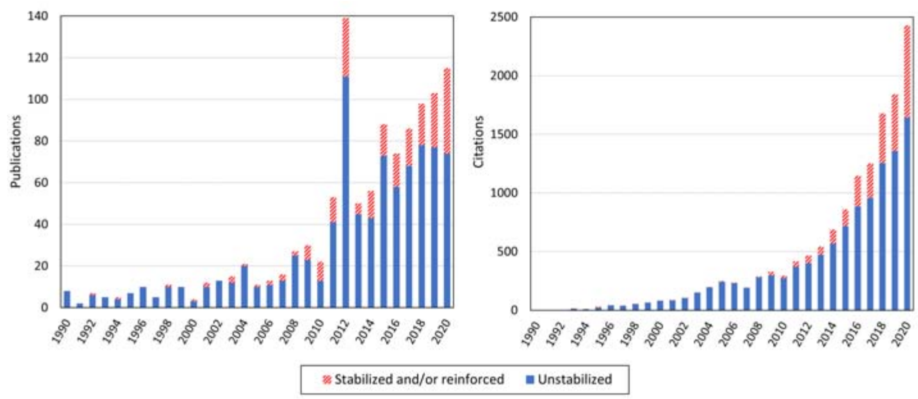

Figure 1: Publications and citations in Web of Science regarding rammed earth that include or not the words "stabilized" and/or "reinforced", between the years 1990 and 2020.

Portland cement is, by far, the most frequently used stabilizer nowadays [18, 22], substantially improving the compressive strength and durability of RE elements [19, 23, 24]. Natural soil to be used for cement stabilization must have a reduced clay content, so the shrinkage of the resulting RE material is also lower than the one observed in URE. These mechanical improvements have made cement stabilization a generally accepted routine practice in RE construction in countries such as Australia, New Zealand or the United States, but its use should be limited due to the severe increase in environmental costs [19–21].

Another RE stabilizer with a long tradition is lime. There is a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [25–29]. When lime is added to a soil, the concentration of Ca^{2+} and OH^- increases due to the hydration reaction of lime. This generates the flocculation of particles, affecting soil plasticity, and an increase in pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [26, 30].

The benefits of lime stabilization of RE have been known since ancient times, being possible to find several examples of historic buildings made of LSRE [31–34]. However, and despite its historical use, lime has been superseded by cement as the main additive to improve the mechanical properties of RE during the last decades, and as a consequence there are few scientific studies dealing with lime-stabilized rammed earth (LSRE).

Usually combined with cement or lime, fly ash (FA) is sometimes added to the RE mixture to increase the amount of amorphous material available and to enhance the cementitious reactions between soil and the main stabilizer [35]. Since FA is a residue generated by coal combustion, its use helps reducing the environmental impacts of cement-stabilized rammed earth (CSRE) [19, 23, 36]. With the same aim of obtaining a more sustainable stabilized material, several studies have proposed over the last years the addition of other waste materials to RE, such as bottom ash (BA) [37], recycled concrete aggregates [38], calcium carbide residue (CCR) [39, 40], ground granulated blast furnace slag [41] or brick waste [36].

In addition to the aforementioned binders used to improve the properties of RE by chemical stabilization, there is another type of additives that enhance the mechanical behavior of RE by means of their shape: fibers. To highlight the different approaches between cement or lime stabilization and fiber stabilization, the latter is sometimes referred to as "fiber-reinforced" rammed earth [16], instead of "fiber-stabilized". It is important to distinguish, nevertheless, whether fibers are used in the form of single short pieces included in the earth mixture or if they are use in the form of fabrics acting as external or internal structural reinforcements [42–44]. Considering the enormous variety of plant aggregates and natural fibers that have been commonly added to earthen construction materials since antiquity [1, 45], it is difficult to establish a comprehensive list or classification; however, Laborel-Préneron et al. [17] proposed to group them in eight categories: cereal straws, wood aggregates, bast fibers, palm tree fibers, waste and residues, leaf fibers, aquatic plant fibers and chips, and sheep wool. Over the last years, some authors have also proposed the stabilization of RE with non-natural fibers, such as as fiberglass [22], polypropylene fiber [46] or waste tire fibers [47], although they have very small use yet and the knowledge regarding their mechanical effects on RE is still limited.

2.2. Soil

Stabilization techniques can be used to improve the mechanical properties of a soil that initially would not be appropriate for RE construction. However, if the goal is to obtain an excellent mechanical performance, the soil should meet some requirements. Burroughs [4] recommended, for cement or lime stabilization, using a soil with linear shrinkage lower than 11 % according to Australian Standard [48], sand content lower than 64 % and fine particles preferably between 21 % and 35 %.

These values of the particle size distribution are in agreement with the ones proposed by Maniatidis and Walker [18] for URE (clay and silt combined between 20 % and 35 % and sand between 50 % and 75 %) and with the envelopes recommended by Houben et al. [49], which are frequently used in URE literature [50]. Maniatidis and Walker [18] also noted that, in order to optimize the benefits of stabilization, soil should mainly consist of sand and fine gravel, with only enough clay to provide cohesive strength and a percentage of silt to act as void filler. As the additive is acting as a binder in SRE, the binding effect of clay is not as important as for URE, and also the presence of clay generally impedes effectiveness of cement stabilization. According to The Australian Earth Building Handbook [51], when using lime as stabilizer the ideal soil should have a plasticity index from 20 % to 30 % and liquid limit between 25 and 50, so lime would be particularly appropriate for stabilization of expansive soils [52].

Also, for SRE, soil should generally be free of humus and plant matter to prevent later deterioration; although under certain conditions, plant matter such as dry straw could be added [53].

2.3. Moisture content and density

The moisture content during manufacturing is known to be an important factor for the strength development of RE [15]. Generally, a value close to the optimum moisture content (OMC), which allows the maximum dry density of the soil for a certain compaction energy, is chosen [50]. Walker et al. [15] recommend adding the OMC ± 1 % to 2 %, while the New Zealand Standard NZS4298 [54] indicates that the moisture content before compaction should be within 3 % of the OMC and never more than 4 % dry or 6 % wet of optimum.

This OMC is determined in most of the studies via Standard or Modified Proctor tests. The Modified Proctor test uses higher compaction energy so the OMC obtained is slightly lower, which, according to some authors [55, 56] would be closer to the compaction effort applied in the construction of a real wall by mechanics means. However, some standards, as the aforementioned NZS4298, specify that the OMC should be obtained via Standard Proctor or equivalent. An alternative to easily assess the correct water content for the mixture is performing the so-called "drop test" [18, 51, 54, 57], consisting on compacting by hand a ball of moist soil that is then dropped onto a hard flat surface from a height of ca. 1.5 m. When the soil is too dry the ball breaks into several pieces, if it is close to the OMC the ball breaks into only a few pieces, and if the soil is too wet then the ball remains in one piece.

Despite the existing agreement in using moisture contents similar to the OMC, when additives are included it is not always easy to evaluate the OMC of the mixture. For example, for lime or cement-SRE, oven drying cannot be used to assess the water content due to the loss of non-evaporable water via chemical reactions (cation exchange, flocculation and pozzolanic reactions) [55]. Some authors, therefore, calculate the OMC of the soil (unstabilized) and directly use it for all the mixtures [35, 36, 58], or calculate the OMC of the soil and then use that value +1 % for the stabilized samples [16].

These procedural simplifications can be considered reasonable if one observes the values obtained by the authors that did vary the moisture content depending on the amount of stabilizer added: Ciancio et al. [55] obtained an OMC between 7.6 % and 9.6 % for lime contents from 0 % to 6 %, Toufigh and Kianfar [22] used a moisture content between 12 % and 13 % for cement contents from 2.5 % to 10 % and also for other additives (guar gum, pozzolanics or fiberglass), and Tripura and Singh [24] indicated water contents around 19 % for 4 % to 10 %

CSRE. It can be observed that the variation in the OMC is very small, as indicated by Hallal et al. [58], and always within the range of acceptance suggested by Walker et al. [15] and NZS4298 [54]. In fact, most studies regarding SRE use moisture values between 8 % and 14 % [3, 22, 36, 39, 41, 43, 55, 59–61], which is an interval very similar to the one observed for URE studies [50].

3. Mechanical properties

3.1. Unconfined compressive strength

The unconfined compressive strength (UCS) has always been the main parameter to characterize the mechanical behavior of RE (stabilized and unstabilized), as it happens with most brittle materials. Additives used with the aim of increasing the tensile or flexural strength of RE have also been studied but their presence in literature is much more limited.

The compressive strength is obtained via uniaxial compression tests perpendicularly to the direction of the earth layers, mainly on small cylindrical samples with diameter equal to twice the height, although cubic specimens of diverse sizes have also been used [50]. The manufacturing and testing techniques also vary, due to the lack of an international standard that prescribed the test procedure for the determination of the UCS of RE samples. It would be essential to develop a standardized test procedure for this material in order to actually make the results obtained by the diverse studies fully comparable.

Table 1 shows the UCS and elastic modulus obtained in several recent studies regarding SRE. The table shows that the most commonly used additive to maximize the compressive strength of the soil mixture is cement, sometimes combined with other additives (particularly fly ash). With high cement contents, around 10 %, it is possible to obtain very high compressive strength, over 5 MPa, meaning an improvement between 1.5 and 5 times the UCS of URE, even reaching a strength 10 MPa in some cases. Lime is also used to enhance the compressive strength of RE, but the improvement is smaller, always under 5 MPa, with common lime contents between 3 % and 5 %.

As mentioned before, the water content at manufacturing is quite homogeneous, generally between 10 % and 13 %, with only a few exceptions [24, 58] using moisture contents near 20 %.

It should be noted that available data from literature does not allow the present study to evaluate or compare the suction conditions of the samples. Nevertheless, it can be mentioned that suction is a key parameter affecting the structural integrity of RE under moisture movement and is the source of strength in URE materials [62, 63]. The influence of suction is more relevant in LSRE, while its effect is almost negligible on cement stabilization due to the disproportionate increase in strength and stiffness for the latter method.

Because of the relevance, effectiveness and widespread use of cement to improve the compressive strength of RE, it is worthwhile to specifically evaluate the relationship between cement content and UCS. Figure 2 represents the results of several studies regarding cement stabilization of RE. Although there is

Ref.	Sample [cm]	Additives (%wt)	MC [%wt]	UCS [MPa]	E [MPa]
[55]	$\varnothing 10$, $h = 20$	Lime (5)	10	1.2 (71 %)	175 (84 %)
[35]	$\varnothing 5$, $h = 10$	Lime(3)+FA(28)	14	1.3	–
[37]	$\varnothing 3.8$, $h = 7$	Cem(6)+FA(12)+BA(18)	10	2.5	118
[59]	$100 \times 160 \times 65$	Cem (10)	13	3.1	–
[16]	$\varnothing 10$, $h = 20$	Cem (6)	12	3.2 (60 %)	801 (136 %)
[36]	$15 \times 15 \times 15$	Cem (20)	13	3.3 (240 %)	–
[58]	$\varnothing 10$, $h = 20$	Lime(4)+Cem(4)	18	4.8 (272 %)	355 (788 %)
[46]	$\varnothing 10.2$, $h = 11.6$	Cem(6)	12	4.9	–
[40]	$\varnothing 4$, $h = 8$	FA(5)+CCR(7)	14	5.2	–
[22]	$\varnothing 7.5$, $h = 15$	Cem (10)	13	5.2 (133 %)	740 (417 %)
[39]	$\varnothing 10$, $h = 20$	Cem(5)+FA(5)	8	5.3 (300 %)	–
[60]	$\varnothing 7.5$, $h = 15$	Cem (10)	13	5.4 (182 %)	–
[47]	$\varnothing 7.1$, $h = 14.2$	Cem(7)+WTTF(1)	–	6.2 (65 %)	416 (22 %)
[14]	$10 \times 10 \times 10$	Cem (10)	16	6.5 (69 %)	–
[24]	$10 \times 10 \times 10$	Cem (10)	19	7.4 (575 %)	–
[61]	$\varnothing 10.4$, $h = 20$	Cem (8)	9	9.4	1166
[38]	$\varnothing 10$, $h = 20$	Cem (7)	7	10.0	–
[41]	$\varnothing 10.4$, $h = 20$	Cem (8)	10	11.1	7500

Table 1: Moisture content (MC), unconfined compressive strength and elastic modulus of SRE samples (in parenthesis improvement of UCS and E with respect to URE, when available). Mixture with highest UCS for each study. Additives abbreviations: Cem - cement; FA - fly ash; BA - bottom ash; CCR - calcium carbide residue; WTTF - waste tire textile fibers.

a significant dispersion, some conclusions can be drawn: there seems to be an upper limit for the compressive strength depending the percentage of cement (UCS [MPa] < 1.59 Cement [%] $- 0.97$) and a lower limit of ca. 2 MPa (so always above the minimum requirements indicated in most existing standards, which are between 1.3 MPa and 2 MPa [54, 64–66]); and for a certain soil and testing conditions there is a linear relationship between the cement content and the UCS of the SRE, according to all the studies in which more than two cement contents were tested.

3.2. Young modulus and Poisson's ratio

When performing uniaxial compression tests to obtain the UCS of SRE, it is common to calculate also the elastic modulus (E) of the material as the slope of the tangent line with the elastic part of the stress-strain curve [37, 47, 55, 58, 61]. Toufigh and Kianfar [22], who performed UCS test for several SRE mixtures, proposed calculating the elastic modulus according equation 1, following the procedure indicated for concrete in standard ASTM C469 [68], also used in [23].

$$E = (\sigma_2 - \sigma_1)/(\varepsilon - 5 \cdot 10^{-5}) \quad (1)$$

where σ_2 is the stress corresponding to 40 % of ultimate load, σ_1 is stress corresponding to a longitudinal strain of $5 \cdot 10^{-5}$ and ε is longitudinal strain produced by stress σ_2. However, there is not a consensus in the formulation of the elastic modulus; other authors [16] propose using the secant modulus (ratio between

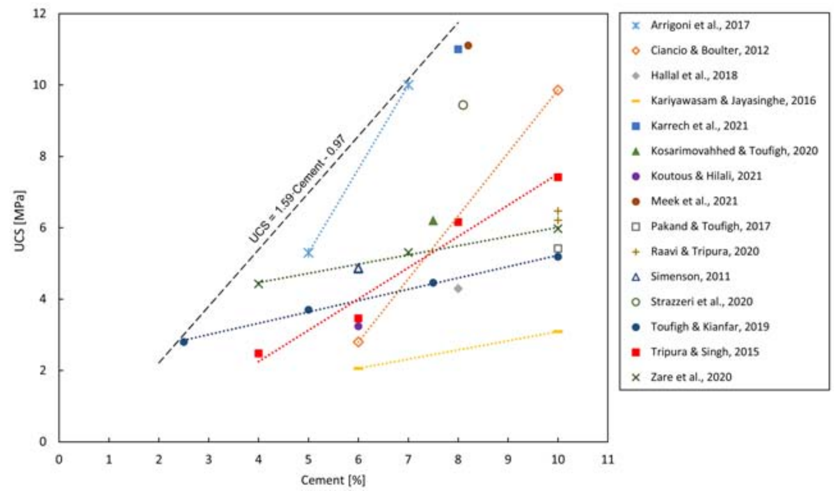

Figure 2: Unconfined compressive strength of CSRE as a function of cement content. Values obtained by Arrigoni et al. [39], Ciancio & Boulter [20], Hallal et al. [58], Kariyawasam & Jayasinghe [59], Karrech et al. [67], Kosarimovahhed & Toufigh [23], Koutous & Hilali [16], Meek et al. [41], Pakand & Toufigh [60], Raavi & Tripura [14], Simenson [46], Strazzeri et al. [61], Toufigh & Kianfar [22], Tripura & Singh [24] and Zare et al. [47].

maximum stress and corresponding peak strain) as the best parameter to describe the elastoplastic mechanical behavior of earthen materials, indicating a value of the secant modulus equal to approximately 0.62 times the initial tangent modulus for URE, CSRE and LSRE. Xu et al. [69] calculated the Young's modulus of URE performing loading-unloading triaxial test and applying the following equation:

$$E = \Delta\sigma_{xx}^{cycle} / \Delta\varepsilon_{xx}^{cycle} \tag{2}$$

where $\Delta\sigma_{xx}^{cycle}$ and $\Delta\varepsilon_{xx}^{cycle}$ are the differences in axial stress and axial strain, respectively, between the maximal and minimal load cycles.

As it can be observed in Table 1 and Figure 3, there is a significant dispersion in the values of the elastic modulus obtained by diverse studies. This dispersion is partially due to the use of different additives, but might be also caused by the variability in the manufacturing and testing techniques and also intrinsic to the heterogeneity of the material, as it was also noted for URE [50]. In Figure 3 it is also possible to observe that most studies indicate a direct relation between UCS and the elastic modulus, so E is expected to increase with increasing UCS, although the dispersion in the results does not allow to define a clear correlation.

As it happens with the compressive strength, cement is the most common stabilizer added to RE to improve its elastic modulus. Studies regarding CSRE [16, 22, 47, 58, 61] indicate elastic modulus within the range from 250 MPa to 750 MPa using cement contents between 2 % and 10 %. The same studies indicate that those values lead to an improvement of 150 % to 500 % with respect

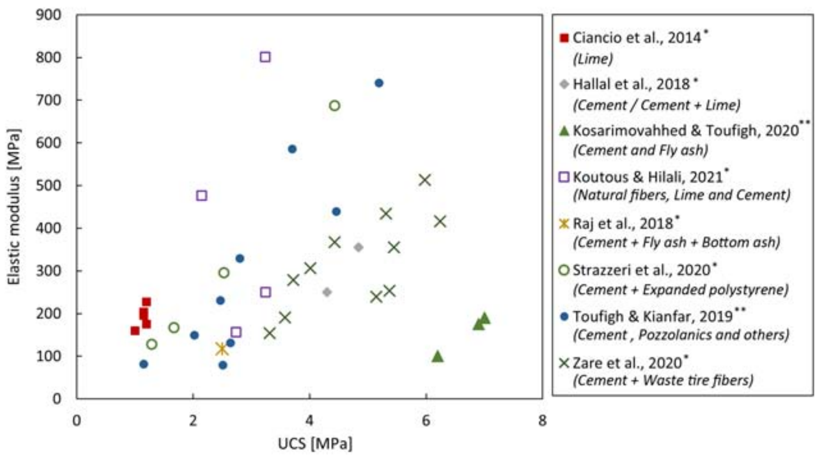

Figure 3: Elastic modulus of SRE as a function of unconfined compressive strength. Values obtained by Ciancio et al. [55], Hallal et al. [58], Kosarimovahhed & Toufigh [23], Koutous & Hilali [16], Raj et al. [37], Strazzeri et al. [61], Toufigh & Kianfar [22] and Zare et al. [47].
*Elastic modulus as the slope of $\sigma - \varepsilon$ curve in its elastic area (tangent modulus).
**Elastic modulus calculated according to Equation 1.

to URE specimens. Smaller improvements of the elastic modulus (40 % to 140 %) are obtained when using lime as stabilizer [16, 55].

Regarding the Poisson's ratio (ν), there are only a few studies calculating its value. Raj et al. [37] and Meek et al. [41] obtained values between 0.16 and 0.20 for RE stabilized with diverse additives including cement, fly and bottom ash, ground-granulated blast-furnace slag and kaolin clay, while Strazzeri et al. [61] obtained a ν value of 0.33 for CSRE with and without expanded polystyrene.

3.3. Tensile and flexural strength

Rammed earth is known to be very weak in tension, so RE elements should not be designed for pure tension [18]. However, the tensile strength (f_t) is a very relevant parameter involved in RE failure, especially under extreme loading conditions, such as earthquakes [70, 71]. These are the main reasons why several authors have tried to improve RE tensile strength by stabilization, as shown in Table 2. It can be seen that the value of f_t in these studies reaches values in the range from 0.25 to 1.16 MPa, and in most of them above 0.4 MPa, which is an improvement over URE frequently above 150 percent.

The most commonly used additive to improve RE tensile strength are fibers [17, 18], both natural (straw, palm, coir, jute, barley,. . .) [14, 16, 58] or synthetic (fiberglass, plastic fibers) [22, 47]. According to The Australian Earth Building Handbook [51], the ideal soil for fiber stabilization should have liquid limit between 30 % and 50 % and plasticity index between 15 and 35.

Fiber stabilization, however, frequently implies a reduction of the compressive strength with increasing fiber contents [47, 53]. This fact can be counterbalanced with the combined use of fibers and cement as evaluated by Zare et al.

Ref.	Sample [cm]	Additives (%wt)	f_t [MPa]	UCS [MPa]	Ratio f_t/UCS
[22]	⌀7.5, $h = 15$	Pozz(10)+Microsilica(1.5)	0.25 (4 %)	2.5 (11 %)	0.10
[58]	⌀10, $h = 20$	Cem (8)	0.33 (106 %)	4.3 (231 %)	0.08
[14]	$10 \times 10 \times 10$	Coir fiber (3)	0.39 (179 %)	4.1 (7 %)	0.10
[16]	⌀10, $h = 20$	Lime (4)	0.40 (0 %)	2.2 (6 %)	0.18
[16]	⌀10, $h = 20$	Cem (6)	0.45 (13 %)	3.2 (60 %)	0.14
[16]	⌀10, $h = 20$	Palm fiber (0.75)	0.45 (13 %)	3.3 (60 %)	0.14
[3]	$44 \times 10 \times 10$	Lime (25*)	0.49	–	–
[16]	⌀10, $h = 20$	Barley fiber (0.75)	0.50 (25 %)	2.7 (35 %)	0.19
[22]	⌀7.5, $h = 15$	Fiberglass (1.5)	0.53 (121 %)	2.5 (13 %)	0.21
[47]	$40 \times 10 \times 10$	WTTF (4)	0.68 (155 %)	3.3 (−12 %)	0.21
[22]	⌀7.5, $h = 15$	Cem (10)	0.77 (221 %)	5.2 (133 %)	0.15
[47]	$40 \times 10 \times 10$	Cem(7)+WTTF(4)	0.89 (231 %)	5.2 (36 %)	0.17
[58]	⌀10, $h = 20$	Cem(4)+Lime(2)+HF(1.25)	0.96 (500 %)	–	–
[14]	$10 \times 10 \times 10$	Cem(10)	0.99 (607 %)	6.5 (69 %)	0.15
[14]	$10 \times 10 \times 10$	Cem(10)+Coir fiber(3)	1.16 (729 %)	6.2 (63 %)	0.19

Table 2: Tensile strength (f_t) and unconfined compressive strength of SRE samples (in parenthesis improvement of UCS and f_t with respect to URE, when available). Additives abbreviations: Pozz - pozzolanics; Cem - cement; HF - hemp fiber; WTTF - waste tire textile fibers. *Percent by volume.

[47] who tried different combinations with diverse contents of cement and waste tire fibers. Actually, the highest f_t values, according to literature, are obtained adding both fibers and cement to the soil mixture [14, 47, 58].

The improvement of RE tensile strength also leads to an increase in the f_t/UCS ratio. If this ratio was approximately equal to 0.10 for URE [50], it raises to between 0.10 and 0.21 in the case of SRE.

There are few studies regarding the flexural strength of RE materials, both unstabilized and stabilized. Jayasinghe and Mallawaarachchi [72] performed four-points bending tests in URE walls obtaining a value of 0.46 MPa when the load was applied parallel to the layers and 0.92 MPa if perpendicular. Ciancio and Augarde [73] performed the same tests obtained values of flexural strength similar to the latter, between 0.80 and 1.00 MPa.

With the aim of improving the flexural strength of RE, authors have proposed using fiber reinforcements. Tripura et al. [74] carried out four-points bending tests (parallel and perpendicular to the earth layers) on RE samples combining cement stabilization, cocoa fiber reinforcement (short fibers mixed in the matrix) and bamboo external reinforcements. All combinations of additives resulted in an increase of the flexural strength if compared with URE; the maximum values were reached with combining all three additives, reaching 1.29 MPa for parallel loading (+139 % with respect to URE) and 2.11 MPa for perpendicular loading (+167 %). Also Vernat-Maso et al [42] performed three-points bending tests to analyze the effect of textile reinforcement in the flexural behavior of rammed earth, concluding that, when the failure mode was not associated with the possible least earth-grid adherence, the reinforced specimens showed a greater load-bearing capacity than that of the unreinforced ones, with an increase in the maximum bending moment of ca. 94 %.

These results indicate that fiber reinforcements (both internal short fibers or structural fabrics) may be very useful to enhance the flexural behavior of RE elements, although further studies would be necessary to draw general conclusions. Also, regarding fabric reinforcements, it essential to ensure the proper adhesion between the reinforcement and the soil matrix in order to obtain the desired improvements in the mechanical behavior of the compound [43].

3.4. Shear strength, cohesion and fracture energy

Rammed earth presents very low shear strength [50], so for RE walls it is frequently considered close or equal to zero in absence of further experimental data [51, 75]. Although there are currently no studies regarding the enhancement of RE shear strength through additivation, some few studies have evaluated the shear behavior of CSRE.

Lepakshi and Venkatarama [76] carried out triaxial compression tests on several RE cylindrical specimens with cement contents from 4 % to 15 %. The results indicate that increasing cement contents lead to an increase in the shear strength (from 0.59 MPa with 4 % cement to 2.18 MPa with 15 % cement). This last value is much higher than common shear strengths indicated by several authors for URE (0.15–0.85 MPa) [70, 77–79].

Pavan et al. [80] performed diagonal compression tests on 10 % CSRE panels according to ASTM-E519 [81] using two different techniques to improve the bond between layers: making blunt conical shaped dents and applying a coat of fresh cement slurry. The shear strength obtained in both cases was equal to 1.24 MPa.

These two studies also evaluated the cohesion and friction angle of CSRE, obtaining the results shown in Table 3. Particularly interesting are the results of Lepakshi and Venkatarama [76], indicating that cohesion linearly grows with increasing cement contents while the angle of internal friction remains almost invariant and equal to ca. 50° for cement contents over 7 %. Also Kosarimovahhed and Toufigh [23] evaluated the cohesion of cement and lime SRE, obtaining a maximum of 1 150 kPa with a combination of 2.5 % cement and 5 % lime.

According to the values of these few studies, shown in Table 3, cement seems to significantly increase the cohesion of RE, which is in the range from 30 kPa to 260 kPa for URE [50]. The increments in the values of the friction angle, on the other hand, are almost negligible.

There are still only a few studies evaluating the fracture energy (G_f) of RE, but all of them indicate that the fracture energy of RE could be improved by chemical additivation (lime or cement). Three-points bending tests and splitting tensile tests were performed to determine this parameter. Arto et al. [3] identified a clear correlation between the fracture energy and the soil-lime ratio, reaching values over 30 N/m with 25 % vol lime. Corbin and Augarde [82] obtained an approximately linear relationship between G_f and cement content, from only 1.5 N/m for URE to 36 N/m for 10 % CSRE. Higher values were reported by Sajad and Toufigh [63]: $G_f = 20$ N/m for URE and $G_f = 63$ N/m for 10 % CSRE.

Ref.	Cement [%wt]	Lime [%wt]	f_s [MPa]	c [kPa]	φ [°]
[76]	4.0	–	0.59	480	27
	7.0	–	1.16	640	55
	10.0	–	1.67	940	52
	15.0	–	2.18	1320	46
[80]	10.0[a]	–	1.24	794	26
	10.0[b]	–	1.24	762	49
[23]	7.5	–	–	205	–
	5.0	2.5	–	490	–
	–	7.5	–	805	–
	2.5	5.0	–	1150	–

Table 3: Shear strength (f_s), cohesion (c) and friction angle (φ) of SRE.
[a]Blunt conical shaped dents between layers.
[b]Coat of fresh cement slurry between layers.

According to these investigations, other additives, such as pozzolan, microsilica, guar gum, fiberglass or PCM do not significantly affect the fracture energy [63]; while the addition of wool decreases the G_f values over a 50 % [82].

4. Insulating properties

4.1. Thermal insulation

URE provides an acceptable thermal insulation, with a thermal conductivity (λ) between 1.0 and 1.4 $\mathrm{Wm^{-1}K^{-1}}$ [50], similar to traditional ceramic bricks [1, 83] and better than other common construction materials such as concrete [83]. Considering this, most studies regarding RE stabilization have focused their efforts on improving the mechanical properties and not so much the thermal behavior.

However, it is possible to enhance the thermal performance of RE walls by incorporating thermal energy storage materials, that store energy by sensible or latent heat, such as expanded polystyrene (EPS) or phase change materials (PCM) [60]. This additives can significantly reduce the thermal conductivity of RE, obtaining λ values lower than 0.4 $\mathrm{Wm^{-1}K^{-1}}$, as shown in Figure 4 (left).

Karrech et al. [67] reached a 62 % reduction of the thermal conductivity of CSRE with a 20 %vol of polystyrene composite (expanded polystyrene beads coated with a bituminous binding agent); and Pakand and Toufigh [60] reduced λ by 24 % using 20 %vol EPS. If PCM are used (about 10 %), the reduction of the thermal conductivity is between 15 and 20 % [60, 84].

The problem with this kind of additives is that they significantly worsen the mechanical performance of the RE structure, causing a decrease in the UCS (Figure 4 (right)). However, when high compressive strengths are important, it should be noted that Pakand and Toufigh [60] indicated that cement stabilization also provides a certain improvement in the thermal behavior, while increasing the mechanical properties.

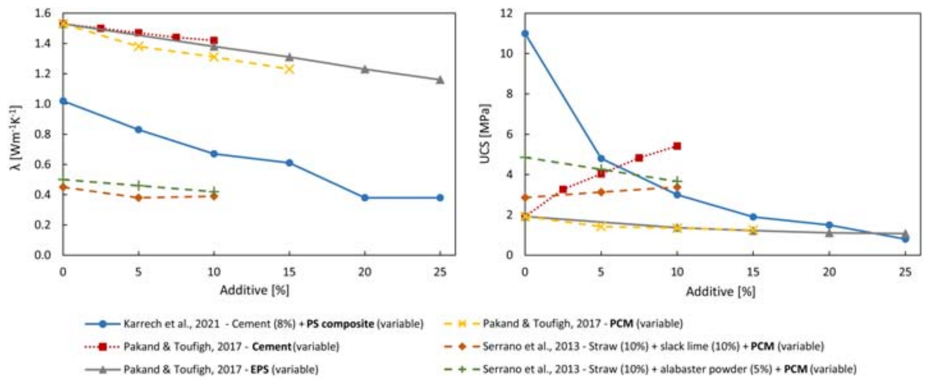

Figure 4: Stabilization of RE for the improvement of thermal conductivity (left) and its effect on UCS (right). Values obtained by Karrech et al. [67], Pakand & Toufigh [60] and Serrano et al. [84].

The effect of moisture content on the thermal behavior of RE should also be taken into account. It has been observed that the thermal conductivity of CSRE linearly increases with the saturation ratio of the material, due to the formation of menisci acting as thermal bridges between particles in partially saturated soils [85, 86].

4.2. Acoustic performance

As with the thermal behavior, URE shows a very good acoustic performance, and therefore it has not been a priority of researchers to study the improvement of this characteristic via additivation. URE has a sound reduction index (R) of about 57 dB for 30 cm to 50 cm-thick walls [15, 87–89], and its porosity provides an excellent reverberation behavior, generating far fewer harsh echoes than other common wall materials [87, 90, 91].

No studies in literature have been found specifically regarding the improvement of these acoustic properties, but deeper investigation in this field would be necessary. In the absence of further research, it would be possible to enhance the acoustic insulation by covering the RE walls with insulating panels, as it is done for any other type of wall.

5. Durability

RE construction are quite sensitive to rain and wind erosion and to the effect of aggressive environments, so they frequently need some kind of protection against weathering [19, 92–94]. This protection can be obtained with external barriers (waterproofing agents or sloping roofs) or through additivation.

Some studies indicate that the use of cement significantly improves the durability of RE against water erosion. Arrigoni et al. [19] measured the accelerated erosion due to sprayed water and mass loss due to wire brushing on URE and SRE mixtures with 5 % cement + 5 % FA and 6 % CCR + 25 % FA, observing that both SRE mixtures (but not URE) passed the tests and achieved sufficient strengths for construction according to The Australian Earth Building Handbook [51]. Also Narloch and Woyciechowski [95] performed water erosion resistance tests on URE and 6 % and 9 % CSRE according to New Zealand Standard NZS 4298 [54], obtaining that none of the CSRE samples showed any surface damage while all the URE specimens had deep cavities despite their shorter exposure time in water, concluding that in a humid continental climate the use of URE is unsuitable due to lack of durability.

However, some studies evaluating the long-term durability (over 20 years) of RE against water, suggest that external protection is needed also for CSRE [96] or even that the stabilization by cement or lime might be inadequate [97].

Erosion is the major cause of concern for earthen structures, but aggressive environments may also decrease the durability of RE. Although additional durability issues (e.g. alkali-aggregate reactions and sulfate induced swelling) could be expected when cement-like additives are used [19], Ghasemalizadeh and Toufigh [92] concluded that the presence of a sufficient amount of cement improves the behavior of RE in sulfate, alkaline and acidic environments. These authors observed that 7.5 % and 12.0 % CSRE remained integrated after 1 year of exposure to the aforementioned environments, while 2.5 % CSRE disintegrated after 6 months of exposure to sulfate and alkaline environments and 9 months in an acidic environment. The sulfate solution was observed as the most destructive environment for RE materials. Luo et al. [98] also measured a reduction of RE compressive strength and cohesion in the presence of sodium chloride, sodium sulfate and calcium chloride, which was much more severe when the sodium sulfate and calcium chloride were applied simultaneously.

Finally, Narloch and Woyciechowski [95] evaluated durability of RE against frost-defrost cycles. The study concluded that a minimum of 9 % cement is needed to reach the frost resistance level required by European Standard EN 206:2013+A1:2016 [99]. According to this research, the presence of gravel in the particle size distribution of the earthen material also plays a key role in the frost resistance of CSRE.

6. Environmental and economic impact of stabilization

6.1. Environmental cost

One of the main benefits of rammed earth construction, and also one of the most important reasons why this technique is experiencing a significant growth over the last years, is its very limited environmental impact [1, 13, 15, 100]. This is due to the fact that the source material is raw earth that can be frequently obtained in the construction site and which needs very low industrial processing, reducing resource and energy consumption, pollution and waste generation.

However, when the mechanical properties of raw earth are not enough to reach the required standards and so additives are included to the mixture, some of the aforementioned environmental advantages are severely reduced. Two of the main indicators that may help understanding how environmentally friendly a construction technique is are the CO_2 emissions and the embodied energy, and both parameters significantly increase for SRE compared to URE, as it is shown in Table 4.

	CO_2 emissions		Embodied energy	
Additives	Values [kg]	Ref.	Values [MJ]	Ref.
None (URE)	3–9	[60, 100]	49	[19]
2.5 % cement	42	[60]	–	
4 % cement	–		280	[9]
5 % cement	86	[60]	–	
6 % cement	–		400	[9]
7.5–8 % cement	131	[23, 60]	500	[9]
10 % cement	179	[60]	630	[9]
12 % cement	–		750	[9]
5 % cement + 2.5 % FA	129	[23]	–	
5 % cement + 5 % FA	–		155	[19]
2.5 % cement + 5 % FA	120	[23]	–	
7.5 % FA	106	[23]	–	
25 % FA + 6 % CCR	–		68	[19]
20 %vol EPS	18	[60]	–	
10 % PCM	1630	[60]	–	

Table 4: CO_2 emissions and embodied energy per cubic meter of RE.

When cement or other industrially manufactured products are used as stabilizers, the environmental costs increase due to the manufacturing process and the transportation distance. Actually, the embodied energy of CSRE walls linearly increases with the cement content [9]; and, for example, a 8 %-cement SRE wall implies more than 14 times the CO_2 emissions and 10 times the embodied energy than the same wall made with URE (Table 4). Nevertheless, the embodied energy in CSRE is only about 15 % to 25 % of the embodied energy in common brick masonry [9].

Although other factors, such as a higher presence of clay or an increase in the required compaction level, may affect the energy consumption, their contribution to the total energy expenditure of the whole process is negligible if compared to the energy content of cement [9]. This is the reason why several recent studies aiming to develop an eco-friendly RE with greater mechanical properties than traditional URE have tried to replace cement or lime with natural stabilizers or waste materials.

Despite the fact that many studies have recently presented alternative additives as a sustainable way to improve RE mechanical characteristics, the huge differences in the methodologies applied to measure the environmental benefits (or even its absence) make it very difficult to compare the results.

One of the most common and direct ways to reduce cement consumption in RE construction is replacing it with CCR and/or FA, which significantly reduces the cumulative energy demand especially if the CCR is a waste, in which case the environmental impacts of URE and SRE are similar when local soil is not suitable by itself for construction [19]. Although the UCS is generally lower when replacing cement with CCR and FA [19, 40], Kosarimovahhed and Toufigh [23] obtained that a combination between cement and alkali-activated FA could lead to a higher strength than only cement, while reducing the CO_2 emissions.

Other waste materials or industrial by-products have been tested, such as crushed brick and concrete from demolition, ground granulated blast furnace slag, silica fume, bottom ash or granitic residual soils [37, 38, 41, 57]. The use of this kind of materials helps reducing the amount of industrial waste products ending up in landfills and minimizing the material and energy consumption and waste generation due to the manufacture process of stabilizers. In addition, natural fibers could be also considered as useful additives for RE, as they have been traditionally used to improve the mechanical behavior of earth constructions and have a small impact in the environmental cost [16, 17].

6.2. Economic impact

Economic and environmental costs are strongly related when considering the stabilization of RE, as the manufacturing process of the stabilizers and the need for transportation not only reduces the sustainability of the construction technique, but also has a significant economic impact. Table 5 shows the cost of some SRE mixtures according to literature (Labor and transportation costs not included).

Additive	Ref.	Cost [$/t RE]
None (URE)	[60]	3.51
2.5 % cement	[60]	4.16
5 % cement	[60]	4.81
7.5 % cement	[60]	5.46
7.5 % cement	[23]	11.25
10 % cement	[60]	6.11
5 % cement + 2.5 % FA	[23]	10.88
2.55 % cement + 5 % FA	[23]	10.47
7.5 % FA	[23]	9.95
15 % EPS	[60]	4.94
10 % PCM	[60]	653

Table 5: Material cost per tonne of RE.

Analyzing the results obtained by Pakand and Toufigh [60], it is possible to observe that the ratio cost-UCS significantly decreases from URE to 2.5 % CSRE and then gradually stabilizes for increasing cement contents, reaching a value of 1.13 $/(MPa · t) (Figure 5). This means that the increase in the cement content (and therefore the cost) leads to a greater strength gain at the beginning but this effect is much less significant for higher cement contents. It must be noted that transportation and labor costs are not included, only the cost of the materials.

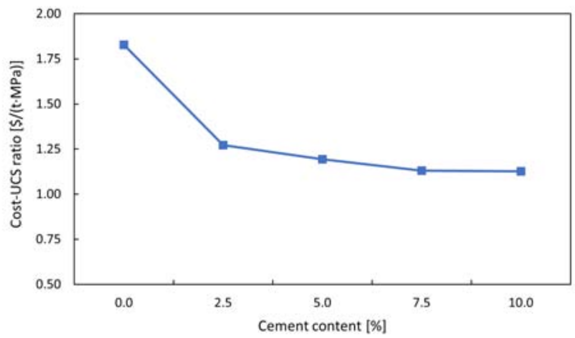

Figure 5: Cost-UCS ratio of RE as a function of cement content. Data: [60].

Defining a single value for the economic impact of stabilizers is not possible due to the great variability in the source material, labor and transportation costs in the different countries, but more thorough investigation may help understanding the relationship between the increase in the costs and the improvements obtained for the material. This applies also to the environmental costs of RE stabilization.

7. Conclusions

Introducing rammed earth construction technique in new buildings implies a need to meet the requirements defined in the current construction standards, and this is the reason why stabilization is becoming increasingly important in RE construction. This study presents a review of the most relevant properties of stabilized rammed earth and their impact in the environmental an economic cost of the technique.

It has been observed that the use of cement is widespread in RE construction, making it possible to achieve high values for some of the most relevant mechanical properties, such as the compressive strength and stiffness, although its negative effect in the environmental performance of the material is frequently not taken into consideration. Recent studies, though, have evaluated the addition of alternative more eco-friendly stabilizers (fly or bottom ash, natural fibers, . . .), frequently used together with cement in order to improve the mechanical behavior and reduce the environmental impacts.

Natural o synthetic fibers are often the solution if the parameter to be enhanced is tensile, flexural or shear strength, although cement and other additives are also used. Rammed earth shows low values of these properties, but they are essential in the behavior and failure of RE elements.

The main conclusions obtained in the present study are listed below:

- There exist several additives that can be included in the mixture, but cement is by far the most common and most thoroughly studied.
- The soil and water content used for SRE is similar to those used for URE, not very specific characteristics are required.
- Cement is frequently used to improve the UCS of RE, with an increase from 60 % to 250 % in most studies compared to URE. The relationship between cement content and UCS seems to be approximately linear. Cement is frequently combined with FA.
- Increasing cement contents lead to an increase in the elastic modulus, but the relationship is not so clear and some dispersion is observed.
- RE tensile strength is usually improved by the use of natural or synthetic fibers. It is observed, however, that increasing fiber contents frequently imply a reduction of the compressive strength, which is sometimes counterbalanced combining fibers and cement.
- Thermal insulation can be enhanced using thermal energy storage additives, such as EPS or PCM, reducing the thermal conductivity over a 15 %. It must be noted, however, that this kind of additives significantly worsen the mechanical behavior of RE. The enhancement of the acoustic properties of RE, on the other hand, has not be thoroughly studied yet.
- Some studies indicate that the use of cement can improve the durability of RE against water erosion, aggressive environment and frost-defrost cycles. The effect of other stabilizers on RE durability remains to be studied.
- The use of stabilizers significantly increases the environmental and economic cost of RE construction, due to the manufacturing process and transportation distances. This impacts can be reduced by replacing industrial stabilizers, such as cement, by industrial by-products (e.g. FA, bottom ash or crushed bricks) or natural additives (e.g. natural fibers).
- Standardizing the testing procedures would be essential to obtain comparable values of the mechanical parameters of rammed earth.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Spanish Ministry of Universities via a doctoral grant to Fernando Ávila (FPU18/03607).

The study is part of the project "*Revalorización Estructural del Patrimonio Arquitectónico de Tapial en Andalucía*" (Structural Revaluation of the Rammed Earth Architectural Heritage in Andalusia), ref. A-TEP-182-UGR18, within the framework of the European Regional Development Fund Program of Andalusia 2014-2020, and has been carried out in the Research Group TEP167 "Solid and Structural Mechanics" Laboratory.

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F. Ávila, E. Puertas, R. Gallego, *Mechanical characterization of lime-stabilized* rammed earth: Lime content and strength development. Construction and Building Materials. 350 (2022) 128871. doi: 10.1016/j.conbuildmat.2022.128871.

Mechanical characterization of lime-stabilized rammed earth: lime content and strength development

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Abstract

Earth construction techniques, such as rammed earth, are present worldwide due to the availability of the material and its mechanical performance. Today they are also attracting attention as an environmentally friendly way of building, although additivation is usually needed. Lime stabilization is an interesting option with long tradition, well-known capacity to improve soil properties and limited environmental impact. This study evaluates the effect of increasing lime contents in the compressive strength and stiffness of rammed earth, and analyses the strength development process of the material. Carbonation depth and ultrasonic pulse velocity are also evaluated due to their relationship with the mechanical behavior. The results show that 12 % lime maximized the compressive strength and stiffness of the rammed earth material; the strength was mostly developed during the first month but needs over a hundred days to be fully developed. A good linear correlation between the ultrasonic pulse velocity and the compressive strength is observed.

Keywords: rammed earth, lime stabilization, strength development, mechanical characterization, carbonation, ultrasonic pulse velocity

1. Introduction

The construction sector, nowadays, is well aware of the severe environmental impact caused by its activities, including resource consumption, waste generation and pollution. This situation, which is getting worse over the years due to the increasing demand for housing as the global population grows, has drawn the attention of builders and researchers to non-conventional construction techniques and materials with lower environmental impacts. One such technique, with very long tradition and a promising future, is rammed earth (RE) [1–4].

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RE building technique consist of compacting, between formwork, 7 to 15 cm-thick layers of sandy soil mixed with a certain amount of water in order to create walls with a thickness of 30–60 cm [5–8]. Natural soil can be directly used to build RE structures, leading to the so-called unstabilized rammed earth (URE), with clay acting as the only binder; but when higher strength or durability are required it is common to add different kinds of additives to the mixture. This technique is called stabilized rammed earth (SRE).

One of the additives with longest tradition for rammed earth stabilization is lime, existing several examples of historic constructions made of lime-stabilized rammed earth (LSRE) [6, 9–13]. The RE used in these heritage buildings usually contained very significant percentages of lime, e.g., between 10 % and 15 % in the medieval walls of Seville (Spain) [14] and in traditional RE houses in Southern Portugal [15], 20 % in the Alcazaba Qadima and the Alhambra of Granada (Spain) [10, 16], also 20 % in the Saadian sugar refinery of Chichaoua (Morocco) [9], and ca. 25 % in the Fujian Tulou (China) [17] or in the Cáceres city walls (Spain) [14].

There is also a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [18–22]. When lime is added to a soil, the concentration of Ca^{2+} and OH^{-} increases due to the hydration reaction of lime. This generates the flocculation of particles (affecting soil plasticity) and increases the pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [19, 23, 24].

However, and despite its historical use, today lime has been superseded by cement as the most common stabilizer for rammed earth [25], and as a consequence there is a lack of scientific research specifically analyzing the effects of lime stabilization in the mechanical properties of RE. Ciancio et al. [7] carried out a study evaluating the optimum lime content for LSRE, obtaining a value equal to 4 % by weight, but lime contents greater than 6 % were not considered. Da Rocha et al. [26] also analyzed LSRE materials, from 3 %wt to 9 %wt, concluding that the uniaxial compressive strength increased with increasing lime contents and indicating the need of long curing times. Also Canivell et al. [27] and Arto et al. [28] have recently evaluated the compressive strength and fracture energy, respectively, of RE materials stabilized with high percentages of lime.

Understanding the mechanical behavior of LSRE is essential in order to properly preserve the large number of heritage buildings made with this technique, but also because of its potential benefits in the development of an environmentally-friendly way of constructing. Lime is considered to be a much less energy-intensive binder compared to the frequently used Portland cement [7], as its manufacturing temperature is significantly lower (ca. 900 °C as opposed to 1 500 °C) [29], which reduces the CO_2 emissions during production. It is estimated that ca. 0.9 t of CO_2 are produced per tonne of cement, while the manufacturing process of lime produces less than 0.7 t of CO_2 per tonne of lime [30–33]. In addition, the carbonation reaction (through which lime uptakes atmospheric CO_2) during the lifetime of the building can counterbalance the carbon emissions generated in the manufacturing and transportation process, leading to a reduction of the net carbon footprint of lime-stabilized materials [29, 34, 35].

Against this background, this study presents an analysis of the effect of lime stabilization in the mechanical behavior of rammed earth, evaluating the compressive strength and stiffness of the material with diverse lime contents and analyzing its strength development process.

2. Materials

2.1. Soil

The main source material used for the RE in this study was a natural soil from a quarry in Padul (Granada, Spain), classified according to the European Soil Classification System (ESCS, ISO 14688-2:2018) as clayey well-graded sand, after been passed through a 10 mm sieve in order to remove the coarser particles. The particle size distribution of the resulting earthen material is shown in Figure 1, been in agreement with recent studies regarding rammed earth stabilization [36–38] and fitting withing the envelope recommended by Houben et al. [39], widely accepted for URE construction and frequently used also for SRE [25]. The soil had chloride and sulfate contents lower than 0.002 % and was free of organic matter and light contaminants. This soil can be considered to be representative of the material traditionally used in RE construction in Southern Spain [13, 14, 16, 28, 40].

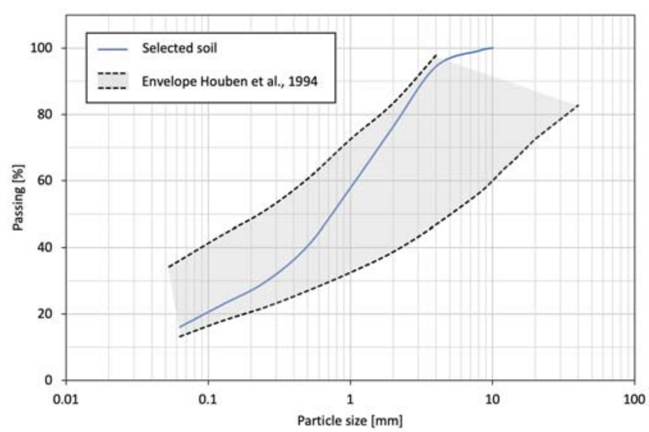

Figure 1: Particle size distribution of the soil.

2.2. Lime

Natural hydraulic lime with minimum compressive strength of 3.5 MPa at 28 days, referred to as NHL 3.5 according to European standard EN 459-1:2015, was used as stabilizer. The main components of NHL are portlandite, reactive silicates and aluminates formed during calcination from the reaction of crushed limestone containing clay or other impurities. Table 1 shows the most relevant chemical and physical properties of the lime used in the present study.

Parameter	Avg. value
SO_3 [%]	1.7
Free lime, $Ca(OH)_2$ [%]	30
Free H_2O [%]	0.7
Residual at 90 µm [%]	5.7
Residual at 200 µm [%]	0.8
Bulk density [kg/dm^3]	0.671
Real density [kg/cm^3]	2.51
Blaine value [cm^2/g]	8500
Setting time [min]	296
End of taking [min]	438
Compressive strength at 28 days [MPa]	4.8

Table 1: Chemical and physical properties of the natural hydraulic lime used in the study, as indicated by the manufacturer.

3. Experimental procedure

3.1. Specimen preparation

In order to perform the experimental tests, 10 cm-side cubic LSRE specimens were manufactured. It is generally assumed that the size and shape of the samples may affect the mechanical properties obtained [5], although the relation between these parameters is still unclear and it is out of the scope of this paper. Similar geometries to the one used for the samples in the present study have been previously used by several authors [3, 27, 36, 41–44].

In order to define the correct amount of water to be added to the mixture, Modified Proctor tests (UNE 103501 [45]) were performed on specimens with diverse lime contents. Modified Proctor is a widely established and easily repeatable test that provides a compactive effort very close to the one that might be applied in the construction of a real wall [7, 41]. It was observed that greater amounts of water were needed in order to obtain the maximum dry density (MDD) with increasing lime contents, that is to say, the optimum moisture content (OMC) linearly increased with the lime content. However, this increase in the OMC with the lime content is quite small (equal to ca. 3 %), as it was noted by Ciancio et al. [7], that reported variations lower than 2 % for lime contents between 0 % and 6 %. Furthermore, other authors [26, 46, 47] propose using constant OMC regardless the lime content, as they indicate that the variation is negligible. The results of the compaction tests also showed that the MDD of the LSRE decreases with the increase in lime content, in a very pronounced way for small lime contents and then gradually stabilizing. The variation of the OMC and MDD as a function of the lime content is shown in Figure 2.

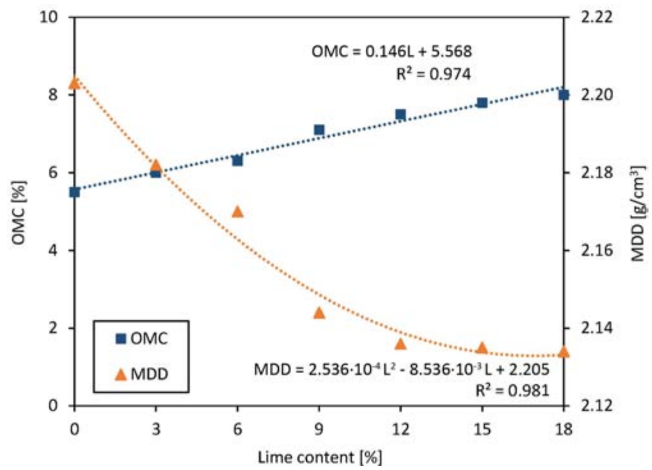

Figure 2: Optimum moisture content and maximum dry density, from Proctor test, as a function of the lime content.

The material was prepared by uniformly mixing the natural soil with a certain amount of lime. Water was added to the mixture until reaching a water content equal to the OMC+2 %, following the recommendations of Walker et al. [4] and the New Zealand Standard NZS-4298 [48].

The mixture was then poured into cubic molds and compacted by layers of ca. 2 cm, so each specimen was made up of five earth layers. The small thickness of the layers was chosen in order to provide a more uniform compaction and to reach a high compaction level by manual means. The material was compacted to 98 % of the MDD, according to NZS.4298 [48]. Once the upper layer was compacted and its surface smoothed, the samples were carefully removed from the mold and stored on wire racks, so all the faces could be in contact with the environment. The specimens were cured under constant conditions of about 25 °C and 40 % relative humidity, replicating common natural ambient conditions in Southern Spain.

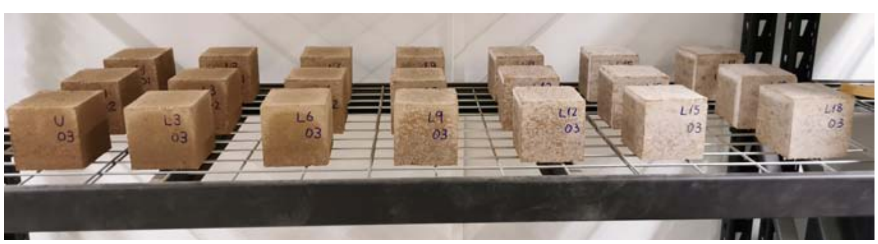

Figure 3: Some of the LSRE specimens, with different lime contents, stored on wire racks during the curing period.

3.2. Experimental evaluation

The uniaxial compressive strength (UCS) and stiffness of the LSRE specimens were determined performing uniaxial compression tests, applying a homogeneously distributed load on the upper face of the sample, perpendicular to the direction of the earth layers. The tests, in the absence of specific standards for RE testing, were performed according to European Standard EN 12390-3 "Testing hardened concrete. Part 3: Compressive strength of test specimens" [49]. A linear variable differential transformer (LVDT) was used to measure the longitudinal displacements for the calculation of the stiffness modulus. In the first part of the study, UCS tests were carried out on specimens with increasing lime contents, from 0 % to 18 % every 3 %.

Once the results were evaluated, more samples were manufactured with the lime content that led to a better mechanical performance (i.e. 12 %). These specimens were subjected to UCS tests at different curing times, from 2 to 100 days, with a minimum of three specimens per curing time. The time intervals between the tests were smaller during the first weeks (every 2–5 days), as a greater variation of the mechanical properties was expected –and observed–, and longer for older specimens (every 10 days approx.). After the compression tests, the depth of the carbonation front in the specimens was measured by using phenolphthalein solution 1 % in ethanol as indicator, carefully cleaning the surfaces before testing using a compressed air gun. The carbonation depth is measured using a sliding gauge at 3 to 5 equidistant points on each of the four faces on a slice of the specimen, perpendicularly to the exposed surface of the cube, as indicated in standard EN-12390-12 [50]. The carbonation depth considered to be representative of the specimen was obtained as the average of those measurements.

During the curing period, the specimens were periodically weighted to control the loss of moisture, and subjected to ultrasonic pulse velocity (UPV) tests. UPV method is one of the non-destructive testing techniques whit a longest tradition for assessing the mechanical properties and inner cracks of building materials. A ultrasonic device, consisting of a transmitting and a receiving transducer, was used to measure the time of pulse of ultrasonic waves over a known path length [51]. Although UPV method has been widely used for concrete, metal of wooden materials, only a few recent studies have applied it to determine RE mechanical properties [27, 43]. The UPV was measured for the manufactured LSRE specimens in a direction parallel to the earth layers.

4. Results and discussion

4.1. Stress-strain behavior

The compressive behavior of RE specimens was obtained from the compression tests carried out according to standard EN 12390-3 [52], as mentioned above. This standard indicates that the results of the tests can be considered valid if all four exposed faces are cracked approximately equally, generally with little damage to faces in contact with the platens, as shown in Figure 4.

Figure 4: Satisfactory failures of cubic specimens, according to EN 12390-3 [52].

Stress-strain curves were obtained from uniaxial compression tests for the specimens with different lime contents after 28 days of curing. Figure 5 shows the stress-strain curves of all tested samples. It is possible to observe that, for almost all the specimens, at the beginning of the test, the material suffers significant strains for small load increments, while the earth particles are settling and so the fine grains fill the empty spaces between the coarser ones. Then, at ca. 0.01 mm/mm strain, the stiffness significantly increases and the material shows linear behavior until approximately 75 % of the maximum stress. This linear phase, however, also comprises plasticity due to the formation of microcracks, so it cannot be considered as linear-elastic [47, 53–55]. This is followed by a plastic phase with a reduction of the stiffness until maximum stress is reached, then crack propagation occurs rapidly until failure.

4.2. Compressive strength and stiffness

According to the evaluation of the stress-strain curves obtained from the experimental tests, the material shows a linear behavior approximately between 35 % and 75 % of the maximum stress, so the stiffness modulus (E) of the samples was calculated according to the following equation, which is based on the formulation proposed in ASTM C469 [56] for concrete samples, and used for rammed earth in previous studies [36, 38]:

$$E = (S_{75} - S_{35})/(\varepsilon_{75} - \varepsilon_{35}) \quad (1)$$

where S_{35} and S_{75} are the stresses corresponding to 35 % and 75 % of the maximum stress, respectively; and ε_{35} and ε_{75} are the longitudinal strains produced by stresses S_{35} and S_{75}, respectively.

The parameter E defined in Equation 1 is a secant stiffness modulus, following the recommendation of the aforementioned standard and Koutous and Hilali [47], which indicates that the secant modulus is the best parameter to describe the elastoplastic mechanical behavior of earthen materials. These authors also noted that the value of the secant modulus is equal to approximately

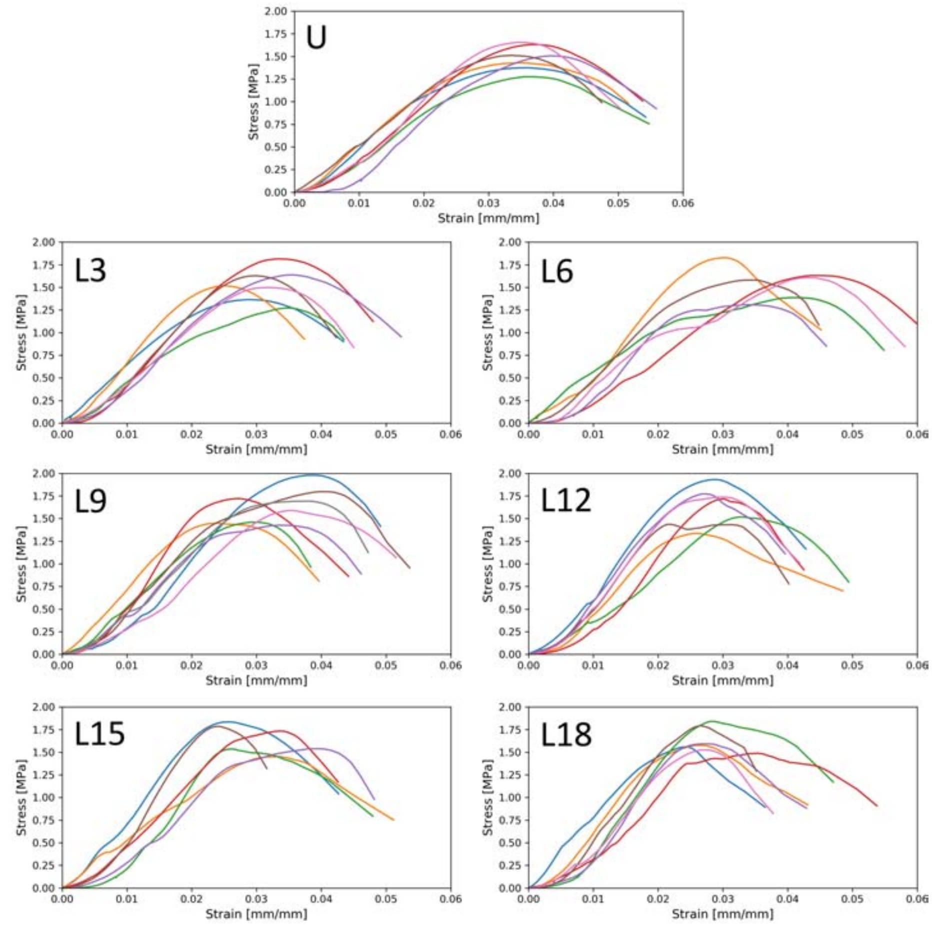

Figure 5: Stress-strain behavior of RE specimens with diverse lime contents at day 28.

0.62 times the initial tangent modulus for unstabilized, cement-stabilized and lime-stabilized rammed earth.

Table 2 shows the main results obtained from the uniaxial compressive tests for each lime content evaluated. The average coefficient of variation (CV) is equal to 11.0 % for the UCS and 17.4 % for the stiffness modulus. These values are reasonable taking into account the intrinsic heterogeneity of the material, and are comparable (and slightly lower) to the CV presented for SRE in previous studies [38, 57].

It is possible to observe that an increase in the lime content increased the UCS and E of the RE specimens and decreased the strain reached at maximum stress. The UCS at 28 days obtained for U specimens is comparable to the values commonly obtained for URE [5], and was increased by about 11 % when adding 9 % of lime, while larger lime contents did not seem to provide greater

Spec.	UCS [MPa]		E [MPa]		ε_c [mm/mm]	
U	1.48	(9.3 %)	64.97	(9.8 %)	0.036	(5.5 %)
L3	1.53	(11.9 %)	73.43	(18.0 %)	0.031	(11.8 %)
L6	1.56	(13.2 %)	72.99	(21.5 %)	0.038	(13.5 %)
L9	1.64	(11.9 %)	81.49	(16.9 %)	0.033	(17.8 %)
L12	1.64	(12.8 %)	91.01	(17.0 %)	0.028	(12.4 %)
L15	1.65	(9.6 %)	92.56	(26.5 %)	0.030	(18.9 %)
L18	1.63	(8.5 %)	93.45	(12.2 %)	0.028	(12.7 %)

Table 2: Uniaxial compressive strength (UCS), stiffness modulus (E) and strain at max. stress (ε_c) obtained for URE and LSRE specimens after 28 days of curing. Coefficient of variation in parenthesis.

strength. The reason why increasing lime contents did not improved strength is probably indicating that above that critical lime content there is an insufficient amount of aluminosilicate material in the soil to support additional stabilization reactions with the lime.

The UCS results obtained in the present study have been compared with those ones reported in literature, although the latter are very scarce and present a great dispersion. Ciancio et al. [7] obtained higher improvements (ca. 70 %) in the UCS with an optimum lime content of 4 %, but the initial strength for URE was extremely low (0.70 MPa), and so it was the maximum strength reached adding lime. Arto Torres [58] also performed compression tests on 10 cm-side cubic samples, with very high lime contents −20 and 25 %vol−, obtaining UCS equal to 2.64 MPa and 2.38 MPa, respectively. A similar dosage (18 %vol lime) was used by Canivell et al. [27], obtaining an average compressive strength of 1.87 MPa. Not very different results were obtained by Koutous and Hilali [47], leading to UCS between 1.58 MPa and 2.55 MPa for 4 %-LSRE specimens. Da Rocha et al. [26] also evaluated the UCS of LSRE, obtaining surprisingly low values (under 1.00 MPa for all lime contents from 3 to 9 %). Despite of the differences, two aspects observed in the present study were also noted by [26]: UCS increases as the lime content increases and UCS increases as the curing time increases.

The huge differences in the results showed in the diverse studies regarding lime stabilization of RE make it very difficult to draw general conclusions, so it would be necessary to carry out specific tests for particular soils and ambient conditions in order to assess the optimum lime content for the compressive strength and the maximum value of this parameter for each RE construction under consideration. If a range of UCS of LSRE should be established to have an order of magnitude, it would be from 1.00 to 2.50 MPa, a range in which the results of the present study fit.

Regarding the elastic (secant) modulus, the values obtained in the present study for the URE specimens are in agreement with those proposed by Maniatidis and Walker [59] and Bui and Morel [1]. Some other studies propose higher E values [38, 41, 60], but the enormous dispersion in the results presented in literature regarding this parameter does not allow to define a value of consensus [5, 25]. Considering the studies specifically evaluating LSRE, only Ciancio et al. [7] indicates the measurement of the stiffness, showing values between 150 MPa to 200 MPa. Again, the lack of results in literature and their variability make it very difficult to draw conclusions about this parameter.

Analyzing the variation of the stiffness when adding different lime contents, it can be observed that no relevant increases were obtained with lime contents lower than 9 %, but it significantly improved (about 25 %) when reaching that lime content. The increase in the secant stiffness modulus was even higher (over 40 %) for L12 specimens and then remained approximately constant when higher percentages of lime were added. The significance of these stiffness improvements is assessed through an ANOVA test, obtaining a p-value of 0.003, much lower than the significance level (0.05), which provides strong evidence to conclude that the population means —mean stiffness for each lime content— are significantly different. Figure 6 shows the evolution of the stiffness with the lime content, together with the variation of the compressive strength.

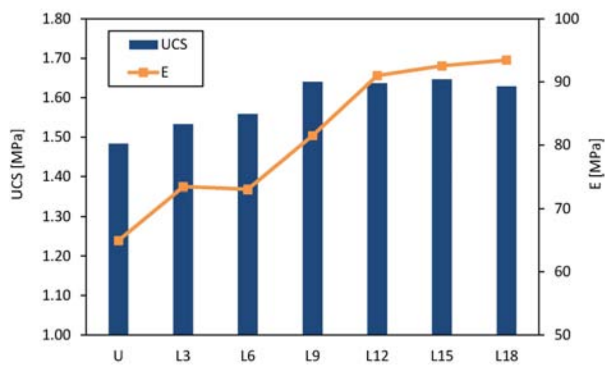

Figure 6: Average uniaxial compressive strength and stiffness for increasing lime contents at day 28 (Table 2).

In the second part of the study, UCS tests were repeated for 12 %-LSRE specimens, as it was observed that this lime content was the limit over which the improvements in the mechanical properties was almost negligible. The tests performed for the L12 specimens evaluated the strength development process for this SRE material. The results show an exponential evolution of the UCS of the specimens along time (Figure 7); Equation 2 is proposed as the expression that fits better the evolution of the UCS of the LSRE specimens over time, with a coefficient of determination $R^2 = 0.82$.

$$\text{UCS} = 2.530\left(1 - \exp\left(-0.386\, t^{0.277}\right)\right) \tag{2}$$

whit UCS in MPa and the curing time, t, in days.

These results and the proposed equation indicates a maximum UCS of 2.53 MPa at infinite time. Sixty five percent of this maximum strength is developed during the first 28 days of curing, and this percentage increases to 75 %

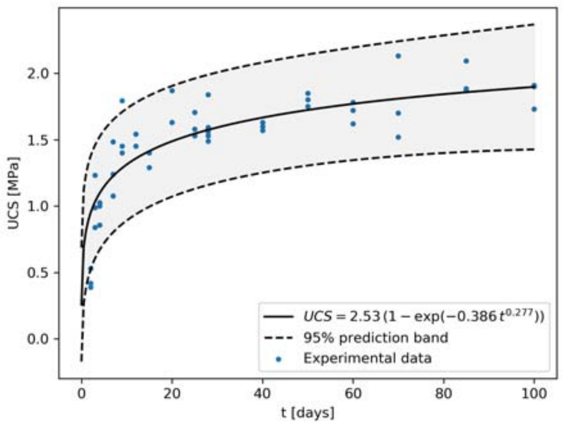

Figure 7: Development of the uniaxial compressive strength over time for L12 specimens.

if waiting until day 100. Although the UCS values obtained for 12 %-LSRE in the present study —1.64 MPa at day 28 and 1.89 MPa at day 100— are not particularly high if compared with some of the most recent results in literature that stabilize RE with diverse combinations of additives (most of them including cement), they are in agreement with most studies considering RE stabilized only or mainly with lime, as mentioned above.

Regarding the strength development process, it is common in literature to analyze the UCS of RE at relatively short periods of time (usually 28 days [7, 27, 58]), despite the fact that it is well known that the strength development of lime-stabilized earth is a long-term process [20, 22, 24]. In fact, some studies regarding LSRE [18, 26] indicate that the UCS of the material is still increasing after 100–360 days of curing. In order to reduce these long curing periods, Da Rocha et al. [26] proposed limiting the lime content and including a significant percentage of fly ash (over 25 %). There are also some examples of ancient LSRE structures constructed centuries ago that may help indicating the potential strength of this material at “infinite” time; this is the case of the Tower of Comares at the Alhambra (Granada, Spain), where cylindrical samples were extracted from its walls and tested in laboratory obtaining a compressive strength of 2.45 MPa [10, 61].

It is well known, therefore, that the strength acquisition process is slow and requires a significant amount of time to be fully developed. However, it is also possible to observe that a huge percentage of the final strength is developed during the first weeks of curing, due to the hydration reaction of lime that starts just after the lime is added to the soil in the presence of water. It was also observed that, during the first ten days of curing, the weight of the specimens significantly decreased, mainly due to the evaporation of the water present in the mixture, and then remained almost completely constant. The weight variation of the samples during their first month of curing is shown in Figure 8. A similar behavior of the moisture loss process was observed by Arto et al. [28] for LSRE specimens cured in natural ambient conditions. Curing conditions with higher relative humidity could reduce evaporation and extend the hydration process of lime, prolonging the time required for the strength to stabilized and allowing the material to reach higher strength values.

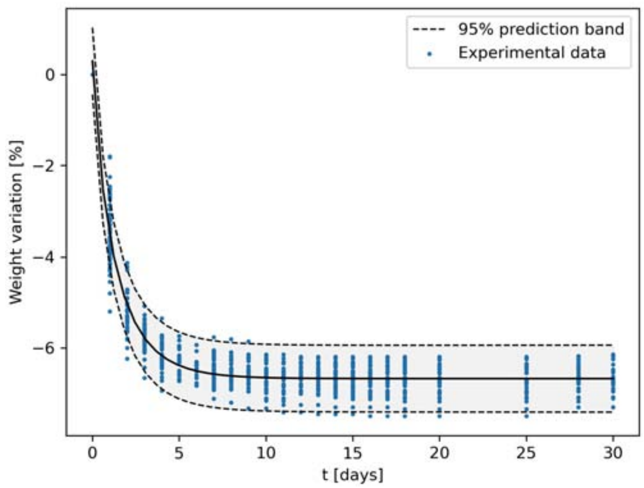

Figure 8: Weight variation of L12 specimens during the first 30 days of curing.

Evaluating the stiffness modulus, it is possible to observe the existence of a linear correlation between this parameter and the UCS of the LSRE specimens, where E is equal to ca. 57 times the UCS with $R^2 = 0.75$, as shown in Figure 9. A linear relationship between these two parameters has been noted in several previous studies regarding RE with diverse stabilizers [36, 38, 59, 62, 63]. Some relevant earth construction standards, such as NZS 4297 [64], also indicate that the stiffness can be linearly obtained from the UCS values if there is not more specific data.

4.3. Carbonation

It is also useful to evaluate the evolution of the carbonation depth in the LSRE specimens, as it is closely related to the strength development process [35]. Carbonation occurs when the lime added to the soil reacts with the CO_2 present in the air. This phenomenon should generally be avoided, as it subtracts the lime to other lime-soil reactions and hence inhibits or limits the formation of cementitious products, reducing the maximum potential strength [19, 24]. Although carbonation speed could be slowed down by limiting the CO_2 concentrations in the curing environment, this is unlikely to be possible in a real construction site, so natural ambient conditions were considered in the present study.

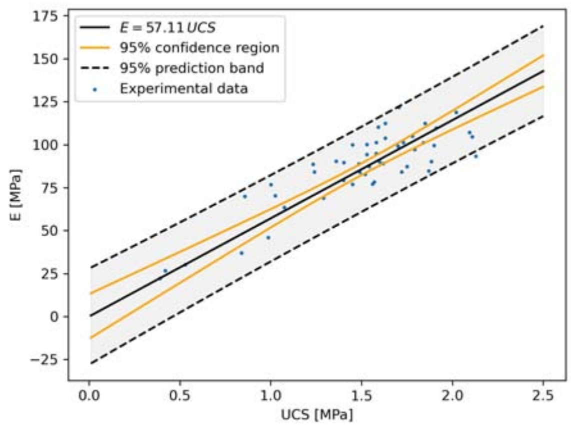

Figure 9: Stiffness modulus as a function of the uniaxial compressive strength.

The carbonation depth in the specimens was measured, after the UCS tests, as the distance between the external faces of the specimen, exposed to carbon dioxide, and the carbonation front. Van Balen and Van Gemert [65] proposed the formula $c = k\sqrt{t}$ to explain the evolution the carbonation depth (c) in lime mortars, where t is the curing time and k is an experimental factor. Basing on this expression and considering the results obtained in the present study, equation 3 is proposed to describe the evolution of the carbonation depth in the 12 %-LSRE specimens, with a coefficient of determination equal to 0.93.

$$c = 4.319\, t^{\,0.430} \tag{3}$$

where c is the carbonation depth in mm and t is the curing time in days.

Although the growth of the carbonate depth is faster during the first days of curing (Figure 10), as it happens with the strength acquisition or moisture loss, the carbonation process continues to develop for a much longer time. In the case of the 100 mm-side cubic specimens used in this study, the samples would be fully carbonated after ca. 300 days of curing. The carbonation speed also depends on the lime content, as it can be observed in Table 3, which includes the carbonation depth of the specimens for diverse lime contents at day 28, when they were subjected to the UCS tests. The carbonation depth after 28 days of curing is higher for samples with lower lime contents, probably because greater lime percentages result in a finer pore structure that impedes CO_2 permeation [17, 19, 66]. Also, as the amount of carbon dioxide in the atmosphere is controlled, a greater lime content in the material takes longer to carbonate and so a reduced carbonation rate occurs with increasing lime content.

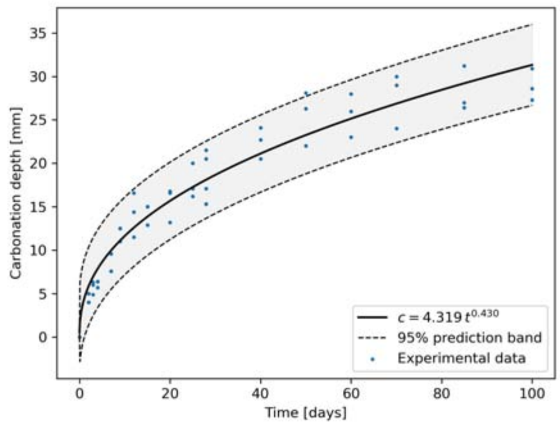

Figure 10: Evolution of the carbonation depth during the curing period.

	L3	L6	L9	L12	L15	L18
c [mm]	32	25	19	18	20	18
C.V. [%]	9.1	7.3	10.7	12.3	9.7	10.7

Table 3: Carbonation depth (c) of LSRE specimens after 28 days of curing. Mean value and coefficient of variation.

4.4. Ultrasonic pulse velocity

The UPV through the RE samples was measured before destructive UCS testing in order to assess a potential relationship between this parameter and the mechanical properties of the material. In fact, the analysis of the results shows a linear correlation between the UPV and the UCS of the LSRE specimens, following Equation 4, where UCS is expressed in MPa and UPV in km/s. This relationship and its 95 % prediction band and confidence region are shown in Figure 11.

$$\mathrm{UCS} = -1.416 + 1.897\,\mathrm{UPV} \tag{4}$$

Although there are very few studies that use the UPV technique for RE materials, some authors have already indicated the existence of a linear correlation between compressive strength and ultrasonic pulse velocity [27, 43, 67]. Therefore, and despite the evident existing dispersion in the values of the mechanical properties of RE materials, which is partially intrinsic to the heterogeneity of the material itself [5], the existing relationship between the UCS and the UPV makes the measurement of the latter a useful method to estimate the mechanical properties without damaging the sample. This can be particularly useful for existing RE structures, especially in the case of heritage buildings where destructive testing techniques cannot be applied. Previous studies have also noted

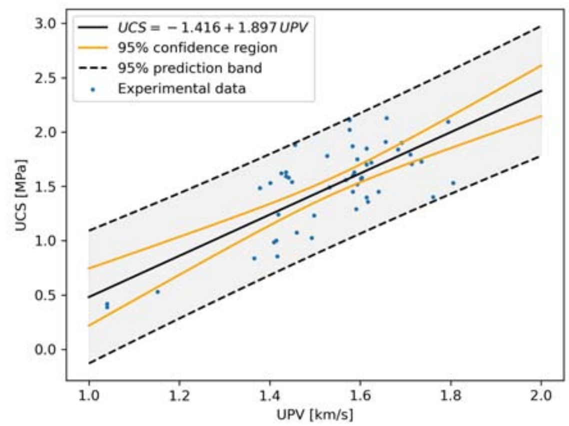

Figure 11: Uniaxial compressive strength as a function of the ultrasonic pulse velocity.

the usefulness of the UPV technique to predict the compressive behavior and to detect damage for other common construction materials, such as concrete [68, 69] or brick and stone masonry [70, 71].

For new constructions, on the other hand, UPV measurements during the curing period can be used to assess the evolution of the mechanical properties. A stabilization in the UPV values would indicate the stabilization of the UCT and stiffness, meaning that the material has already developed the majority of its strength (initial part of the strength development curve).

5. Conclusions

Rammed earth is a traditional building technique that is attracting a renewed interest due to its low environmental impact and limited construction costs. Over the last decades, the scientific research regarding RE construction has been mainly focused on unstabilized or cement-stabilized material, in addition to some other modern additives. On the other hand, very few studies have evaluated the mechanical characteristics of RE stabilized with lime, even though it is a traditional additive widely used in soil stabilization, causing an environmental impact lower than other common stabilizers such as cement, and which is present in several historic RE buildings.

In the present study, several RE samples with different lime contents and curing periods have been evaluated in order to analyze the effect of lime stabilization on the mechanical properties of the material. The results show an increase in the UCS and stiffness when increasing the lime content, in agreement with some other previous studies [7, 26], until a certain percentage of lime from which no improvement of the mechanical properties was obtained. This strength standstill is related to the lack of the aluminosilicate material in the soil, so the optimum lime content (minimum lime content for which the maximum strength is reached) may vary depending on the mineralogical characteristics of the soil, so it would be recommended to perform some UCS tests for the specific soil to be used in a construction before choosing the lime content. For the material used in the present study, representative of the soils traditionally used in RE construction in Southern Spain, the optimum lime content for the compressive strength and stiffness was equal to 12 %.

The mechanical properties of the 12 %-LSRE samples were also evaluated during 100 days of curing, observing an exponential evolution of the UCT that shows that a significant percentage of the strength is developed during the first 20–30 days, but also indicating that the strength development process could last hundreds of days (about 75 % of the predicted strength was reached by day 100). Similar behavior was observed for the material stiffness, which showed a linear relationship with the UCS, although the stiffness values showed higher dispersion, also noted in previous studies [25].

Also carbonation of the specimens, considered detrimental to strength development, was evaluated. Carbonation was observed to develop faster in samples with low lime contents, were the coarser pore structure leads to a faster carbon dioxide permeation. This phenomenon, however, occurs in a slower way than other lime-soil reactions, following a potential evolution of the form $c = a\,t^b$.

In addition, non-destructive UPV tests were performed. This technique has proved to be a useful method to estimate the mechanical properties of the material without damaging the sample, due to its linear relation with the compressive strength of the material. UPV tests could be easily performed on RE walls in a construction site, were the stabilization in the values obtained could be used as an indicator that the mechanical parameters have also increased and reached a stable value.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Spanish Ministry of Universities via a doctoral grant to Fernando Ávila (FPU18/03607).

The study is part of the project "*Revalorización Estructural del Patrimonio Arquitectónico de Tapial en Andalucía*" (Structural Revaluation of the Rammed Earth Architectural Heritage in Andalusia), ref. A-TEP-182-UGR18, within the framework of the European Regional Development Fund Program of Andalusia 2014-2020, and has been carried out by members of the Research Group "Solid Mechanics and Structures" (TEP167) at the Sustainable Engineering Structures Laboratory (SES-Lab) of the University of Granada.

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