الجمهورية الجزائرية الديمقراطية الشعبية

Republique Algerienne Democratique Et Populaire

وزارة التعليم العالي والبحث العلمي

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

جامعة الشهيد الشيخ العربي التبسي – تبسة

Université Chahid Cheikh Larbi Tébessi – Tébessa –

Faculté des Sciences et de la Technologie

Département de Génie Civil

MEMOIRE

Présenté pour l'obtention du **diplôme** de **Master Académique**

En Filière : Génie Civil

Spécialité : Structures

Par : ABID Inas & ABABSIA Meriem

Sujet

Mechanical characterization of rammed earth construction material

Présenté et soutenu publiquement, le **25/06/2024**, devant le jury composé de :

M. Hmida HAMIDANE	MCB	Président
M. Ismail LAYADI	MCB	Rapporteur
M. Ali FERNANE	MAA	Examinateur

Promotion : 2023/2024

ACKNOWLEDGMENTS

First of all, we would like to thank my master thesis director Ismail LAYADI for his continuous support, his enthusiasm and his confidence in me. His guidance helped us in all the time of research and writing of this thesis.

Words cannot express our gratitude to the professors for their constant feedback and support during these years. The are the main reason we started this research, and this master thesis would not have been possible without them.

My dissertation committee also played a major role in this work, which is even more valuable. In particular, we would like to thank my thesis referees, Hmida HAMIDANE and Ali FERNANE for the time they devoted to reading our manuscript and their reviews and comments.

Finally, we would like to thank my family for their tremendous support and encouragement. These few lines are not enough to express my gratitude, without them we would not have reached this point. We are also really grateful to our friends, those we met during these years of master studies and those who have been with me for a long time, because they filled these years with wonderful moments that gave us the strength needed to move forward and reach my goals.

ABSTRACT

In recent years, earthen constructions attracted the interest of researchers and companies in the construction sector and found to be a great alternative to the existing cementitious techniques. Rammed earth construction technique is creating renewed interest as an environmentally sustainable building solution for the construction sector. The earth material considered for rammed earth construction is a soil graded from clay to fine gravel with a small water amount. The technique consists of compacting the soil in layers with equivalent thicknesses using a wooden or steel formworks. The formwork is then removed and the soil is left for curing.

An experimental test program is carried out in the purpose of characterizing the geotechnical and mechanical properties of rammed earth material. The geotechnical properties are obtained from the combination of sieving/sedimentation analysis and standard proctor test. Whereas, the test program on the mechanical properties includes normal and diagonal compression tests on unstabilized/stabilized and unreinforced/reinforced rammed earth material. Data acquisition and post-processing of test results are performed using the Digital Image Correlation (DIC) technique for better understanding of the behavior and failure modes of the rammed earth material. Experimental results showed that the stabilization and fiber reinforcements have an influence on the normal and diagonal compressive strength of the rammed earth material.

KEYWORDS

Earth Material, Rammed Earth, Particle Size Distribution, Optimum Moisture Content, Stabilization, Fiber Reinforcement, Normal Compression, Diagonal Compression, Digital Image Correlation.

ملخص

في السنوات الأخيرة، جذبت الإنشاءات الترابية اهتمام الباحثين والشركات في قطاع البناء ووجدت أنها بديل رائع للتقنيات الأسمنتية الحالية .تخلق تقنية البناء بالأرض المدكوكة اهتمامًا متجددًا كحل بناء مستدام بيئيًا لقطاع البناء .إن المادة الأرضية المستخدمة في بناء الأرض المدكوكة هي تربة متدرجة من الطين إلى الحصى الناعم مع كمية صغيرة من الماء. تتكون هذه التقنية من ضغط التربة في طبقات ذات سماكة متساوية باستخدام قوالب خشبية أو فولاذية .ثم تتم إزالة القوالب وتترك التربة للمعالجة.

تم تنفيذ برنامج اختبار تجريبي بغرض توصيف الخواص الجيوتقنية والميكانيكية لمواد الأرض المدكوكة .يتم الحصول على الخصائص الجيوتقنية من خلال الجمع بين تحليل الغربلة/الترسيب واختبار بروكتور العادي. حيث أن برنامج اختبار الخواص الميكانيكية يشتمل على اختبارات الضغط العمودية والقطرية على مواد الأرض المدكوكة غير المثبتة/المثبتة وغير المسلحة/المسلحة بالألياف .يتم إجراء الحصول على البيانات والمعالجة اللاحقة لنتائج الاختبار باستخدام تقنية ارتباط الصور الرقمية (DIC) لفهم أفضل لسلوك وأوضاع الفشل لمواد الأرض المدكوكة .أظهرت النتائج التجريبية أن التثبيت والتسليح بالألياف لها تأثير على مقاومة الضغط العمودي والقطري لمادة الأرض المدكوكة.

الكلمات الدالة

المواد الأرضية، الأرض المدكوكة، توزيع حجم الحبيبات، محتوى الرطوبة الأمثل، التثبيت، التسليح بالألياف، الضغط العمودي، الضغط القطري، ارتباط الصور الرقمية.

TABLE OF CONTENTS

CHAPTER I : An Overview on Earth Based Construction Materials

CHAPTER II : Rammed Earth

CHAPTER III : Geotechnical and Mechanical Properties of Rammed Earth

CHAPTER IV : Experimental Program - Part 01 : Identifying the Geotechnical Properties of Rammed Earth

CHAPTER V : Experimental Program - Part 02 : Identifying the Mechanical Properties of Rammed Earth

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In past centuries, the earth was used for construction purposes using various traditional building techniques such as rammed earth, plaster, mud brick, and block. Due to the advent of technology and the availability of powerful machinery, soil can now be developed using one of these techniques, and current work focuses on the use of rammed earth as a building material.

Rammed earth is a traditional building technique used in many places around the world since ancient times, and today it is generating renewed interest as an environmentally sustainable building solution. The rammed earth construction technique consists of compacting the soil in layers between formwork, which are removed once the required height of the wall is reached. The source material for rammed earth is soil graded from clay to fine gravel, plus a certain amount of water and sometimes, other additives.

This Master theses is divided into five chapters. A brief outline is discussed below:

Chapter I : An Overview On Earth Based Construction Materials

This chapter highlights the use of earth as a construction material using different techniques, particularly rammed earth. The various advantages and limitations of earthen materials are discussed. The importance of these constructions and the necessity of the conservation of rammed earth heritage are being highlighted along with the importance of the enhancing.

Chapter II : Rammed Earth

This chapter deals with an overview on the rammed earth material. The historical context, development, advantages/limitations and environmental/economic benefits of the rammed earth construction material are presented.

Chapter III : Geotechnical and Mechanical Properties of Rammed Earth

This chapter deals with the experimental testing methods found in literature used for the assessment of the geotechnical and mechanical properties of the rammed earth. The testing methods concerned, on the one hand, the evaluation of particle size distribution and optimum moisture content for the geotechnical properties, on the other, compression, tension and shear tests for the mechanical properties.

Chapter IV : Experimental Program - Part 01 : Identifying the Geotechnical Properties of Rammed Earth

In this chapter, the first part of our experimental program on rammed earth material regarding the geotechnical properties is presented. The earth material used for this end was extracted from the soil of the Dokane commune at Tebessa region in Algeria. Both dry/wet sieving, and sedimentation analysis are used for the particle size distribution evaluation. Then, the optimum moisture content (OMC) and dry density are obtained from the standard proctor test.

Chapter V : Experimental Program - Part 02 : Identifying the Mechanical Properties of Rammed Earth

This chapter deals with the second part of our experimental program on rammed earth material concerning the mechanical characterization. Two types of tests were performed, normal to layer compression test and diagonal compression test. The first test studied the effect of the stabilization technique on the compressive strength and behavior of rammed earth specimens. The second test investigated the fiber reinforcement effect on the diagonal compressive strength and behavior of rammed earth specimens. The post-processing of test results was analyzed using the Digital Image Correlation (DIC) technique giving a better understanding of the behavior and failure modes of the rammed earth material.

CHAPTER I : An Overview on Earth Based Construction Materials

1 Introduction

This chapter provides an overview of earth building materials, especially rammed earth structures. Different earth construction techniques and their various advantages as sustainable building materials are highlighted.

2 Historical Overview

As described in (Avila cruces, 2023), the human being has used earth as a construction material from the very beginning. 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. 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.

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. 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 Figure 1.1.

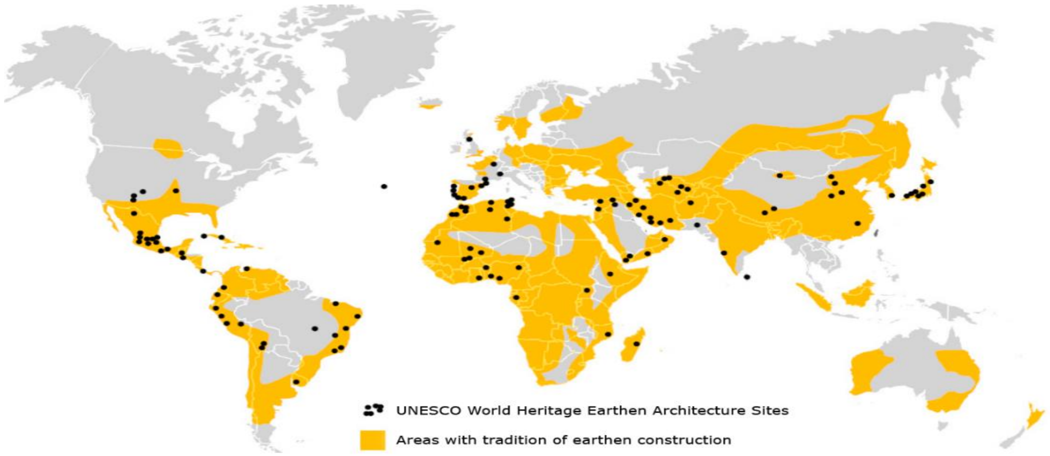


Figure 1.1 Areas of the world with tradition of earth construction and UNESCO World Heritage Sites (Avila cruces, 2023) (Gandreau et al, 2012)

The historical presence of earth constructions in the world is analyzed by (Avila cruces, 2023), highlighting the most remarkable buildings in each continent, taking into account their historical and architectural relevance. The analysis is presented as follows.

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 (Bui and Morel, 2009). Somewhat later are the rammed earth foundations found in the locations of the ancient civilization of Assyria, dating from ca. 5000 BCE (Minke et al, 2006), or the ancient Persian cities of Tepe Yahya (3400 BCE) (Walker et al, 2005) and Chogha Zanbil (13th century BCE) (Figure 1.2a), 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, 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 (Bui and Morel, 2009).

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 1.2b). 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 (Avila cruces, 2023).

(a) (b)

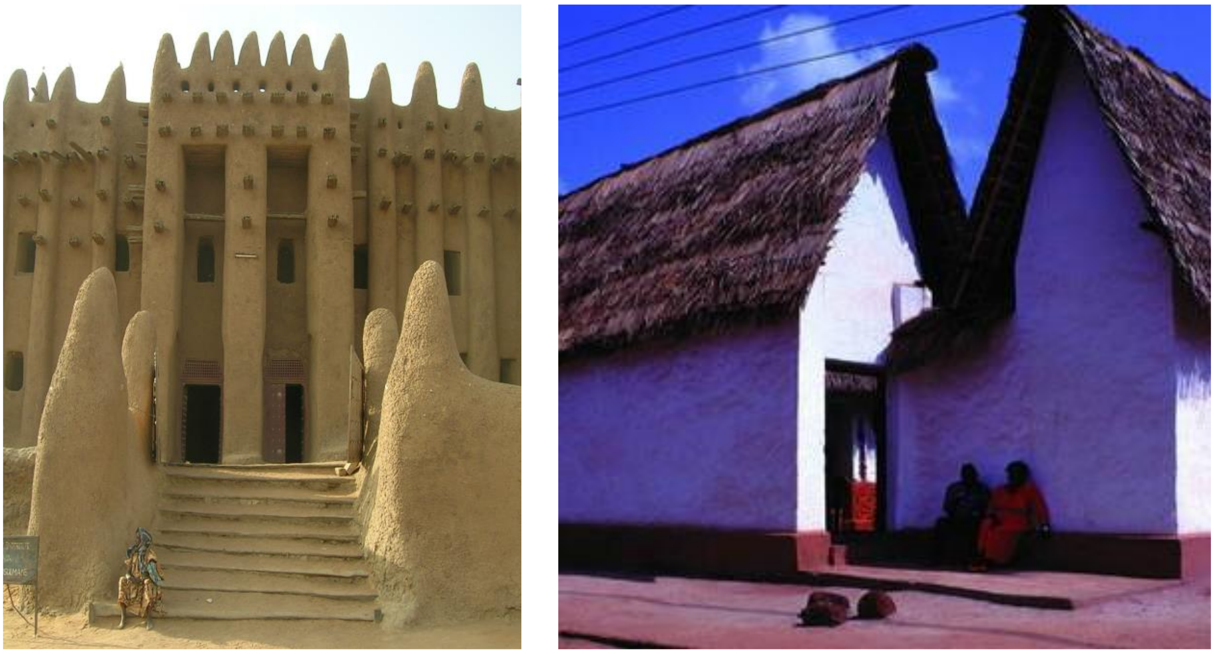
Figure 1.2 Historic earth constructions in Asia: (a) Chogha Zanbil ziggurat, Iran and (b) rammed earth wall of the Ancient City of Ping Yaoa, China (Fernando J Avila cruces, 2023)

2.2 Africa

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 thousand years (Alex, 2018). 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 (Ciancio et al, 2013), and its low cost and great potential for reuse of materials (El Nabouch et al, 2017) (Kennedy et al, 2004).

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 1.3a), which began to be built in the 3rd century BCE; the Fortified Historic Town of Harar Jugol (Ethiopia, 13th century) (Nowamooz et al, 2011); or the traditional architecture of Asante (Ghana, see Figure 1.3b), Sukur (Nigeria) or Koutammakou (Togo) (Avila cruces, 2023).



(a) **(b)**

Figure 1.3 Earth construction in Africa: **(a)** Old Town of Djenné, Mali and **(b)** traditional earth house in Asante, Ghana (Fernando J Avila cruces, 2023)

2.3 Europe

In Europe, the use of earth for construction has historically been very present. Some studies (Minke et al, 2006) affirm that in the area corresponding to present-day Germany, earth was already used in the Bronze Age as an infill in timber 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 (Minke et al, 2006).

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 1.4a) and Germany, some of which are still inhabited today (Minke et al, 2006).

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 (Venkatarama et al, 2009), 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 watch towers 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 (Walker et al, 2005).

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: the Alhambra in Granada (Figure 1.4b), 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 (Avila cruces, 2023).

(a) **(b)**

Figure 1.4 Earth construction in Europe: (a) wattle and daub house in the medieval town of Provins, France and (b) the Alhambra of Granada, Spain (Avila cruces, 2023)

3 Earth based construction techniques

The concept of earth construction implies using the local soil. According to (Houben and Guillaud, 2008), there is a wide variety of earth construction techniques that exists which depends on the way of implementation and the soil proportion in clay and water. These techniques are wattle and daub; cob; rammed earth; earth bricks (adobe) or compressed earth blocks (CEB) assumed to be a popular modern earth technique. The most common techniques are adobe masonry and rammed earth walls. Figure 1.5 shows the distinction between these techniques (El Nabouch, 2017).

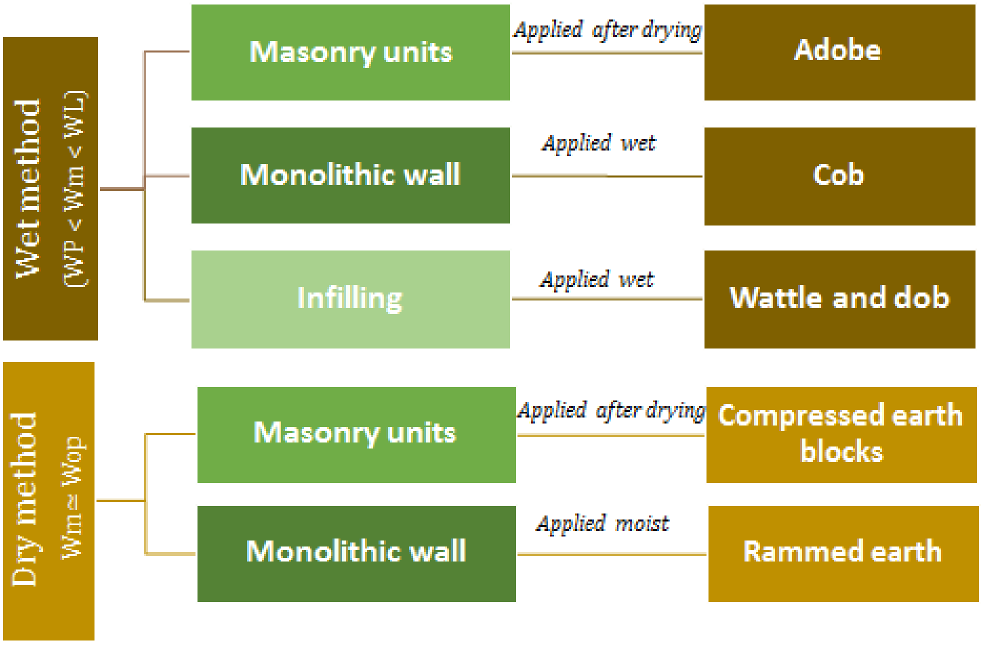


Figure 1.5 Earth construction processes classification, (Wm=manufacture water content, Wop = optimum Proctor water content; WP = water content at plastic limit; WL = water content at liquid limit) (El Nabouch, 2017) (Hamard et al, 2016)

3.1 Wattle and daub

For the wattle and daub, some various techniques exist depending on the region. In the typical technique, the earth is filled against a structure of timber elements. This technique was used for almost 6000 years (Graham, 2004). The earth, in this case, had no structural function, it can include straw and the mixture is in general very clayey. On the other hand, the timber holds the bearing capacity. This technique is for non-bearing walls and can be used for external and partition walls up to 20 cm thick. Figure 1.6 shows two houses made of wattle and daub in Germany and France, consecutively (El Nabouch, 2017).

Figure 1.6 (a) Building in the central German city of Bad Langensalza made of wattle and daub and (b) House in France, Alsace (El Nabouch, 2017)

3.2 Adobe

Adobe is also an ancient construction technique that consists of filling molds with moist earth to obtain finally the desired shape (Figure 1.7), the adobes are then left in the sun to dry. They are ready to be used as masonry units. The applied mortar is usually made from the same earth used in the production. Many examples can be found for this type of construction in rural and urban buildings as shown in Figure 1.8 (El Nabouch, 2017).

Figure 1.7 Production of Adobe in Ecuador, (El Nabouch, 2017) (Minke, 2001)

Figure 1.8 Examples of existing adobe constructions in Aveiro district, Portugal (El Nabouch, 2017) (Silveira et al.,2012)

3.3 Cob

As for the cob technique, it consists of mixing clay, sand with organic fibers like straw with the addition of water and the mixture is usually applied by hands without any formwork as in Figure 1.9a.

The technique was abundantly used in Europe, where it is termed "Cob" in England and "Bauge" in France, it is similar to the one of the adobes but involves the use of more straw fibers mixed in. Many examples also exist as in Saudi Arabia (Figure 1.9b) and the old historic buildings in Shibam, Yemen which involves both rammed earth and cob (El Nabouch, 2017).

Figure 1.9 (a) Technique of Cob construction; (b) Masmak Castle in Riyadh, Saudi Arabia (El Nabouch, 2017)

3.4 Compressed earth bricks (CEB)

Comparing to the traditional earth construction, the CEB (compressed earth bricks) technique is considered to be recent in the earth construction. This method consists of using specific presses to compact earthen materials using molds to finally obtain heavier earth blocks and more resistant than adobe bricks. The pressure can be applied manually or mechanically (Figure 1.10). This method is considered to be an improvement of the adobes by increasing the mechanical properties (mainly the density). Figure 1.11 shows an example for apartments in Morocco made from CEB blocks (El Nabouch, 2017).

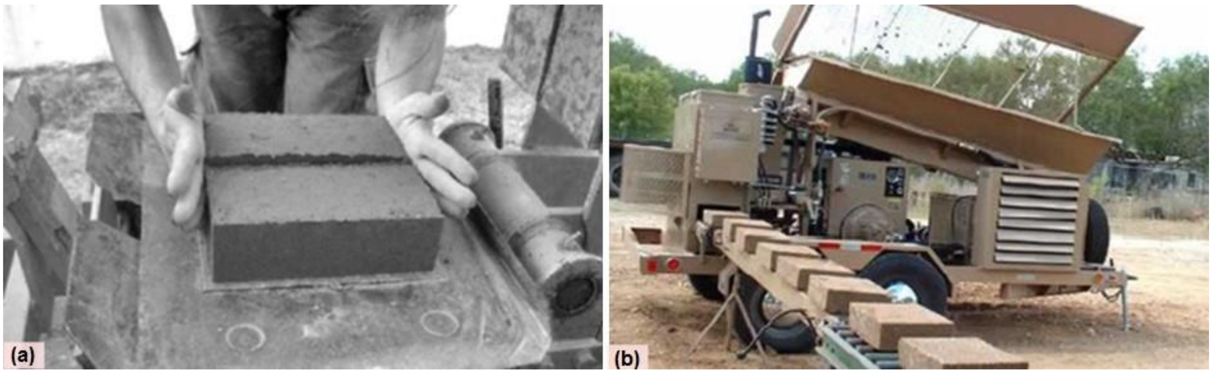


Figure 1.10 Compressed earth blocks manufactured by means of: (a) a manual press (Gomes, 2008); (b) hydraulic press (El Nabouch, 2017) (Burlaco, 2011)

Figure 1.11 Apartments from CEB in Marrakesh, Morocco, (El Nabouch, 2017) **(Guillaud, 1987)**

3.5 Rammed earth

Rammed earth walls are built by compacting soil between temporary formworks. The formwork usually consists of two parallel surfaces separated and interconnected by spacers as shown in Figure 1.12a. The principal binder of the grains is the clay. The mixture of the earth is compacted into layers of approximately 15 cm by the use of a rammer. The average thickness of the wall is 50 cm. As each form is filled, another form is placed above it, and the process is carried on until achieving the desired wall height. Forms can be removed directly as soon as the form above is begun (El Nabouch, 2017).

The compaction of rammed earth layers is traditionally performed manually using a rammer generally made of wood with different base shape (Figure 1.12b). Nowadays the manual rammer is replaced by a more powerful pneumatic rammer that increases the rapidity of Manufacturing and the density of the material (Figure 1.13). Pneumatic rammers are normally powered by compressed air.

In the traditional technique, the frames are usually made out of wood. Nowadays, metallic shutters are being used instead. The formwork should be well braced in order to assure the stability and preventing any deformation due to the high compressive force induced by the rammer during the compaction process.

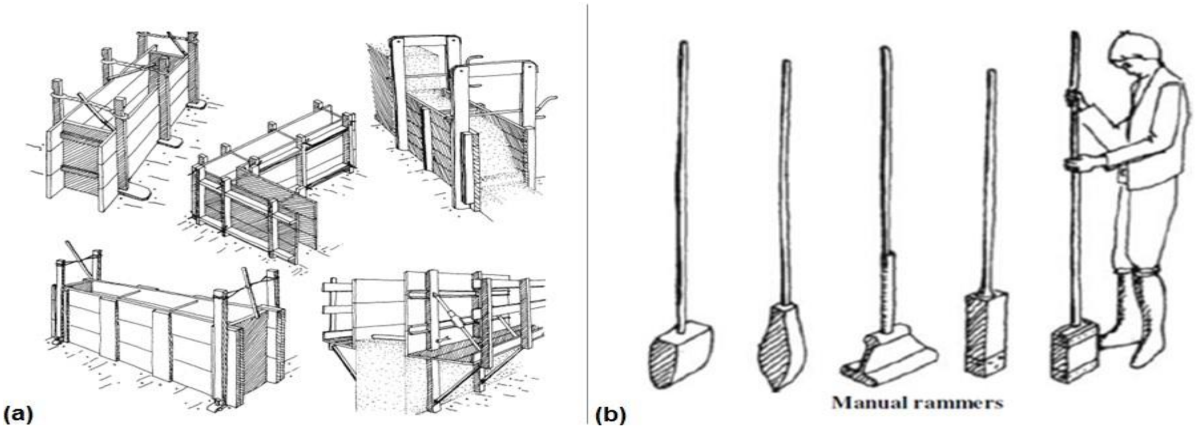


Figure 1.12 (a) Formwork used in for traditional rammed earth (El Nabouch, 2017) (Minke, 2006); (b) Rammers used to compact rammed earth (El Nabouch, 2017) (Minke, 2006).

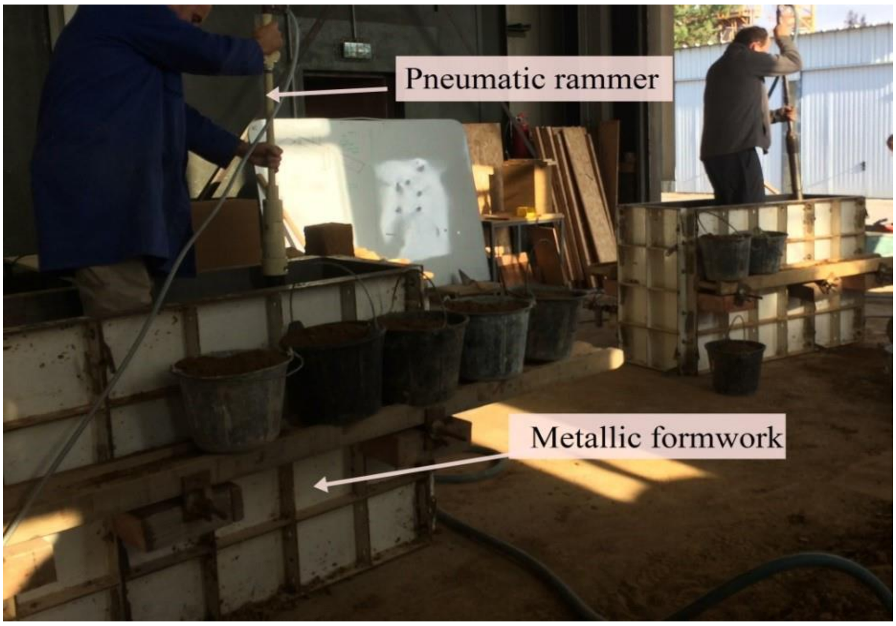


Figure 1.13 The use of pneumatic rammer and metallic formwork in modern techniques, (El Nabouch, 2017)

The walls take some time to dry completely as the compression strength increases with the curing time. Figure 1.14 shows a traditional house made of rammed earth in France and Figure 1.15 exhibit the typical earth layers of a test wall. Rammed earth is generally founded on a base built from (stone, pebbles) about 50 cm high to protect the walls from rising damp (Pignal, 2005). In the case of modern construction, this masonry base is usually made from concrete (El Nabouch, 2017).

Figure 1.14 Traditionnel house in « Pont de beau voisins », Rhône-Alpes, France (El Nabouch, 2017)

Figure 1.15 Visible compacted layers with different thickness of a rammed earth wall (El Nabouch, 2017)

4 Standardization of Earth based Construction

Several earth construction standards have been developed in diverse countries, but many of them are based on the traditional geometrical relationship and building recommendations (Avila cruces, 2023). 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 (Siddiqua et al, 2018). 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 according to (Avila cruces, 2023).

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 (Laborel et al, 2016). 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 (Serrano et al, 2013). 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 (Walker et al, 2005), 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 (Bauluz et al, 1992) about compressed earth blocks for walls and partitions, including definitions, specifications and test methods.

4.2 America

The American Society for Testing and Materials (ASTM International) has published a design 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 and the other specifically focusing on historic buildings made of this material. 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 (SADCSTAN, SADC ZW HS 983:2014 Rammed Earth Structures-Code of practice (2014)) 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 guide called "Design of Earthen Wall Construction" (Gomes et al, 2014) 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) (Hall et al, 2003) 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 (Houben et al, 1994).

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 (Corbin et al, 2015), which already had its own standard for rammed earth since 2000 (ZWS 724:2000).

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 (Silva et al, 2014), and the standard IS:13827-1993 on the improvement of the seismic strength of earth constructions (Keable et al, 2014), 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 (Bui et al, 2013). 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” (Jaquin et al, 2012). 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 (Bui et al, 2013).

In New Zealand, there are since 1998 three standards that regulate the construction of rammed earth walls: NZS 4297, NZS 4298 and NZS 4299 (Miccoli et al, 2014) (Silva et al, 2014). 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.

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.

CHAPTER II : Rammed Earth

1 Introduction

In past centuries, earth was used for construction purposes using various traditional techniques such as rammed earth. In this section, the historical context and development of the rammed earth are presented, followed by an overview on the advantages/limitations and the environmental/economic benefits.

2 Historical context and development of rammed earth:

2.1 History and Developments in Rammed Earth Construction:

Different types of structures have been built using the rammed earth construction technique. The developments and applications of rammed earth construction, since BC period are detailed in the Table 2.1. Few examples of rammed earth constructions are illustrated in the Figures 2.1, 2.2.and 2.3. The earlier rammed earth constructions utilized mainly the local soil/materials and resulted in environment-friendly structures. Buildings of 2–6 storey height have been successfully built with load bearing unstabilised rammed earth walls. Because of the lower strength, the unstabilised rammed earth walls are made thicker (>400 mm), mainly to reduce compressive stresses developed due to 32 gravity loads and for lateral stability (Venkatarama Reddy, 2022).

Table 2.1 History and developments in rammed earth construction (Venkatarama Reddy, 2022)

Circa	**Place**
475 BC	China
300 BC	Great wall of China
246–209 BC	• Great Wall of China • Monuments by Assyrians, Babylonians, Persians & Sumerians
200 BC	Africa
300 AD	Watch towers - Europe
650–815 AD	Monumental structures
1368–1644 AD	Tulou rammed earth buildings, Fujian Province, China
1600 AD	Buildings in Ladakh and Bhutan
1660–1865 AD	Swiss pisé structures
1796–1850 AD	Six-storey apartment and residential buildings, Weilburg, Germany
1857 AD	Church of Holy Cross in Staatsburg
1900 AD	Rammed earth chalk buildings in UK
1914–1942 AD	Exploration/research on rammed earth material
1948 AD	4000 rammed earth houses in Punjab province, India
After 1970 AD	• Modern rammed earth constructions across the world • R&D in rammed earth

Figure 2.1 Unstabilised rammed earth house, Weilburg, Germany, (Constructed in 1850, picture on12 October 2008 (Venkatarama Reddy, 2022)

Figure 2.2 Sixstorey load bearing unstabilised rammed earth building, Weilburg, Germany, (Constructed in 1826, picture on 12 October 2008) (Venkatarama Reddy, 2022)

Figure 2.3 Old Pise-Haus (rammed earth house) in Weilburg (Built in 1826, picture taken on 12 October2008)

Venkatarama Reddy, 2022

The inorganic additives such as cement have been explored for the rammed earth construction since 1940s. The cement stabilisation facilitates in building thinner structural walls (150–300 mm). Also, in the case of cement stabilised rammed earth, the wall strength can be easily varied by adjusting the cement content. Figures 2.4, 2.5 and 2.6 show some of the recent cement stabilised rammed earth buildings. There are several successful examples of cement stabilised rammed earth buildings in Australia, USA, Europe, Asia and many other countries (Verma and Mehra 1950; Easton 1982, 1982, 2008; Hall 2002; Houben and Guillaud 2003; Walker et al. 2005; Tejas 2007; Windstorm and Schmidt 2013; Reddy et al. 2014, 2019). The load bearing cement stabilized rammed earth buildings of 1–3 storeys have been built in India since 2000. Large numbers of cement stabilised rammed earth houses were built in the rehabilitation projects in Gujrat, India (Tejas2007; Kiran and Tejas 2019). A three-storey cement stabilised rammed earth wall dormitory building. This building is located in the region where the outside temperatures in summer cross 43 °C. The load bearing walls are 300 mm thick, designed to have high thermal mass for passive cooling effect. Figure 2.4 shows a three-storey school building using load bearing cement stabilised rammed earth in Bangalore, India (venkatarama Reddy et al. 2014). The building has 400 mm thick walls in the ground floor and reducing to 300 mm in the top floor. The floor slabs have a span of 7.8 m. shows a three-storey residential cement stabilised rammed earth building (Venkatarama Reddy, 2022).

Figure 2.4 Three-storeyed load bearing cement stabilised rammed earth school building, Bangalore, India, built in 2009, corridor has few RC columns for housing rainwater pipes Venkatarama Reddy, 2022

Figure2.5 Three-storeyed load bearing cement stabilised rammed earth residential building, Bangalore, India, built in 2017, designed by architect Mr. Harsha S (Venkatarama Reddy, 2022)

Figure 2.6 Three-storeyed load bearing cement stabilised rammed earth dormitory building, India, built in 2019 (Venkatarama Reddy, 2022)

2.2 Rammed Earth

The rammed earth is a monolithic construction and finds applications in the construction of walls, roofs/floors, foundations, built-in furniture, embankments, earthen bunds, etc. The rammed earth construction process mainly involves the compaction of the processed partially saturated soil in progressive layers in a rigid formwork (Figure 2.7). The rammed earth construction is primarily an in-situ operation, though there are attempts to popularise the precast rammed earth elements for use in the construction of the walls (Lindsay 2012; Otto Kapfinger and Marko Sauer 2015). The rammed earth constructions can be classified into two broad categories: (1) stabilised rammed earth and (2) unstabilised rammed earth. The unstabilised rammed earth elements are constructed, mainly using natural materials (soil and aggregates). Generally, the stabilised rammed earth construction uses inorganic stabilizers (such as cement or lime) in addition to the natural materials such as soil, gravel and aggregates. The rammed earth structures have several distinct advantages when compared to the conventional types of constructions:

(a) The rammed earth is an environment-friendly and low embodied carbon material

(b) Bulk of the raw materials used are local and available within a short distance from the construction site

(c) The rammed earth structures possess aesthetically pleasing appearance, resembling closed to a sedimentary rock with stratified layers (Figure2.8).

(d) Varieties of texture and color finishes can be achieved for the rammed earth using specifically selected raw materials and special construction processes (Figure 2.8).

(e) The plan form as well as the vertical cross section can be varied easily through proper design of the formwork (Figure. 2.9). There is scope for creating built-in artwork into the rammed earth surfaces (Figure 2.10).

(f) The rammed earth buildings can have better living environmental conditions with better indoor air quality. The walls can be designed to be dense and bulky having considerable thermal mass offering scope for passive environmental performance design.

(g) The compressive strength of the rammed earth wall is higher when compared to the strength of a masonry wall using masonry units made from a similar material composition and density.

(h) Thinner (150mmor more) rammed earth walls can be designed for load bearing purposes. It is easy to implement different wall thicknesses (of desired oddsizes) across different floor heights of a building. A comparison between the stabilised and unstabilised rammed earth construction is provided in Table 2.2 (Venkatarama Reddy, 2022).

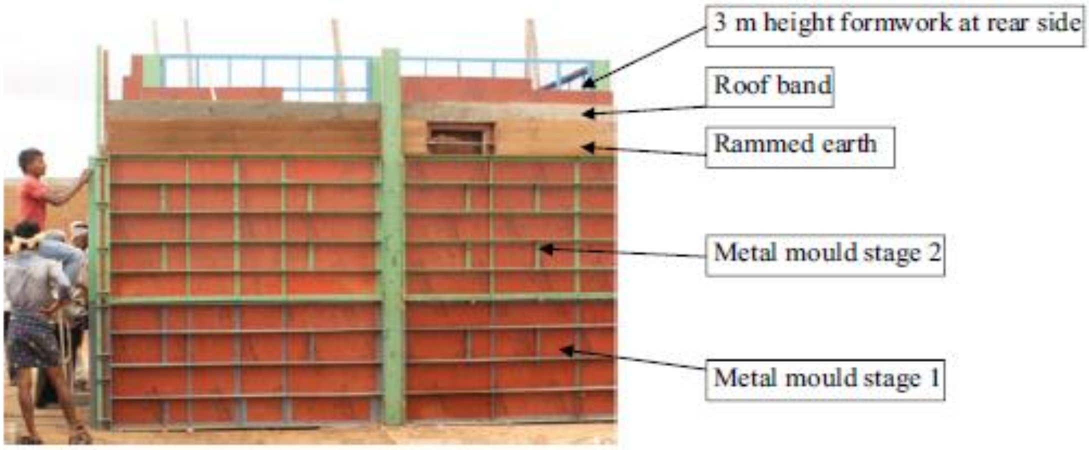


Figure 2.7 Metal formwork for rammed earth wall construction (Venkatarama Reddy, 2022)

Figure 2.8 Different coloured textures in rammed earth using natural soils (Venkatarama Reddy, 2022)

Figure 2.9 Curve shaped (in plan) rammed earth wall (Venkatarama Reddy, 2022)

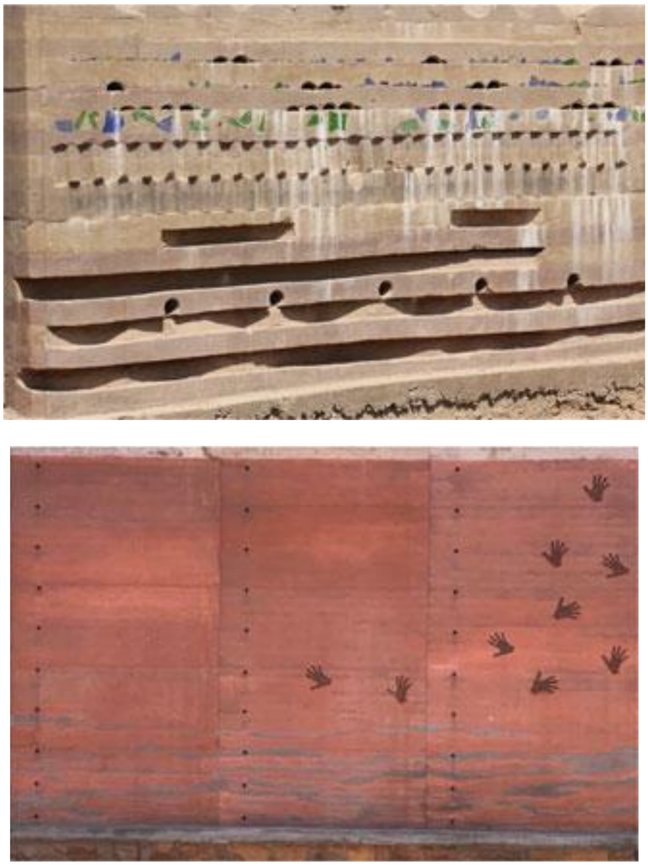


Figure 2.10 Artwork in cement stabilised rammed earth walls at Hunnarashala Bhuj, India (Venkatarama Reddy, 2022)

Table 2.2 Comparison between stabilised and unstabilised rammed earth (Venkatarama Reddy, 2022)

Unstabilised rammed earth	Stabilised rammed earth
• Use of natural materials and negligible environmental costs at the end of life • Good moisture buffering properties • Lower cost and scope for self-help construction • Low embodied carbon • Lower strength and hence thicker walls • Loss of strength and stiffness on moisture absorption • Prone for erosion due to rain impact • Prone for termite/insect infestation and damage especially in tropics and sub-tropics	• Higher strength, even in saturated condition • Easy to achieve desired strength and scope for taller structures • Possible to build thinner walls • Use of inorganic stabilisers such as cement and lime • Higher embodied carbon when compared with carbon in unstabilised rammed earth • Better durability and good erosion resistance against rain impact • Free from termite/insect damage

2.3 Modern rammed earth

The in-situ rammed earth constructions are widely practiced, and such construction practices are economical especially when the labour costs are low. Since the last 2–3 decades, there are attempts towards the off-site fabrication of rammed earth wall elements assembling them into a building. Prefabrication potentially allows for better quality control in the factory production, can minimise the construction time and is convenient to carry out rammed earthworks in congested places. Rammed earth prefabricated wall elements are heavy, demand heavy specialised equipment for lifting and placing, and also add to the transportation and handling costs. Such operations might increase the cost of prefabricated rammed earth. Prefabrication concepts have been explored for both the stabilised and unstabilised rammed earth constructions.

Otto Kapfinger and Marko Sauer (2015) and Rauch (2007) provide details of some of the prefabricated unstabilised rammed earth buildings and the projects completed using prefabricated rammed earth since 1997. The Kräuter Zentrum in Laufen and the Swiss Ornithological Institutes Visitor Centre in Sempach are the most recent ones using prefabricated rammed earth panels. Figure 2.11 shows the positioning of the prefabricated rammed earth panels. There are few prefabricated rammed earth structures in France (Hall and Swaney 2012). M/s. Rammed Earth Works Group has built prefabricated stabilised rammed earth buildings in USA (Venkatarama Reddy, 2022).

Figure 2.11 Unstabilised prefabricated rammed earth panels transported and assembled at site (Venkataram Reddy, 2022)

2.4 Method of Casting Rammed Earth

The rammed earth construction needs a dismountable rigid formwork. Some of the typical form works are shown in Figures 2.12, 2.13 and 2.14. The moulds consist of two leaves linked by lengthy bolts. The rammed earth casting process involves the following steps (Venkatarama Reddy, 2022):

(a) Setting the mould

(b) Processing the soil

(c) Mixing the soil, gravel/aggregates and stabiliser in dry state

(d) Mixing the materials with water

(e) Pouring the partially saturated soil-aggregate-stabiliser mixture into the mould

(f) Compacting the processed material into a desired density

(g) Dismantling the formwork

(h) Curing.

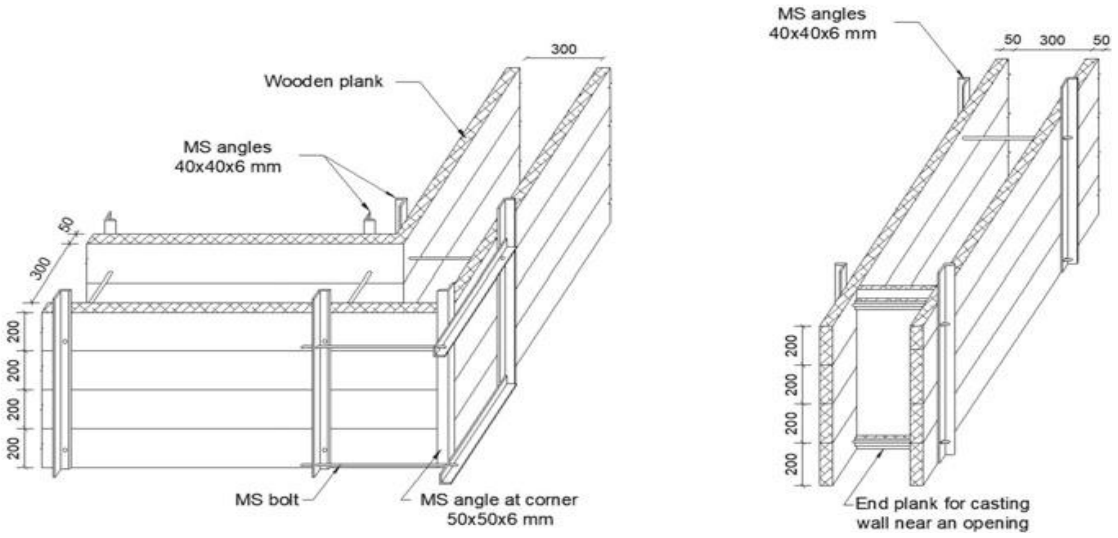


Figure 2.12 Wooden formwork (as per IS 2110 code) (Venkatarama Reddy, 2022)

Figure 2.13 Long continuous wooden formwork (Venkatarama Reddy, 2022)

Figure 2.14 Formwork for the entire height and length of rammed earth wall (Venkatarama Reddy, 2022)

2.5 Compacting the Processed Material

Rammed earth compaction is carried out in layers. Generally, the compacted layer thickness varies between 60 and 150 mm. The investigations of Lepakshi (2017) and Lepakshi and Reddy (2018) have shown that the optimum layer thickness yielding maximum strength and stiffness of rammed earth is in the range 80–100 mm. The strength of rammed earth greatly depends upon its dry density. The strength and density are linearly related (Reddy and Kumar 2011). Hence, the dry density of the compacted layers of rammed earth should be controlled. Therefore, a definite quantity of the wetted processed mix should be poured into the mold and then compacted to the desired thickness in order to achieve a specified dry density.

A sample calculation for arriving at the mass of the material in each layer is provided below:

Mold length: 3.0 m.

Wall thickness: 0.23 m.

Compacted layer thickness: 0.10 m.

Dry density: 1850 kg/m3.

Molding moisture content: 11% (by mass).

Quantity of processed soil mixture needed in one layer = (3.0 × 0.23 × 0.10) (1850 × 1.11) =141.69 kg.

Known quantity (141.69 kg) of the mix is poured into the mold, uniformly spreading the loose processed earth mixture, and then, compaction is carried out using the rammer such that a uniform layer thickness (100 mm) is achieved. After the compaction, dents are created on the freshly laid compacted layer as illustrated in Fig. 2.15. Such dents help in interlocking of the compacted layers in the RE. The compaction process continues till the desired height for the RE is achieved. Figure 2.16 shows a part of compacted RE wall where on one side 3.0 m height form work sheet is present and on the opposite side the formwork is stripped (Reddy, 2022).

The RE wall compaction process in a particular segment of the building may take3–5 days; hence, the formwork can be dismantled a day after completing the last layer of the wall. After dismantling the formwork, the RE wall should be covered with a wet gunny cloth or burlap and continue curing for four weeks. The water should be sprayed onto the burlap 3–4 times a day, until the curing period is completed. Figure 2.17 shows a RE wall covered with burlap, undergoing curing Venkatarama Reddy, 2022

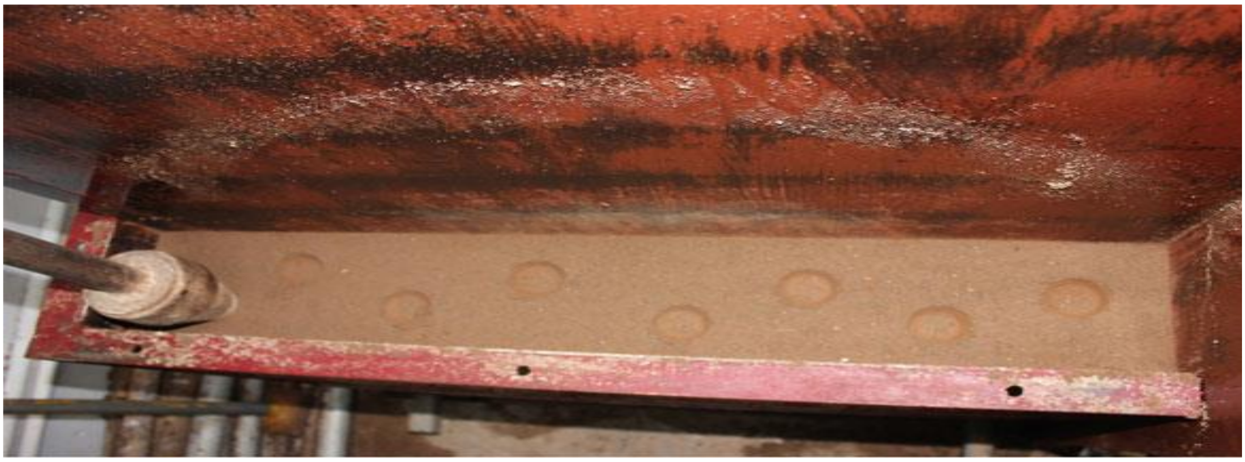


Figure 2.15 Dents made on the fresh compacted layer of RE wall (Venkatarama Reddy, 2022)

Figure 2.16 Part of the RE wall exposed during formwork stripping (Venkatarama Reddy, 2022)

Figure 2.17 Cement stabilised rammed earth wall covered with burlap for curing (Venkatarama Reddy, 2022)

3 Advantages and limitations of rammed earth constructions:

3.1 Advantages of rammed earth constructions

The building sector is responsible for more than 40% of the total emission of greenhouse gases, and it contributes to the high levels of pollution. According to ADEME 2015, the amount of waste from the building sector was around 44% of the total waste in France. This waste is usually not recyclable and is disposed of in landfills leading to loss of land and pollution. Thus, there is a necessity of alternative construction material which has more eco-friendly characteristics compared to concrete and steel. Earthen materials provide a viable solution to this problem since earth is available in abundance and can be sourced at the construction site. It reduces the consumption of natural resources not only during the construction but also during its lifetime. Thus, earthen construction such as rammed earth represents a sound alternative to conventional construction techniques, from both energetic and mineral resources point of view and, thus, exactly fulfills the criteria for the urgent and intense ecological transitions needed for the sustainability of society. It has numerous characteristics as a sustainable construction material, and the various advantages have been mentioned below (Chauhan, 2021):

1. Reduction of embodied energy: Embodied energy is the total energy consumed by all the processes associated with the production of building, from mining and processing of natural resources to manufacturing and transportation. The embodied energy required for an earthen material is around 1% of the energy needed for construction with cement-based materials. Morel et al. 2001, studied the environmental benefits of construction using local materials. A comparison was made between the energy consumed by a rammed earth house and a concrete house. It was found that rammed earth consumes less energy (70 GJ) compared to the concrete house (239GJ).

2. Hygro-regulator effect: Earthen construction leads to the reduction of operational energy due to the hygro-regulator effects. In atmospheric conditions where the relative humidity is high, earthen walls absorb moisture due to the presence of clay particles. When the relative humidity of the surrounding atmosphere becomes low, this absorbed vapor is released back. Thus, it helps in maintaining the hygroscopic conditions and reduce the need for air conditioning.

3. Thermo-regulator effect: It also reduces the operational energy due to the thermoregulatory effects. The hygro-regulatory effects discussed above also impact the average temperature inside the earthen building. During the hottest hours of the day, evaporation takes place in the earth mass which is an endothermic process which, requires heat and thus reduces the temperature of the surrounding. Similarly, during the cold hours of the day, condensation takes place in the earth mass, which is an exothermic process releasing heat and thus raises the temperature.

4. Recycling or demolition of building: The recycling and the demolition of the building also contribute to a significant amount of energy consumption. The amount of waste generated

from construction and demolition of a building is responsible for filling between 13-30% of the total landfills around the world. For raw earth construction, recycling is not a problem because the same earth can be reused for construction activity and does not need any landfills for its storage. This advantage is lost if the earth is stabilized using chemical binders. In addition to these advantages, earth construction has several other benefits such as acoustic insulation properties, fire resistance, etc.

3.2 Limitations of rammed earth constructions

Despite the numerous advantages of the earth with regards to sustainability, various limitations hinder the widespread use of earthen materials such as rammed earth for construction. One of the biggest limitations of using an earthen material is its sensitivity to water which makes its use challenging to be generalized. Indeed, moisture ingress in duce changes in the consistency of the earth from solid to plastic. This leads to a change in the mechanical strength and rigidity. When earthen structures are present in a dry climate, they are durable which can be seen from different historical monuments which are still in well-preserved conditions. On the other hand, in wet climatic conditions, durability and stability decrease, especially for unstabilized earth. Rainfall can cause surface erosion and capillarity from the ground surface leads to an increase in saturation and thus decrease in the strength and rigidity. These unfavorable humid pathologies lead to different problems and uncertainties in the stability of earthen buildings. Different measures can be followed to avoid these problems such as overhanging roofs and protective foundations. Despite that, the changes in relative humidity during typical working environment cannot be avoided. During the lifespan of the building, the ambient conditions are continuously evolving, which affect s the mechanical performance. Thus, the lack of characterization of this hydric influence is a major disadvantage for its direct practical application.

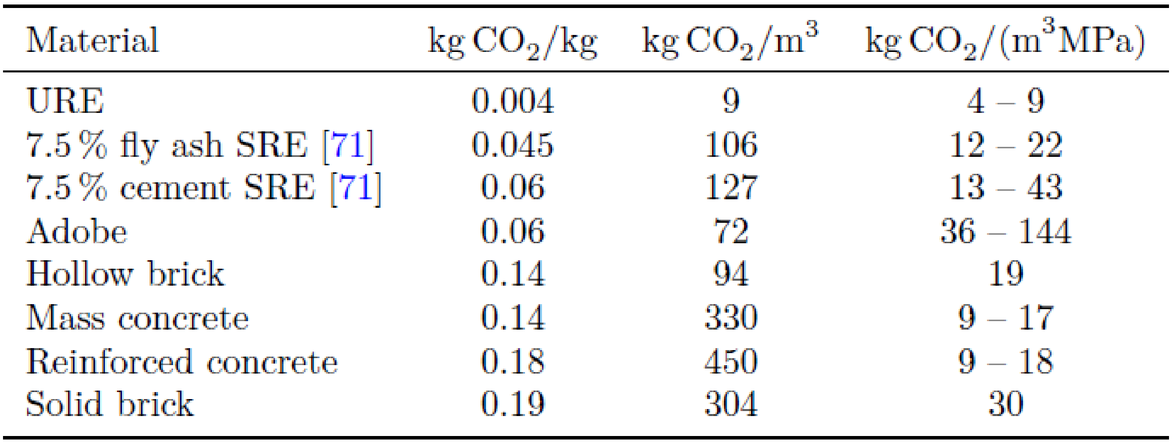
Another drawback that the earthen construction faces are the lack of technical guidelines and codal provisions. Although some countries have their own set of guidelines and standards, there are uncertainties in the design methodologies. In addition, there is a lack of coherence between guidelines from different countries. This is partly because of different environmental conditions in these countries which makes it difficult to be generalized. There is a lack of standardized procedures for the determination of mechanical parameters in the laboratory. Some of the procedures used are from concrete or soil mechanics which are not suitable since it does not take into account the properties specific to earthen materials (Chauhan,2021).

4 Environmental and economic benefits

4.1 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 (Minke et al. 2006, Walker et al. 2005 and Bestraten et al. 2011). 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 et al 2006, 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 CO2 emissions as a key indicator of the material environmental performance, it is possible to observe (Table 2.3) that unreinforced rammed earth (URE) generates lower emissions than any other building material or technique (Avila Cruces, 2023).

Table 2.3 CO2 emissions of main building materials. Emissions per weight, per volume and per volume and compressive strength (Avila Cruces, 2023)



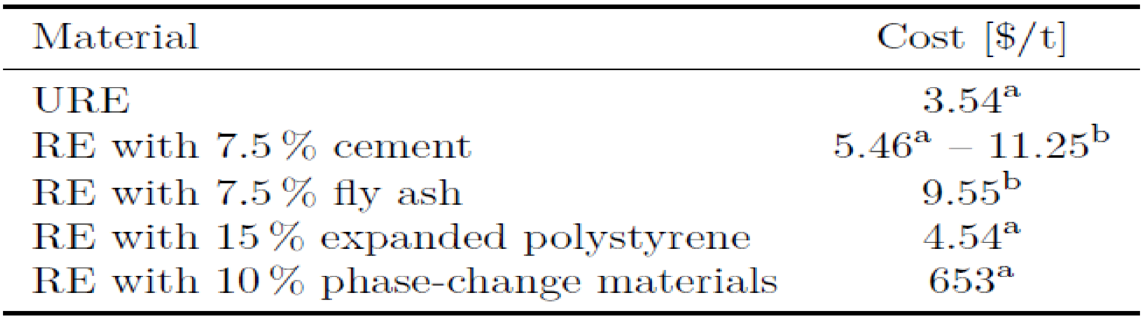
Material	kg CO_2/kg	kg CO_2/m^3	kg $CO_2/(m^3MPa)$
URE	0.004	9	4 – 9
7.5 % fly ash SRE [71]	0.045	106	12 – 22
7.5 % cement SRE [71]	0.06	127	13 – 43
Adobe	0.06	72	36 – 144
Hollow brick	0.14	94	19
Mass concrete	0.14	330	9 – 17
Reinforced concrete	0.18	450	9 – 18
Solid brick	0.19	304	30

Taking into account that between 20% and 40% of solid waste generated in developed countries comes from the construction and demolition sector, 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 (Avila Cruces, 2023).

4.2 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. These economic advantages make RE an excellent choice for lower-income countries and regions, where costs can be reduced from 30% to 60% compared to conventional concrete-based construction. In addition, the predominant use of manual labor contributes to the creation of local jobs. In countries where labor costs are high, the industrialization of the process (e.g. prefabricated RE) may help to reduce the overall costs. 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 Particle Size Distribution (PSD) of the soil, leading to higher material and transportation costs. Another way to improve the Rammed Earth material properties is the use of additives, although it also increases the manufacturing costs, as shown in Table2.4 (Avila Cruces,2023).

Table 2.4 Material cost of RE mixtures.



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]

4.3 Rammed Earth Structures—Potential and Prospects

The rammed earth can be used for different components of the building or the structure. The historical rammed earth structures, though bulky, showed the potential of rammed earth for the construction of the buildings. With the advent of knowledge on the soil stabilization and the construction techniques, the stabilised rammed earth has been explored for the building construction even in the seismically active areas. According to (Venkatarama Reddy, 2022), the R&D work on rammed earth pursued across the world touches upon the following aspects :

1. Optimization of mix proportions and mix design procedures
2. Mechanical characteristics and durability of rammed earth
3. Behavior of rammed earth under compression, shear and flexure
4. Fiber reinforced rammed earth
5. Reinforced rammed earth
6. Earthquake-resistant rammed earth structures
7. Prefabricated rammed earth elements.

Modern rammed earth construction has caught the attention of the architects, the engineers and the other building professionals, because of the inherent advantages of low embodied carbon and greenness, offering scope for aesthetically pleasing finishes and potential/scope to shape into different forms. Also, there is large scope for maximizing the utilization of local materials and resources, as well as the industrial by-products and the mining industry wastes (Venkatarama Reddy, 2022).

5 Conclusion:

This chapter has explored rammed earth as a sustainable and aesthetically pleasing construction technique, tracing its ancient roots to its modern adaptations. The durability and strength of rammed earth is an important issue to be addressed. Many examples of historical constructions in the world are clear evidence of the durability of this material if properly designed and maintained. Obviously, a better understanding of rammed earth from the mechanical and structural point of view will allow us to master its disadvantages and therefore pursuing advanced studies that will permit to protect our earth heritage and to consider its implementation in modern construction as a sustainable building material for the future application.

CHAPTER III : Geotechnical and Mechanical Properties of Rammed Earth

1 Introduction

This chapter provides an overview on the experimental testing methods used for the rammed earth characterization. In the first part, experimental tests used for the geotechnical characterization to obtain the particle size distribution and optimum moisture content are presented. The second part is devoted to the mechanical characterization including compression, tension and shear tests.

2 Geotechnical properties

2.1 Particle Size Distribution

The particle size distribution is one of the most important physical characteristics of soil. Classification of soils is mainly based on the particle size distribution which provides a description of soil based on a subdivision in discrete classes of particle sizes (Fabbri et al, 2022).

2.2 Standards and Procedures

Several standards for soil classification and particle size distribution exist. It is possible to separate them in two types: the wet sieving particle size for the coarser particles (> 80 μm) and the sedimentometry for the fine fraction (1–80 μm). It is important to specify that the laser granulometry is not suitable for the measurements of the granularity on clay soils, mainly because of the difficulties of dispersion of the particles. To be applied the previous dissolution of the soil in water and a wet method should be used.

North American standards (ASTM C136, 2014) deal with wet sieving and (ASTMD422, 2011) with sedimentometry. The British BS 1377 Part 2.9 (BS 1377-2, 1990) and Canada BNQ-2501-025 (BNQ 2501-025(2013) standards include procedures for wet sieving and sedimentometry. It is the same for the European standard EN ISO 17892-4 (ENISO 17892-4, 2018). Whether they are North American, British or European, they are very close or even similar in particular in characterization methods (sieving and sedimentation) (Fabbri et al, 2022).

Coarse soils are usually tested by sieving, but fine and mixed soils are usually tested by a combination of sieving and sedimentation, depending on the composition of the soil. The sieving method described is applicable to all non-cemented soils with particle sizes less than

125 mm. Two sedimentation methods are described: the hydrometer method and the pipette method.

The test method or combination of methods should be specified prior to testing or be selected on the following basis. If a sample has less than about 10% of particles smaller than 0.063 mm, sedimentation test is not normally required. If all particles of the sample are smaller than 2 mm and the sample has less than about 10% of particles larger than 0.063 mm, a full-sieve test is not normally required. For all other samples, a combination of a sieve test and a sedimentation should be performed in order to determine the full-particle size distribution (Fabbri et al, 2022).

2.3 Sieving method

The test consists of separating the agglomerated grains from a known mass of soil by fractionating it under water with a series of sieves and weighing the cumulative and dried rejection on each sieve (dried usually at 105 °C). The mass of the cumulative rejection for each sieve is related to the total dry mass of the soil sample submitted for analysis. Either a moist or a dry sample may be tested. The sieve test consists in the determination of the masses of material retained on the various sieves with decreasing diameter sizes. The number of sieves used and their aperture sizes shall be sufficient to ensure that any discontinuities in the grading curve are detected. In the standard EN ISO 17892-4 (ENISO 17892-4, 2018), it is recommended (but not imposed) to use the sieves of 63, 20, 6.3, 2.0, 0.63, 0.20, 0.0063 mm because these values represent the size limits for coarse materials as defined in EN ISO 14688-1 (ENISO 14688-1, 2018).

Dry sieving is not appropriate particularly for clayey earths/soils because grains that result from the agglomeration of particles are sieved without separation (Fabbri et al, 2022).

2.4 Sedimentation

Based on the Stokes’ law, the method is based on the measurement of the sedimentation time of solid particles in suspension in a solution of water mixed with sodium hex a meta phosphate as a deflocculating agent. The sedimentation analysis is an analysis completing the sieving analysis for particles usually with a diameter of less than 80 µm. The test is based on the fact that in a liquid in which a deflocculating agent has been added (sodium hex a meta phosphate), the decantation rate of the fine particles depends on their size. The principle follows Stokes’ law linking the diameter of the grains and their sedimentation rate. By convention, this law is applied to the elements of a soil to determine the equivalent diameters of the particles.

The test can be carried out using two different methods (Fabbri et al, 2022):

2.4.1 Hydrometer method

A part of the soil is dried then mixed with water containing the dispersing agent, and then the hydrometer is introduced into the graduated cylinder. The density of the mixture is measured with the hydrometer at various time intervals (e.g.: 30 s, 1 min, 2 min, 4 min, 8 min, 30 min, 1 h, 2 h and 24 h). From the density measured at a given time, the size of the suspended particles can be determined. The hydrometer shall be torpedo shaped, made of glass, as free as possible from visible defects and preferably manufactured to a national standard. The hydrometer stem and bulb shall be circular in cross section and symmetrical around the main axis, without abrupt change in cross section.

2.4.2 Pipette method

Based on the same principle and theory, the pipette method consists of taking a fraction of the mixture (soil dispersed in water containing a dispersant) at different times and depths, and then drying and weighing the residue. It is also possible to initially define the particle sizes in order to know their quantity, and then calculate the corresponding sampling times. The pipette shall have a nominal volume of 2% of the volume of the soil suspension and shall be mounted in a pipette configuration.

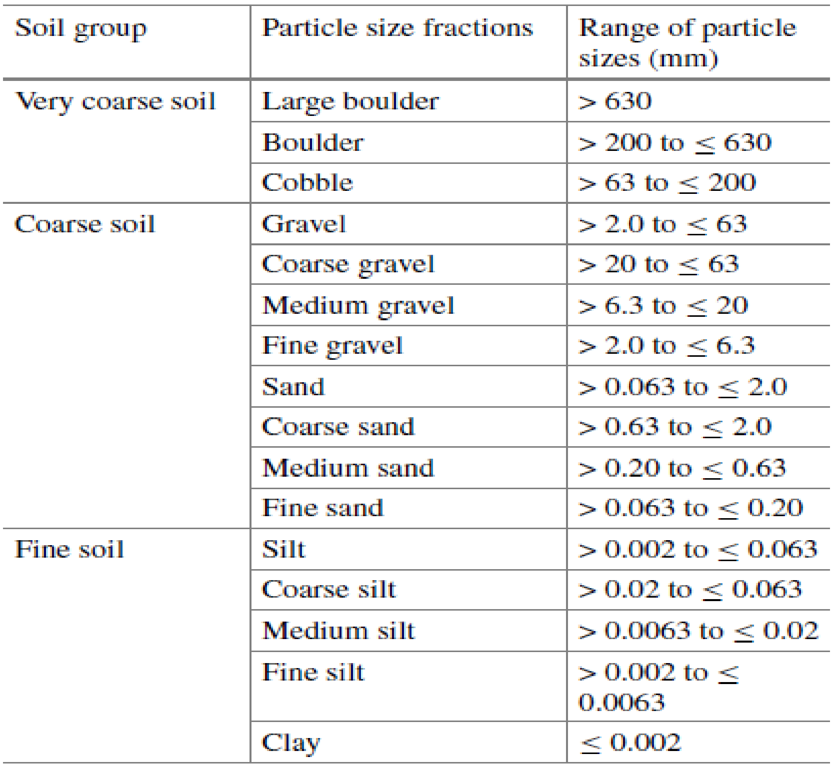
This sedimentation measurement method has also been automated and modernized with the use of a sedigraph. An X-ray beam measures the concentration of suspended particles at a sedimentation height that decreases with time. The particle diameters are obtained instantly corresponding to the elapsed time and sedimentation height.

A source of error in these different procedures could be linked to the incomplete dispersion of soil clays. If clay particles are not separated correctly, they form aggregates with a larger size. It results in low values for clay and high values for silt and sand. The rate of sedimentation is also affected by temperature, the density of the dispersing solution and by a too abrupt introduction of the hydrometer or of the pipette.

2.5 Soil classification

As defined in the standard EN ISO 14688-1 (ENISO 14688-1, 2018). Table 3.1 shows the terms to be used for each size fraction, together with the corresponding range of particle sizes. Clay can be defined from a granular point of view (particle size) and also from a geological point of view (mineral composition). But, in most publications, clay is defined as a particle with a diameter of less than 2 μm. According to the standards and their origin, the limits between the particle size and their names can vary, especially the limit silt–sand. In the standards EN ISO 14688-1 (ENISO 14688-1, 2018), USDA (USDA, 1987) and ASTM-D2487 (ASTM-D2487, 2017), this limit is fixed respectively to 0.063 mm, 0.05 mm and 0.075 mm.

Table 3.1 Particle size fractions according to the EN ISO 14688-1 (Fabbri et al, 2022)



Soil group	Particle size fractions	Range of particle sizes (mm)
Very coarse soil	Large boulder	> 630
	Boulder	> 200 to ≤ 630
	Cobble	> 63 to ≤ 200
Coarse soil	Gravel	> 2.0 to ≤ 63
	Coarse gravel	> 20 to ≤ 63
	Medium gravel	> 6.3 to ≤ 20
	Fine gravel	> 2.0 to ≤ 6.3
	Sand	> 0.063 to ≤ 2.0
	Coarse sand	> 0.63 to ≤ 2.0
	Medium sand	> 0.20 to ≤ 0.63
	Fine sand	> 0.063 to ≤ 0.20
Fine soil	Silt	> 0.002 to ≤ 0.063
	Coarse silt	> 0.02 to ≤ 0.063
	Medium silt	> 0.0063 to ≤ 0.02
	Fine silt	> 0.002 to ≤ 0.0063
	Clay	≤ 0.002

2.6 Granulometry

The granulometry is a key factor for the suitability of the soil as rammed earth material. The particle size distribution curve is obtained from a combination of dry and wet sieving, and sedimentometry. The composition of rammed earth soil is analogous to concrete. It contains an inert aggregate fraction (sand and gravel) and a binding agent (silt and clay). The relative proportions of gravels, silts, sand, and clay providing a well graded material are more suitable for construction as it makes it possible to reach a high degree of imbrications of grains.

Houben et al. 1994 suggested a range of particle size distribution for the soil to be suitable for rammed earth construction purposes (Figure 3.1). It means that if the particle size distribution of the soil is within the envelope proposed, the soil can be used as rammed earth material. It is the most well-known guideline related to the granulometry of the soil.

However, there is evidence in the literature that granulometry is not sufficient for the suitability of soil. Ciancio et al. 2013 highlighted that it is not always recommended to predict the mechanical performance of rammed earth only on the basis of soil properties. Hall et al. 2004 studied the compressive strength of 10 different soil mixes corresponding to the particle size distribution parameters suggested (Figure 3.1). It was found out that only 4 out of 10 samples had sufficient compressive strength of 1.3 MPa according to (Zealand, NZS 4297:1998 Engineering design of earth building 4297(1998) 60) standards.

Other studies such as Champire et al. 2016 studied three different soils (labelled as STR, CRA, and ALX) which came from old rammed earth buildings. The particle size distribution curve (Figure 3.2) shows that the soils were not in the envelope proposed by Houben et al. 1994. They concluded that granulometry cannot be solely used as a criterion for suitability of soil as rammed earth material. It was suggested that nature of clay is useful in addition to amount of clay, which is characterized by granulometry (Chauhan, 2021).

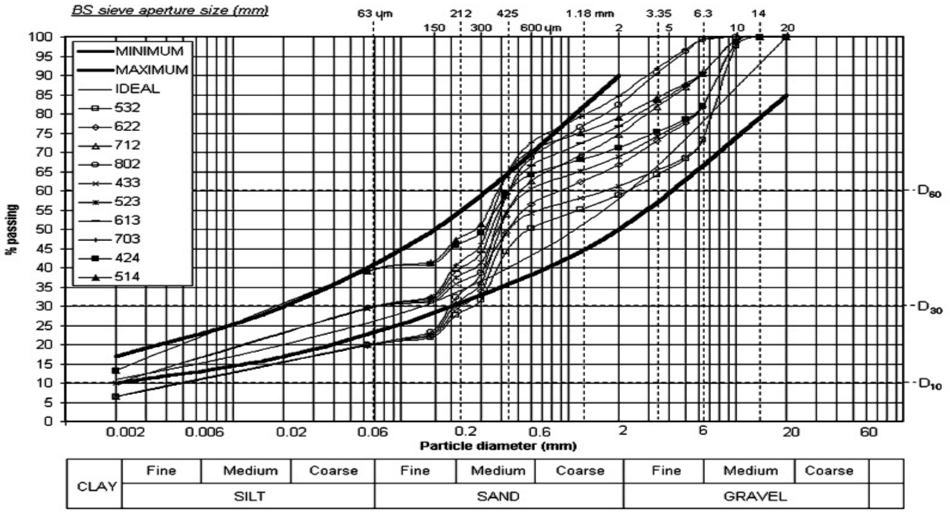


Figure 3.1 Particle size distribution of different soil mixes and limit envelopes according to (Chauhan, 2021) (Houben et al. 1994)

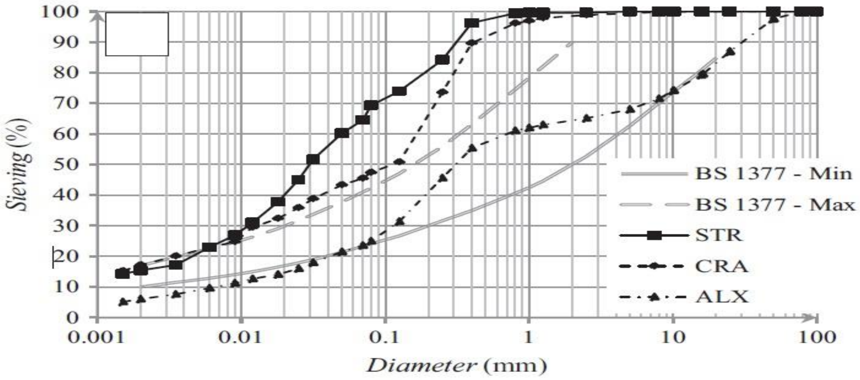


Figure 3.2 Particle size distribution of tested material and upper and lower bounds according to (chauhan, 2021) (Houben et al. 1994) represented as BS1377-Min and BS1377-Max

2.7 Optimum Moisture Content and Dry density

Dry density is one of the main parameters influencing the strength of rammed earth. The dry density is dependent on the granulometry, moisture content during compaction, the energy input for compaction, and the type of compaction (static or dynamic). The dry density value for different earth structures usually ranges from 1700 kg/m3 to 2200 kg/m3.

In order to achieve the maximum dry density, it is important to determine the optimum moisture content (OMC) and the appropriate method of compaction for determination of OMC. Different compaction techniques have been used in the literature such as ‘standard’ Proctor test using 2.5 kg rammer and ‘modified’ Proctor tests using 4.5 kg rammer (BS 1377-4, 1990), vibrating hammer generally used for granular soils, heavy manual compaction test etc., (Chauhan, 2021). 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 an OMC that could be excessively high (Kouakou et al, 2009) (Hartzler, 1996) (Avila cruces, 2023).

Various authors studied the variation of compressive strength with the dry density obtained after compaction. Morel et al, 2007 studied the compressive strength of compressed earth blocs (CEBs) for unsterilized soil and soil stabilised with cement. Figure 3.3 shows that the compressive strength increases with increase in dry density. Jaquin et al, 2009 used vibrating hammer test to determine the optimum moisture content (Figure 3.4). Burroughs, 2010 used modified Proctor test as the compaction effort applied provides a greater simulation of compaction to on-site ramming.

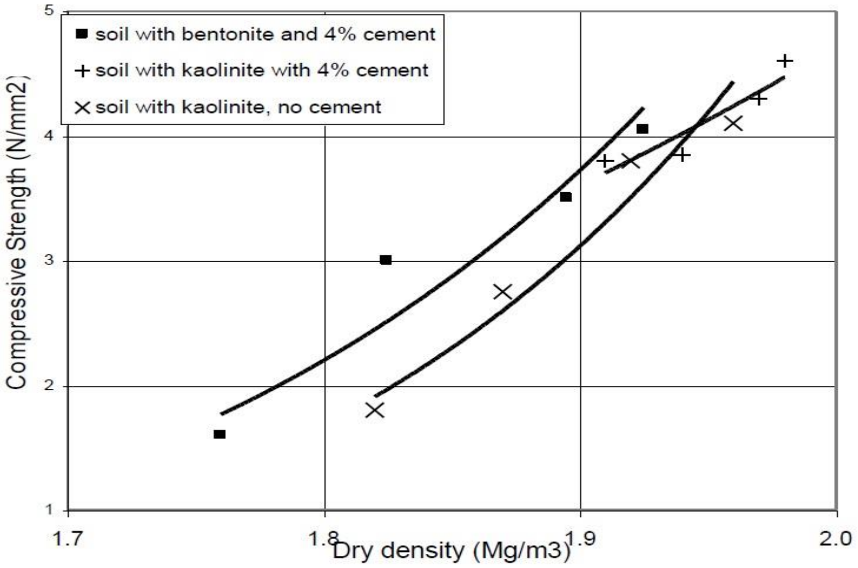


Figure 3.3 Variation of compressive strength with dry density for different types of soil (Chauhan, 2021)

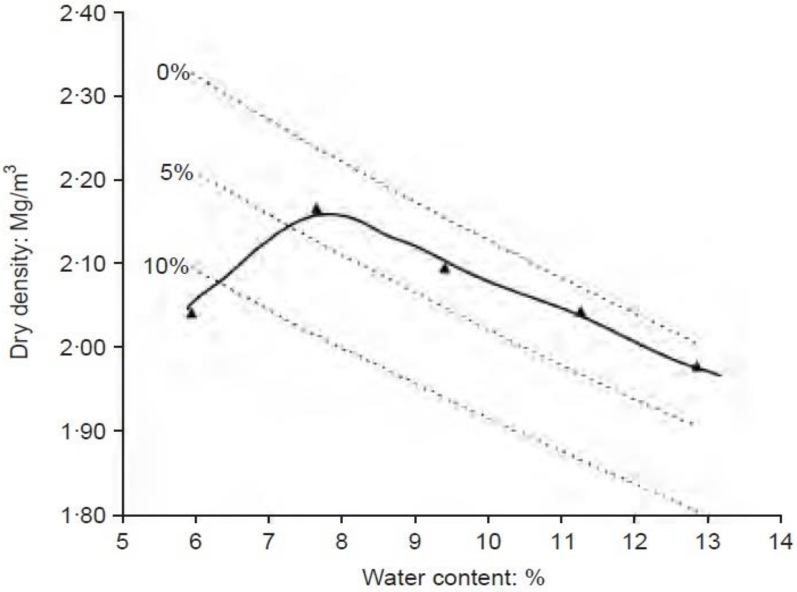
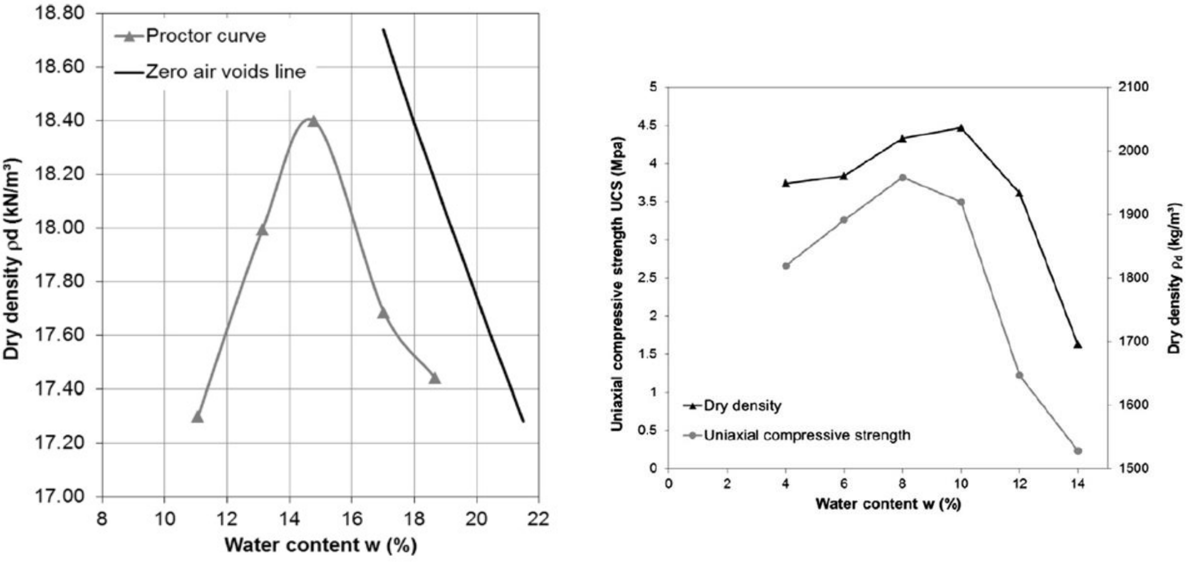


Figure 3.4 Determination of OMC using vibrating hammer test (Chauhan, 2021) (Jaquin et al. 2009)

Beckett et al, 2012 used the Light Proctor test for optimum moisture determination in accordance with British Standard BS 1377- Part4: Compaction following the work of Hall et al, 2004. Gerard et al, 2015 determined the optimum compaction conditions using a specific Proctor method. Dynamical compaction of soil in layers imparting greater compaction energy than standard Proctor was done at different moisture contents. The compaction of each layer was achieved when the handle of the hammer (2.5 kg) “rings” when dropped over the compacted soil. These samples were further tested in uniaxial loading condition to obtain the uniaxial compressive strength and dry density in function of compaction water content. Based on the compressive strength value, the optimum conditions of compaction (OMC = 8% and ρd= 2000 kg/m3) were chosen (Figure 3.5b).

This kind of specific Proctor provides a much denser sample as compared to standard Proctor where the maximum dry density reached was 1840 kg/m3 (Figure 3.5a). The comparison of dry density between these two methods has been shown in Figure 3.5b.



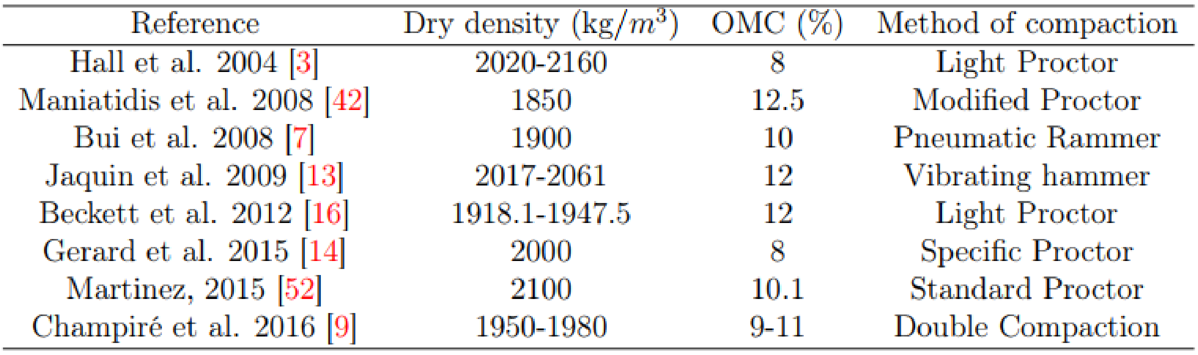
(a) Standard Proctor curve of the soil studied

(b) Uniaxial compressive strength and dry density as a function of compaction water content

Figure 3.5 Comparison of dry density between the standard Proctor test (a) and specific Proctor method (b) (Chauhan, 2021)

The different methods of compaction used in the literature to determine the optimum moisture content for maximum dry density have been summarized in Table 3.2. Thus, different methods have been used in the literature to determine the optimum conditions with the objective is to reach the dry density of rammed earth walls.

Table 3.2 Dry density and OMC from different experimental campaigns on rammed earth (Chauhan, 2021)



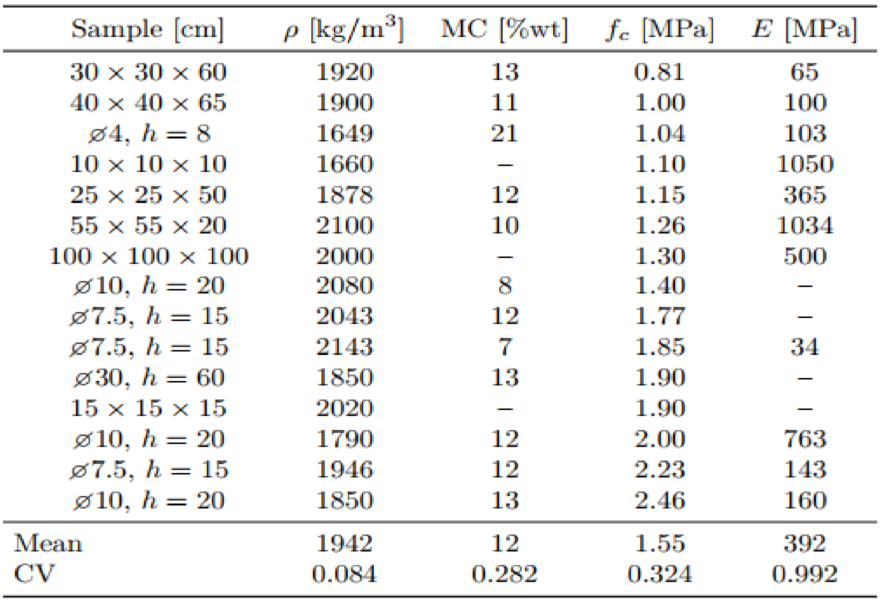
Reference	Dry density (kg/m^3)	OMC (%)	Method of compaction
Hall et al. 2004 [3]	2020-2160	8	Light Proctor
Maniatidis et al. 2008 [42]	1850	12.5	Modified Proctor
Bui et al. 2008 [7]	1900	10	Pneumatic Rammer
Jaquin et al. 2009 [13]	2017-2061	12	Vibrating hammer
Beckett et al. 2012 [16]	1918.1-1947.5	12	Light Proctor
Gerard et al. 2015 [14]	2000	8	Specific Proctor
Martinez, 2015 [52]	2100	10.1	Standard Proctor
Champiré et al. 2016 [9]	1950-1980	9-11	Double Compaction

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 3.3), most of them using small-size samples with different shapes and only a few (Maniatidis et al, 2008) (Miccoli et al, 2015) (Bui et al, 2019) 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 1.0MPa to 2.5MPa, excluding some few exceptions (Avila cruces, 2023).

Table 3.3 Density (ρ), moisture content (MC), compressive strength (fc) and elastic modulus(E) of unstabilized rammed earth (Avila cruces, 2023)



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

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 (Bui et al,2019) standard for compressive strength of soil cement cylinders (Corbin et al, 2014) or proposed specific procedures derived from ASTM standards for cement mortars (Loccarini et al, 2020) and from masonry design rules (ASTM, D1633-17. Standard test methods for compressive strength of molded soil cement cylinders, 2017).

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), (Ruzicka et al, 2015) (Lenci et al, 2012) but the relation between these parameters and the UCS of RE is still unclear. Figure 3.6 shows that an increase in the material density leads to a greater UCS, although there is a very significant dispersion. Maniatidis and Walker (ASTN, D1633-17 Standard test methods for compressive strength of molded soil cement cylinders, 2017) conducted compression tests on samples with different sizes and shapes, conclude scale cylinders (10 cm, h = 20 cm) and full-scale prisms (30×30×60 cm3) 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 20mm. Also, Sajad et al, 2019 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 (Rocha et al, 2014) (ASTN, D1633-17, 2017) (Sajad et al, 2019) 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 form work 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 (Avila cruces, 2023).

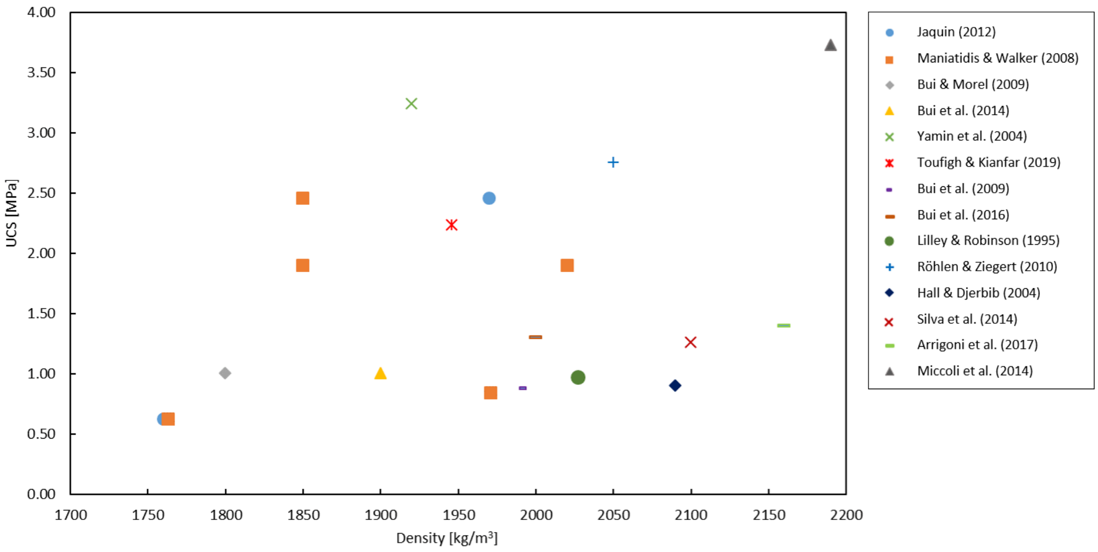


Figure 3.6 Unconfined compressive strength (UCS) as a function of density (Avila cruces, 2023)

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 2014) 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 1MPa to 2.5MPa (Avila cruces,2023).

3.2 Tensile strength

As happens with any other type of earth construction, RE has very low strength in tension and shear, especially when moist (Bui et al, 2014), meaning that RE 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), (Kosarimovahhed et al 2020, soudani et al 2016) it is often neglected in design and has not been yet thoroughly studied. Authors studying this parameter have carried out Brazilian tests (Bui et al 2016) or pull-off tests (Raj et al 2018) 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 0.35MPa, which are in accordance with the values found in literature (Minke et al, 2006) (Bui et al, 2016) (Soebarto et al, 2016) (Taylor et al, 2008).

Bui et al. (Kosarimovahhed et al 2020) 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 that 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 (Avila cruces, 2023).

3.3 Shear Strength

The rammed earth is a monolithic material with visible stratified compacted layers. Since the rammed earth is monolithic, it ultimately fails in shear mode even under concentric compressive loads (Walker et al. 2005; Jayasinghe 2007; Jayasinghe and Kamaladasa 2007; Bui et al. 2007; Reddy and Kumar 2009, 2011). Figure 3.7 shows typical shear failures of RE specimens (Cylinder, Wallette and wall) when subjected to compression. In rammed earth, shear slip can occur due to a shearing action along the interface of rammed earth layers. Also, the diagonal tension failure occurs due to poor shear strength of rammed earth material. The behavior of rammed earth under shear needs to be understood with reference to: (a) establishing the shear strength parameters and the failure envelopes and (b) global behavior under raking or in-plane loads causing shear failure of the rammed earth structural elements.

The shear strength of the rammed earth parallel to the compacted layers can be determined through the triplet shear tests and the raking in plane shear tests on the Wallette's. The diagonal shear test is another technique used for assessing the shear strength indirectly. The ASTM E519-15 code gives diagonal tension (shear) test procedure for the masonry. This procedure can be adopted to assess the diagonal shear strength of the rammed earth.

(a) **(b)**

Figure 3.7 Failure patterns for RE prism, (a) Cylinder and (b) Wallette specimen (Venkatarama reddy, 2022)

3.3.1 Triplet Shear Strength

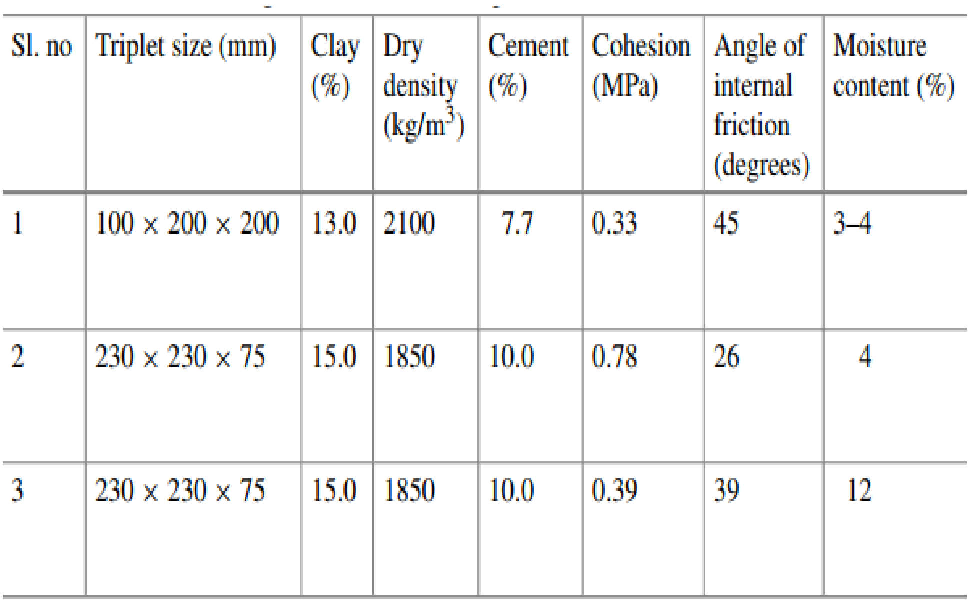
Figure 3.8 shows a triplet shear test setup. The test setup ensures that shearing takes place at the interface of the compacted layers. The RE triplets can be subjected to normal stress in the form of pre compression, while assessing the shear strength of the interface between the compacted layers as shown in Figure 3.9. The investigations of Pavan et al. 2020b show linear relationships for the normal stress and the shear stress. Figure 3.9 shows typical failure at the interfaces of a RE triplet (Venkatarama reddy, 2022).

Figure 3.8 Triplet shear test set-up (Venkatarama reddy, 2022)

Figure 3.9 Failure along the interfaces of triplet specimen (Venkatarama reddy, 2022)

The shear strength parameters determined using triplet shear test are given in Table 3.4, (Venkatarama reddy, 2022) (Cheah et al. 2012) (Pavan et al. 2020a). Using 7–10% cement and soil with 13–15% clay (optimum clay), the results show that the cohesion is in the range 0.3–0.8 MPa. The cohesion value reduces by alfin the wet condition. The angle of internal friction varies in between 26 and 45°.

Table 3.4 Shear strength of RE from triplet shear tests (Venkatarama reddy, 2022)



Sl. no	Triplet size (mm)	Clay (%)	Dry density (kg/m^3)	Cement (%)	Cohesion (MPa)	Angle of internal friction (degrees)	Moisture content (%)
1	100 × 200 × 200	13.0	2100	7.7	0.33	45	3–4
2	230 × 230 × 75	15.0	1850	10.0	0.78	26	4
3	230 × 230 × 75	15.0	1850	10.0	0.39	39	12

3.3.2 Diagonal Tension (Shear) Strength

The diagonal tension test on a square rammed earth panel can be used for assessing the shear strength of the rammed earth indirectly following the test procedure given for the masonry inASTME519-15 code. Figure 3.10 shows the diagonal tension test setup, where the displacements and the related strains along both the diagonals can be monitored. These strains can be used to determine shear strains. When the vertical load is applied onto the steel loading shoes along the diagonal, causing compression along the loaded diagonal, and tension along the other horizontal diagonal. A state of pure shear is created in the central region of the diagonal panel (Venkatarama reddy, 2022).

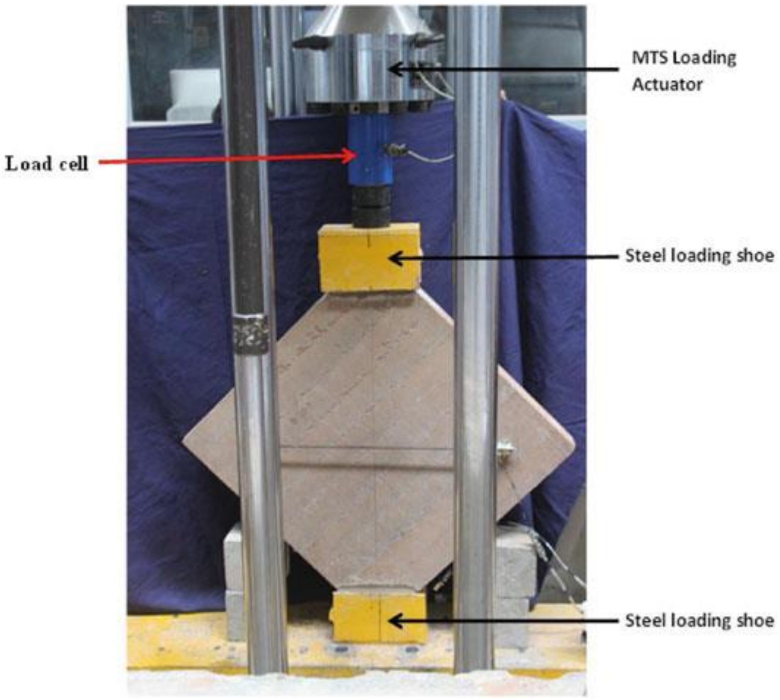


Figure 3.10 Diagonal tension (shear) test set-up (Venkatarama reddy, 2022)

The shear stress (τ), shear strain (γ) and shear modulus (G) of the rammed earth panels can be calculated as per ASTM standard (ASTM-E519) procedure, as follows:

$$\tau = 0.707\ (P \div A)$$

$$\gamma = \varepsilon h + \varepsilon v$$

$$G = (\tau \div \gamma)$$

Where:

A = [(h + w) t] ÷ 2; h, w, t are height, width and thickness of the rammed earth panel, respectively,

P = Applied load along the vertical diagonal,

εh = strain along the horizontal diagonal,

εv = strain along the vertical diagonal.

Figure 3.11 shows the typical failure pattern of the RE diagonal test panels. The diagonal panels failed due to the development of splitting vertical cracks across the rammed earth layers along the loaded diagonal. The shear slip or sliding shear mode of failure is absent in the diagonal tests. Such failure modes are mainly attributed to higher interfacial shear strength of RE than the material shear strength. The investigations of Pavan et al. 2020b showed a diagonal shear strength for 10% cement RE panels as (1850 kg/m3 dry density) 1.24 and 0.75 MPa for the dry and wet cases, respectively. The corresponding shear strains at the peak stress were 0.00061 and 0.00043 for the dry and the wet cases, respectively. The secant shear modulus at 50% of peak shear stress was found to be 3700 and 2700 MPa for the dry and the wet cases respectively. The specimen moisture content at the time of the testing, in the so investigations was 3 and 12% for the dry and the wet cases, respectively (Venkatarama reddy, 2022).

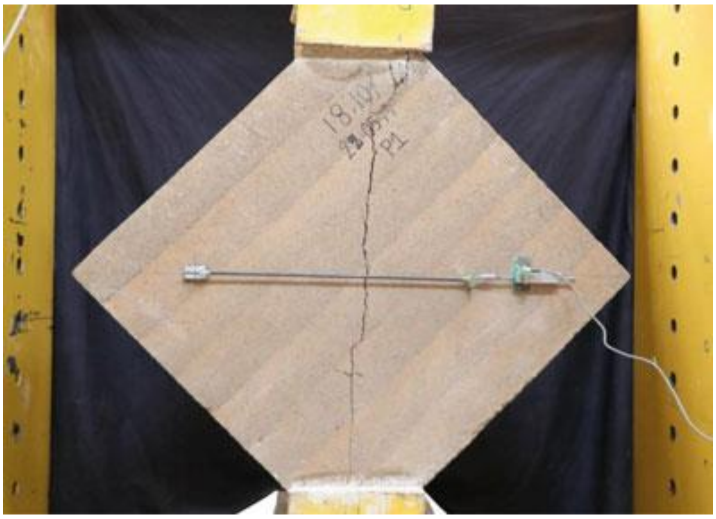


Figure 3.11 Failure along the loaded diagonal of the diagonal tension test on RE panel (Venkatarama reddy, 2022)

4 Conclusion

Despite the interest toward the evaluation of the granulometry of the soil for rammed earth material, it has been affirmed that granulometry is not a necessary factor for the suitability of soil for rammed earth construction and a large variety a soil types can be used. On the other hand, dry density is found to be one of the main parameters influencing the strength of rammed earth. The compressive strength of rammed earth increases with increase in dry density and observed to have a value between 1 MPa and 2.5MPa. However, its tension and shear strength found to be very low.

CHAPTER IV : Experimental Program - Part 01 : Identifying the Geotechnical Properties of Rammed Earth

1 Introduction

The earth material used for this study was obtained from the soil of the Dokane commune at Tebessa region in Algeria. In this chapter, its geotechnical characterization including particle size distribution (PSD), optimum moisture content (OMC) and dry density are presented and discussed.

2 Particle Size Distribution (PSD)

The percentage of different size of particles of the studied earth material was measured using the particle size analysis, by both: dry and wet sieving analysis for the coarse particles, then completed by sedimentation analysis for the fine particles, in accordance with the European Standards [NF P 94-056], [XP P 94-041] and [NF P 94-057].

2.1 Sieve Analysis:

Four (4) kg of the earth material was first oven-dried for 24 hours then sieved through 5 mm sieve in order to have a representative elementary volume for the small-scale samples to be manufactured.

The wet sieving is carried out by washing the earth material through a series of sieves for particle size greater than 80 µm, which are: 80 µm, 100 µm, 140 µm, 200 µm, 280 µm, 400 µm, 560 µm, 800 µm, 1,25 mm, 1,6 mm, 2,5 mm. The retained particles are then oven-dried for 24 hours and sieved through the aforementioned sieves (Figure 4.1). The dry weights of the earth particles retained on each sieve are then noted and used for finer (%) measurements. The resulted particle size distribution curve from the sieve analysis is shown in Figure 4.5.

Figure 4.1 The sieving machine used for the sieve analysis

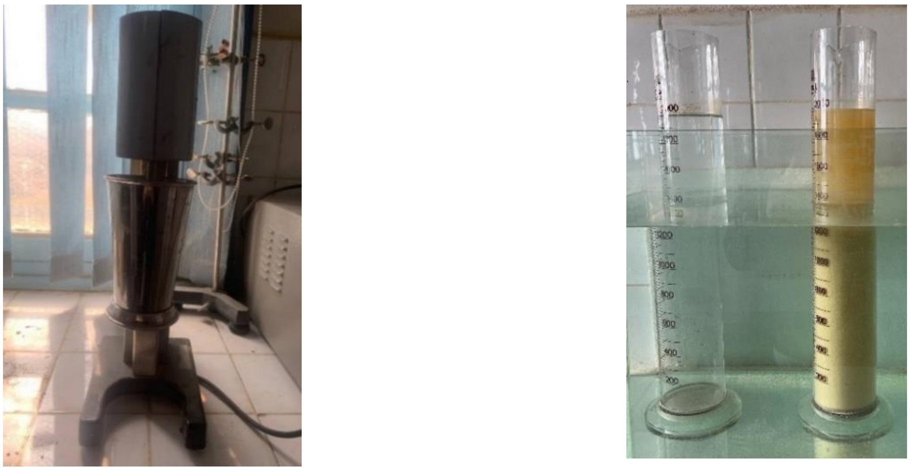
2.2 Sedimentation Analysis:

The sedimentation analysis is performed on the particles passing through 80 µm sieve. It is based on the density variations measurements during the sedimentation process using a hydrometer. The size of the particles is determined from the density measurements of the mixture at various time intervals (30 s, 1 min, 2 min, 4 min, 8 min, 30 min, 1 h, 2 h and 24 h).

First, 80 grams of the passing is mixed in a cylindrical glass cup containing water and a dispersing agent to disaggregate the particles (Figure 4.2). The mixture is then placed in a graduated glass cylinder and completed with distilled water until reaching 2000 ml and placed in a bath equipped with thermometer, together with another graduated glass cylinder filled with only distilled water for the hydrometer cleaning procedure (Figure 4.3).

(a) **(b)** **(c)**

Figure 4.2 80g of the passing (a), dispersing agent (b) and the resulted mixture (c)



(a) **(b)**

Figure 4.3 Earth material dispersion mixer (a) and the prepared two graduated glass cylinders (b)

In the beginning of the test, the mixture in the graduated cylinder is agitated first, then the hydrometer is introduced in the mixture to quantify the density at each time intervals indicated above. The temperature is also noted at different time intervals (Table 4.1). The sedimentation test apparatus is presented in Figure 4.4.

Table 4.1 Hydrometer and Temperature readings at various time intervals

Elapsed time (Minutes)	Temperature (°C)	Actual Hydrometer Reading
½	24.5	1020.1
1	24.5	1018.2
2	24.5	1017.5
5	24.5	1016.9
10	24.5	1016.7
20	24.5	1016
40	24.7	1015.2
80	24.9	1014.5
160	24.9	1014
320	24.9	1013
1440	24.5	1009

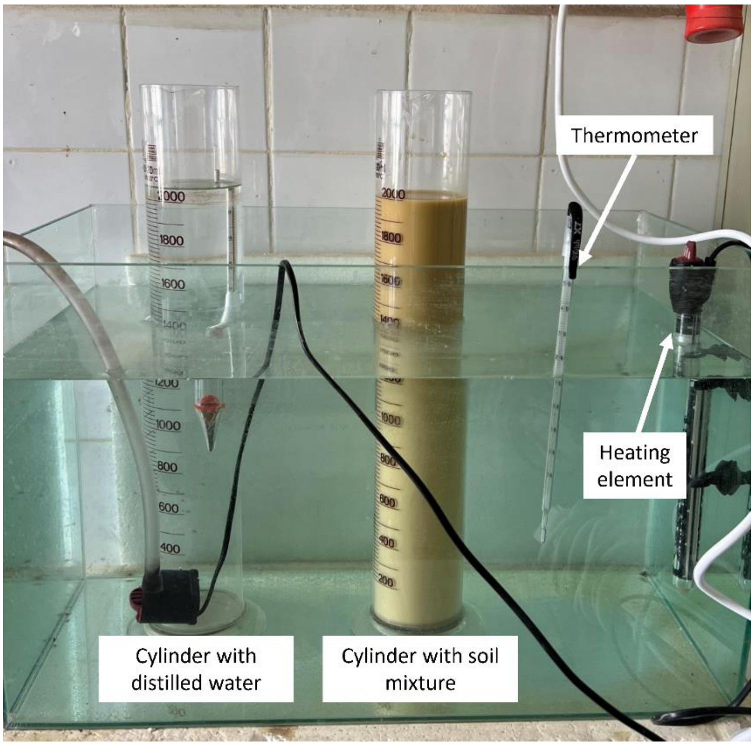


Figure 4.4 The sedimentation test apparatus

Particle size distribution obtained from sieve analysis are combined with the results from the hydrometer analysis and illustrated in Figure 4.5. The PSD curve is compared to an envelope curve adapted from recent findings and found to be in agreement. The envelope curve is taking into account the PSD results obtained in: (Houben and al. 1994), (Bui and Morel, 2009), (Toufigh and Kianfar, 2019), (Nowamooz and Chazallon, 2011) and (Silva et al., 2014), which means that the studied earth material is accepted for the rammed earth construction process.

The PSD results shows that the studied earth material is a coarse soil containing only 10 % of finer particles. However, as found in the literature, almost any type of local soil can be used as a source material for rammed earth construction (Avila Cruces, 2023).

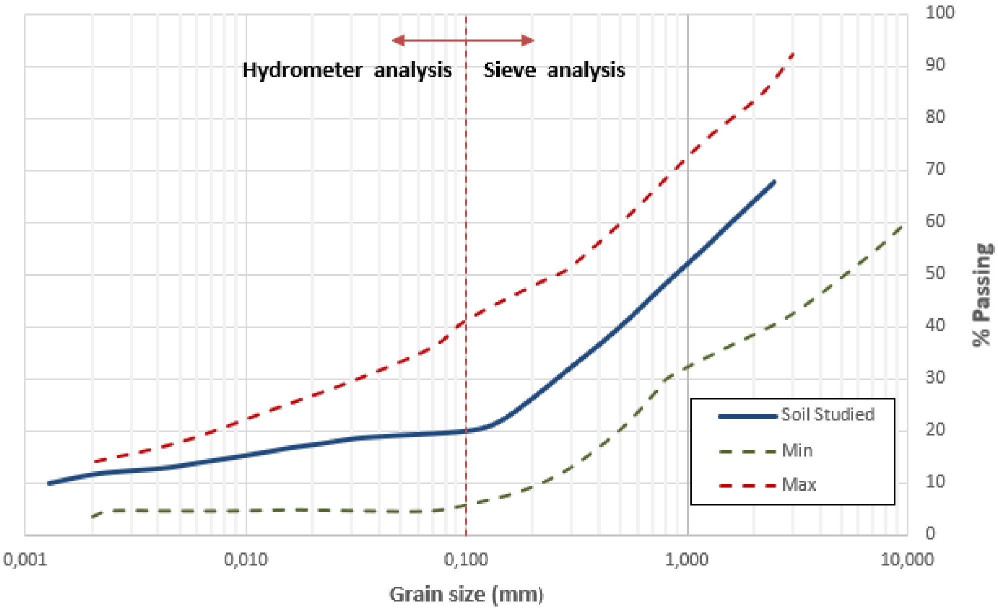


Figure 4.5 Particle size distribution curve of the studied earth material compared to a curve envelope adapted from the literature

3 The Standard Proctor test:

The standard Proctor test is carried out to investigate the Optimum Moisture Content (OMC) and Dry density of the studied earth material. The test preparation and procedure are performed in accordance with the standard NF P 94-093.

The test consists of humidifying the studied earth material with several water contents values (8%, 10%, 12%, 14% and 16%). The moist soil is then introduced in the standard Proctor mold and compacted within Three layers (Figure 4.6a). A 2.49 kg hammer is used for the compaction process performing 25 blows on each layer (Figure 4.6b). The compaction energy resulted from the compaction process is calculated based on the Equation 01 and found to be equal to 572 J/m3 based on a free fall height of 0.305 m (NF P 94-093). However, it is worth mentioning that the compaction energy applied on the rammed earth walls in the construction process in not the same as the one applied in the Proctor compaction laboratory tests (Avila Cruces, 2023). The cylindrical proctor specimens resulted from the compaction process are presented in Figure 4.7.

$$E = \frac{HmgN_1N_2}{V_{mold}} \tag{1}$$

Where:

H: Height of free fall of the hammer

m: Mass of the Hammer

N_1: Number of layers

N_2: Number of blows

V_{mold}: Volume of the mold

For each of the water content values, the dry density of the earth material is calculated and the OMC curve (variations of dry density vs the moisture content) is established. The OMC vs dry density curve is presented in Figure 4.8.

(a) **(b)**

Figure 4.6 Partitioning the earth material to three layers (a) and compaction of the third layer in the proctor mold (b)

The OMC is then determined based on the variation of the dry density and found to be equal to 12.6% (Table 4.2).

Table 4.2 Standard Proctor test results

Optimum Moisture Content (%)	Dry Density (g/cm3)
12.6	1,91

Figure 4.7 Standard Proctor cylindrical specimens after compaction

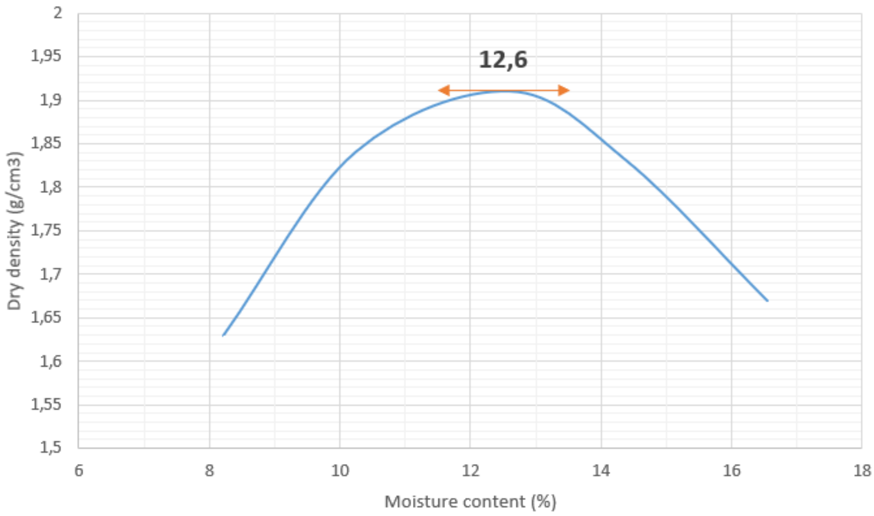


Figure 4.8 Optimum moisture content Vs Dry density curve

4 Conclusion

This chapter focused on the evaluation of the geotechnical properties for the studied rammed earth material. For the particle size distribution, two types of analysis have been performed: sieve and sedimentation analysis. Sieving has been evaluated with dry and wet methods to capture the particle size greater than 80 µm. For the particles passing through 80 µm, sedimentation method has been performed. The PSD curve resulted from the combination of the two methods showed that the studied earth material is a coarse soil containing only 10% of finer particles. Furthermore, a standard proctor test has been performed to obtain the OMC and dry density. The results indicated an OMC equal to 12.6% which will be used in the next chapter for the rammed earth specimen mixture.

CHAPTER V : Experimental Program - Part 02 : Identifying the Mechanical Properties of Rammed Earth

1 Introduction

This chapter focused on the mechanical characterization of the studied rammed earth material. First, specimen preparation is presented showing the different mixture used in the case of stabilization and reinforcement. Afterward, the mechanical characterization tests of the studied rammed earth material including the test set-up and the digital image correlation analysis are presented. The results of the normal to layers compression test and diagonal compression test are then discussed.

2 Specimen Preparation

2.1 Stabilized specimens

First, the earth material without stabilization is prepared in a recipient to be mixed with 12% water content corresponding to the OMC found in Chapter 04 (Figure 5.1). A wooden mold is manufactured for the rammed earth compaction process with a dimension of 10x10x30cm. The mold is well tightened using two clamps to prevent buckling and tilting during compaction as indicated in Figure 5.2.

Figure 5.1 The earth material prepared for the specimen manufacture

(a) **(b)**

Figure 5.2 The ma-nufactured wooden mold dimensions (a) and (b)

The moist earth material is then introduced in the wooden mold and compacted in three (3) layers. To have the same layer thickness for all specimen, the earth material is divided and weighed for each test. The same 2.49 kg hammer of the Proctor test is used here for the rammed earth compaction process performing 25 blows on each layer. At the end of the compaction process, the rammed earth specimens are unmolded immediately and left for 28 days. The resulting 10x10x20cm prismatic specimens are shown in Figure 5.3.

Figure 5.3 10x10x20cm prismatic specimens without Stabilization

For the stabilized specimens, 3% of cement or lime are used and added to the mixture with the same water content of 12% (Figure 5.4). Same compaction process is also used for the stabilized specimens. The resulting prismatic specimens are shown in Figures 5.5 and 5.6.

(a) **(b)**

Figure 5.4 The stabilization material used: Lime (a) and Cement (b)

Figure 5.5 10x10x20cm prismatic specimens with Lime Stabilization

Figure 5.6 10x10x20cm prismatic specimens with Cement Stabilization

2.2 Reinforced specimens

The earth material without reinforcement is prepared first and mixed with 12% of water. The wooden mold in this case has a dimension of 10x20x40cm well tightened also with two clamps as shows in Figure 5.7.

The moist earth material is then poured in the 10x20x40cm wooden mold and compacted in three (3) layers with approximatively 6.7cm thickness. The Proctor test hammer of 2.49 kg is also used, in this case, performing 50 blows on each layer (Figure 5.8). The rammed earth specimens are unmolded immediately at the end of the compaction process.

(a) **(b)**

Figure 5.7 The manufactured wooden mold dimensions (a) and (b)

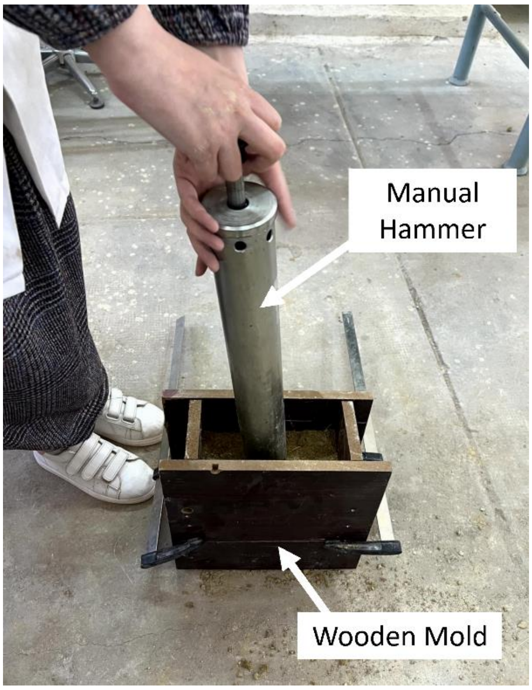


Figure 5.8 The adopted rammed earth compaction process

Two types of fibers were used for the reinforcement of the earth material (Figure 5.9): Straw and coir fibers. A 0.5% of the fibers was added to the moist earth material with 12% of water using the same compaction process as in the case of the unreinforced specimens. The resulting prismatic specimens are shown in Figures 5.10 to 5.12.

(a) **(b)**

Figure 5.9 The reinforcement fiber used: Straw (a) and Coir (b)

Figure 5.10 10x20x20cm prismatic specimens without Fiber reinforcement

Figure 5.11 10x20x20cm prismatic specimens without Straw Fiber reinforcement

Figure 5.12 10x20x20cm prismatic specimens without Coir Fiber reinforcement

3 Experimental test

3.1 Unconfined compression tests

3.1.1 Test set-up

A total of nine (9) 10x10x20cm unstabilized and stabilized specimens were prepared for testing under normal to layer unconfined compression. The aim is to characterize the compressive behavior of the rammed earth material in the direction normal to layers and to investigate the effect of stabilization on the compressive strength. The normal load was a controlled force applied in 1 kN increments until failure.

For data acquisition, the Digital Image Correlation (DIC) technique was used to assess the displacement and strain fields of the specimen surface in the deformed state under loading. For image recording, a camera was placed facing the specimen. To ensure permanent lighting on the specimen surface, a light source (projector) was used. The DIC setup is presented in Figure 5.13.

A painted speckle was added on the front surface to create the required contrast for the image processing as indicated in Figure 5.14. The image processing and analysis was performed using the 7D software developed by (Vacher et al, 1999). The data acquisitions were then achieved using an acquisition system for recovering data results with regard to force and image recording.

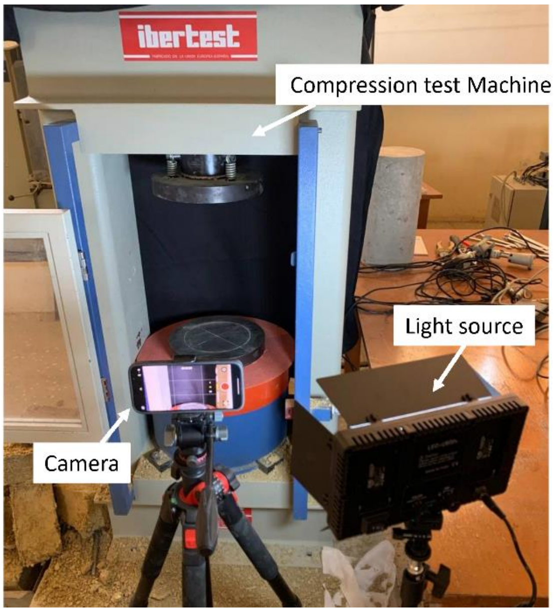


Figure 5.13 The Digital Image Correlation set-up

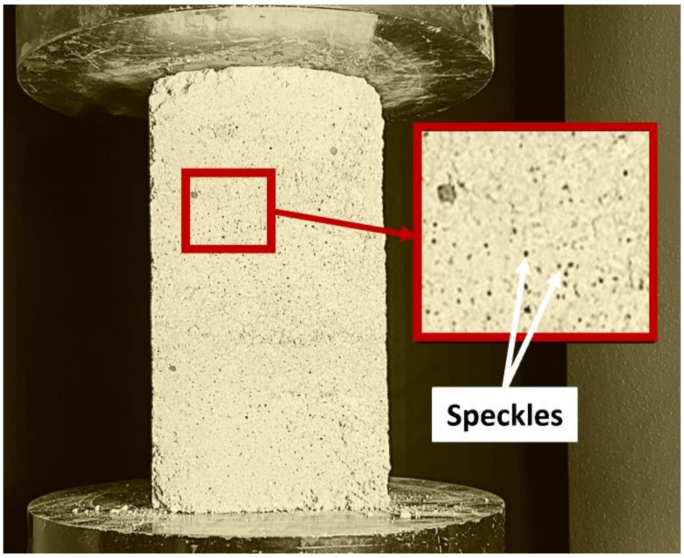


Figure 5.14 The painted speckle projected on the specimen front surface

3.1.2 Results and discussion

The response of the tested specimen is highlighted in Figures 5.15 to 5.20 in terms of compressive strength, the load-displacement relationship and the strain fields recorded using the DIC technique. The analysis was carried out in incremental, i.e., the image in the considered step is compared to the initial one (the image at point A is compared with the initial of point 0, the image of point B also with that of point 0, etc.).

The compressive strength of the unstabilized and stabilized rammed earth found for each specimen are summarized in Figure 5.15 and Table 5.1. It should be mentioned that specimen C01 was crashed before the execution of the test due to incorrect maneuver.

Figure 5.15 and Table 5.1 shows that the compressive strength of the rammed earth is affected by adding 3% of a stabilization material to the mixture. About 3% to 6% increasing in the compressive strength was recorded in the presence of a stabilization material. The Cement stabilization provided the greater increase with 6% higher strength, about 2 times more gain compared to the Lime stabilization with 3% (Figure 5.15).

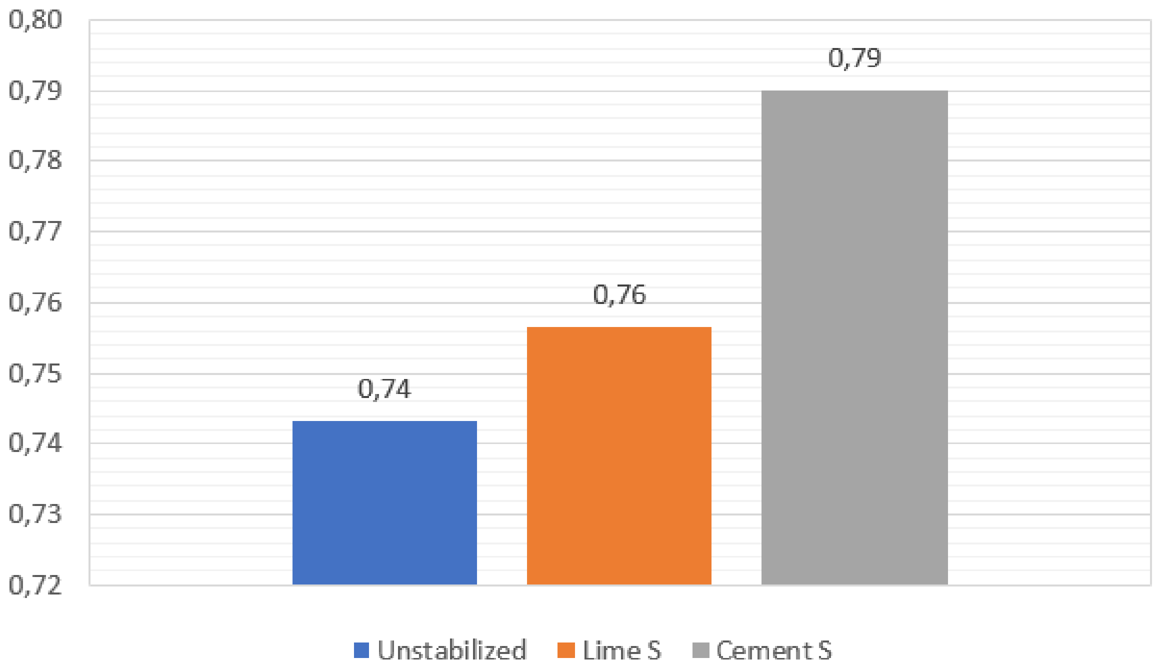


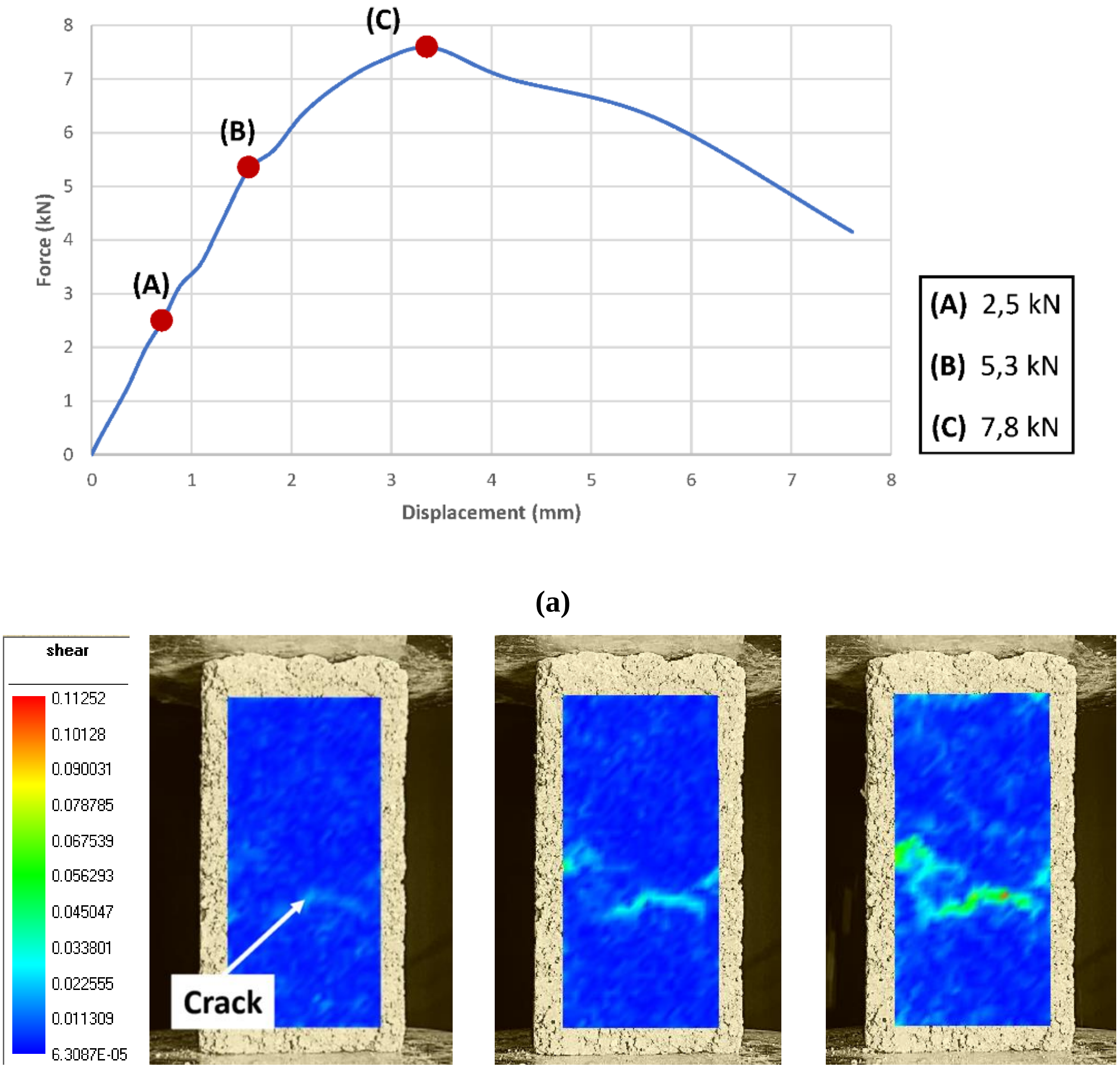
Figure 5.15 Mean compressive strength of the unstabilized and stabilized rammed earth specimens

Table 5.1 Compressive strength values of the unstabilized and stabilized rammed earth specimens

Specimen		Normal compressive strength (MPa)
Unstabilized	N01	0.78
	N02	0.76
	N03	0.69
	Mean	**0.74**
Lime stabilization	L01	0.72
	L02	0.85
	L03	0.7
	Mean	**0.76**
Cement stabilization	C01	-
	C02	0.61
	C03	0.97
	Mean	**0.79**

The load-displacement relationship indicates a quasi-brittle behavior of the tested specimen (Figure 5.16a). Figure 5.16b to 5.16d indicates the deformation mechanism of the unstabilized specimen N01 at three level (A), (B) and (C) corresponding to 2.5kN, 5.3kN and 7.8kN applied Forces, respectively. The DIC analysis shows that the crack was first initiated at the first-second layer interface at 2.5kN of applied load corresponding to level (A) in Figure 5.16b. The crack has diffused horizontally with increasing applied load (Figure 5.16c). The wider diffusion of the cracks connecting the right and left sides was observed at the pic level (C) leading to the failure of the specimen (Figure 5.16d).

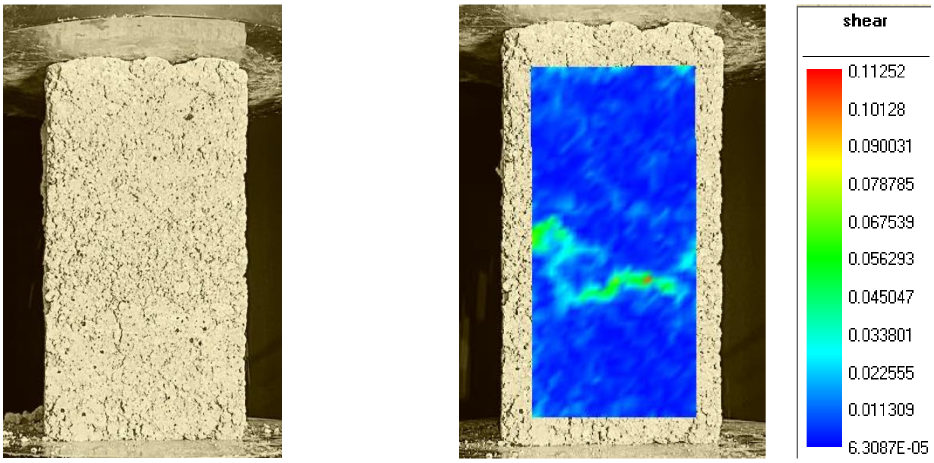
A different deformation scheme was observed for the stabilized specimens. The cracks in this case were initiated out of the layer interface and firstly developed in the upper part of the specimens and diffused to the bottom at increasing load (Figure 5.17 and 5.18).



(a)

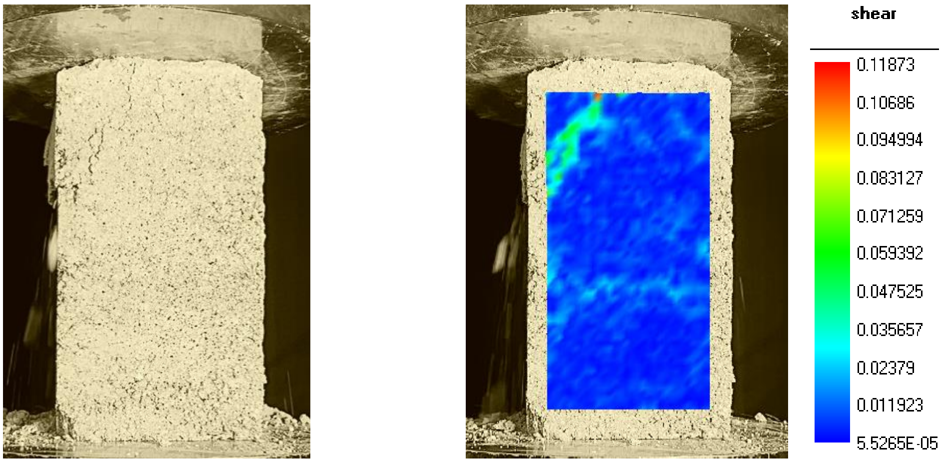
(b) (c) (d)

Figure 5.16 Load-displacement curve (a) and DIC strain fields at three level of specimen N01 (b) to (d)



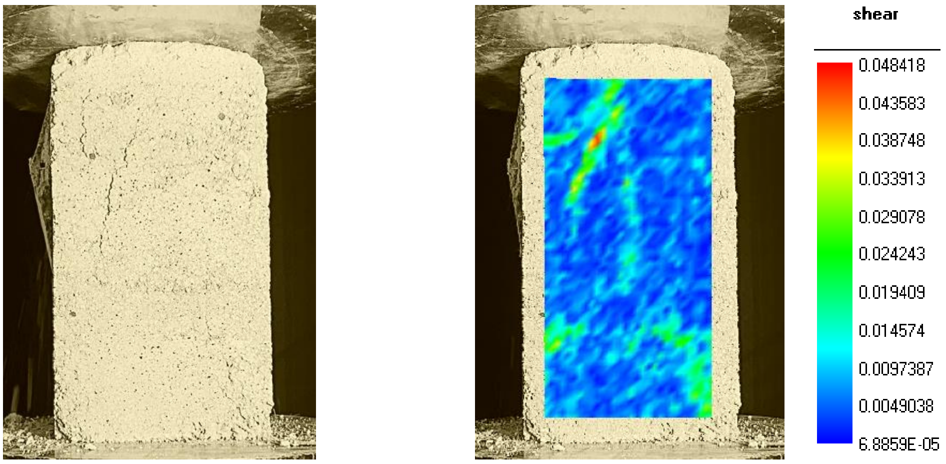
(a) **(b)**

Figure 5.17 Deformation pattern at Pic level of specimen N01: Visual observation (a) and DIC strain fields for (b)



(a) **(b)**

Figure 5.18 Deformation pattern at Pic level of specimen C03: Visual observation (a) and DIC strain fields for (b)



(a) **(b)**

Figure 5.19 Deformation pattern at Pic level of specimen L01: Visual observation (a) and DIC strain fields for (b)

The principal directions of deformation were also evaluated using the DIC analysis. At pic level (C), the direction of principal vectors shows an embracing mechanism at the first-second layer interface characterized by tensile and compression stresses all along the interface as indicated in Figure 5.20.

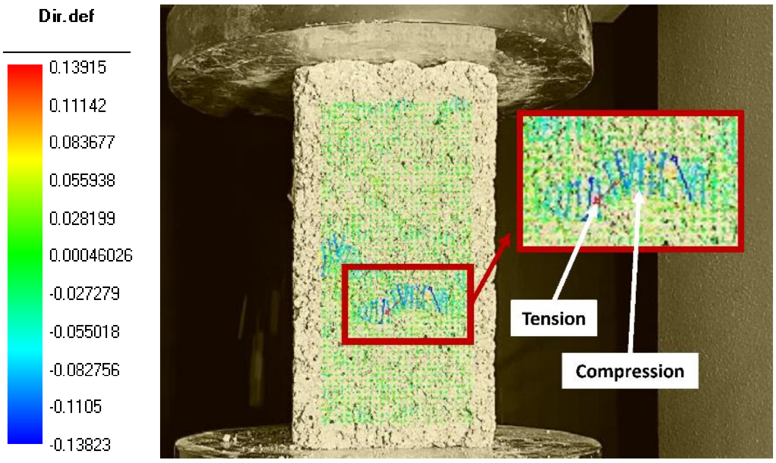


Figure 5.20 Principal directions of deformations at Pic level from DIC analysis: Specimen N01

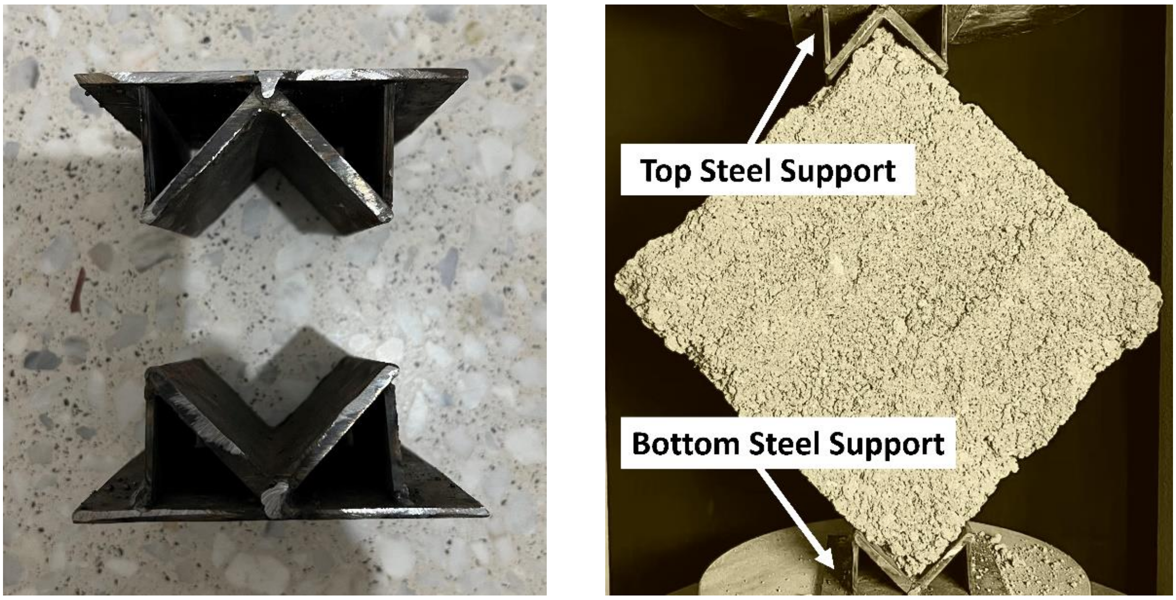
3.2 Diagonal shear tests

3.2.1 Test set-up

The other nine (9) 10x20x20cm unreinforced and reinforced specimens were prepared for the diagonal compression test. The aim of the diagonal compression test is to reproduce a stress state close to that observed in the case of the rammed earth wall subjected to diagonal stresses due to lateral loading. The diagonal load was also a controlled force applied in 1 kN increments until failure.

The Digital Image Correlation (DIC) technique was also used in this case for the data acquisition to assess the displacement and strain fields of the specimen surface in the deformed state under loading.

The specimen was held in place on the testing machine by means of two manufactured steel supports Figure 5.21a. The adopted experimental set-up is indicated in Figure 5.21b.



(a) **(b)**

Figure 5.21 The manufactured steel supports (a) and the adopted experimental set-up (b)

3.2.2 Results and discussion

The diagonal compressive strength was calculated using the equation Eq 5.1 and Eq 5.2 (Borri et al, 2011):

$$f_d = 0.5 \cdot \frac{F_{\max}}{A_n} \qquad \text{(Eq. 5.1)}$$

$$A_n = \left(\frac{w + h}{1}\right) \cdot t \qquad \text{(Eq. 5.2)}$$

Where:

f_{d}: Diagonal compressive strength

$F_{\max}$: Maximal diagonal load

A_n: Specimen net section

w, h and t: Specimen width, height and thickness, respectively.

The results of the diagonal compression test on the 10x20x20cm unreinforced and reinforced specimen are presented in Figures 5.22 to 5.26 in terms of compressive strength, the load-displacement relationship, the strain fields and the principal directions of deformations recorded using the DIC technique. The analysis was also carried out in incremental steps.

It should be mentioned that the top layer of the stabilized specimens was split up from the other two layers and specimen C03 was crashed due to incorrect maneuver. Therefore, the stabilized specimens have a new dimension of 10x13.4x20cm that has been considered for the rest of the test.

Figure 5.22 and Table 5.2 summarized the results in terms of diagonal compressive strength of the unreinforced and reinforced specimens. It can be noticed that the presence of fiber reinforcements in the rammed earth mixture has an important effect on the diagonal compressive strength of the material. An important gain, about 33%, in the diagonal compressive strength was observed for both types of fibers from 0.018 MPa to 0.027MPa.

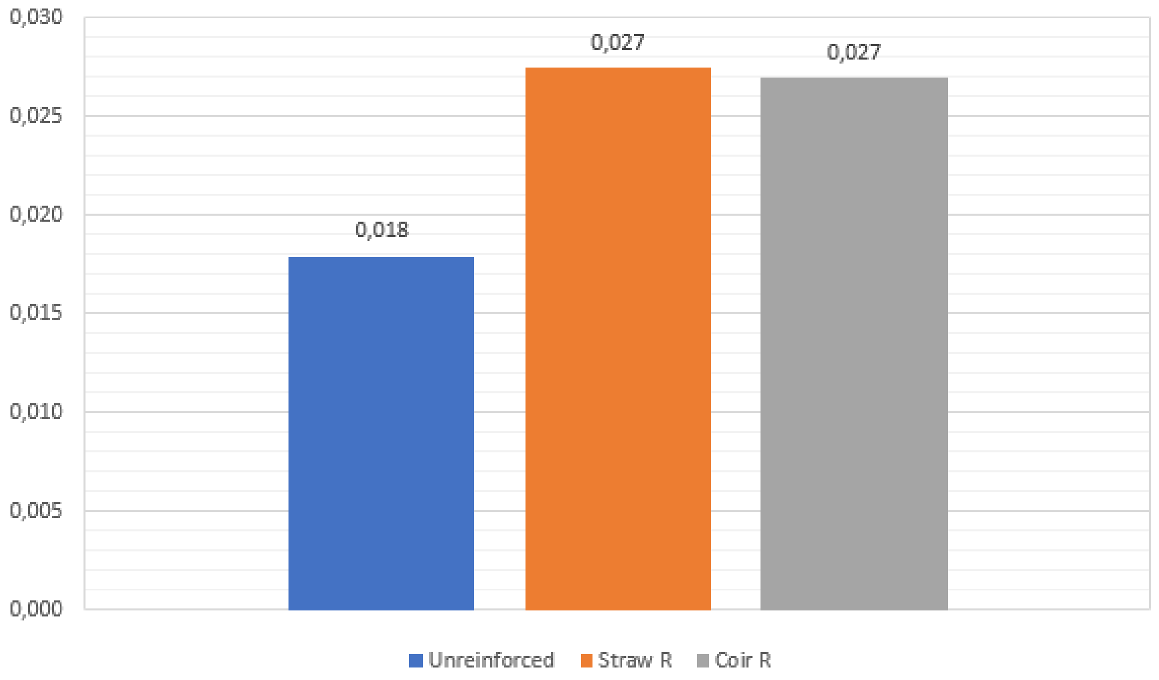


Figure 5.22 Mean diagonal compressive strength of the unreinforced and reinforced rammed earth specimens

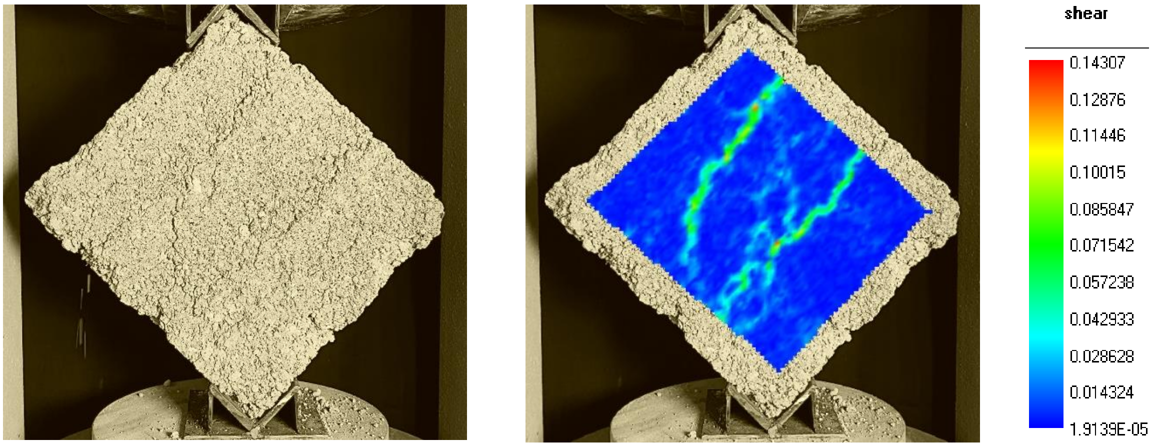
Table 5.2 Diagonal compressive strength values of the unreinforced and reinforced rammed earth specimens

Specimen		Diagonal compressive strength (MPa)
Unreinforced	N01	0.016
	N02	0.018
	N03	0.02
	Mean	**0.018**
Straw reinforcement	S01	0.024
	S02	0.033
	S03	0.025
	Mean	**0.027**
Coir reinforcement	C01	0.024
	C02	0.030
	C03	-
	Mean	**0.027**

With increasing applied load, the DIC analysis showed a diffusion of the cracks mainly all along the layer interfaces connecting the two sides of the specimen. This leads to the split and failure of the specimen as indicated by the considered deformation pattern at the Pic level in Figure 5.23.

The DIC analysis of the unreinforced specimen in terms of principal directions of deformation at the Pic level indicates a tensile stress observed along its diagonal (Figure 5.24).

In the case of the reinforced specimen, where only two layers are considered, a similar deformation scheme, to some extent, was observed for the reinforced specimens. The cracks were also mainly concentrated at the layer interfaces but initiated with diagonal cracks developed from top to bottom leading to the failure of the specimen (Figure 5.25 and 5.26).



(a) **(b)**

Figure 5.23 Deformation pattern at Pic level of specimen N01: Visual observation (a) and DIC strain fields for (b)

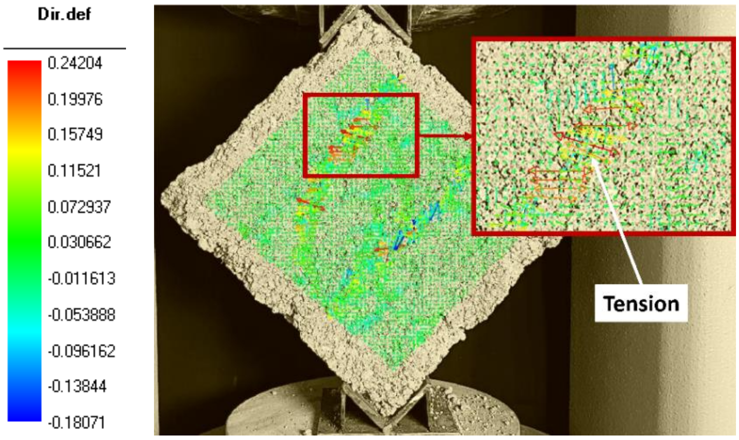
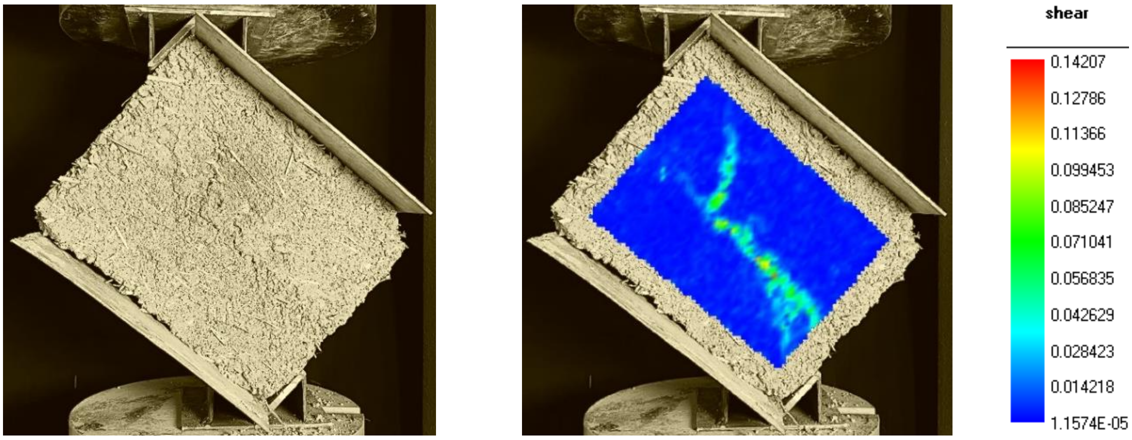
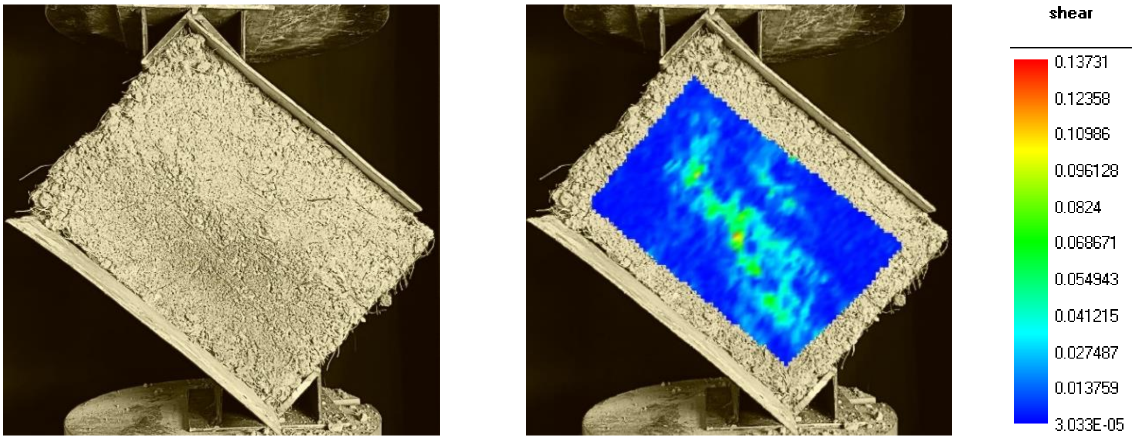


Figure 5.24 Principal directions of deformations at Pic level from DIC analysis: Specimen N01



(a) **(b)**

Figure 5.25 Deformation pattern at Pic level of specimen S03: Visual observation (a) and DIC strain fields for (b)



(a) **(b)**

Figure 5.26 Deformation pattern at Pic level of specimen C02: Visual observation (a) and DIC strain fields for (b)

4 Conclusion

This chapter provided an experimental test program carried out on unstabilized/stabilized and unreinforced/reinforced rammed earth material. The test set-up using the digital image correlation technique has been explained first. Then, the experimental results using the DIC analysis has been discussed including the strength of RE material, deformation pattern and the principal direction of deformations.

The stabilization and reinforcement techniques of rammed earth material have been found to have an important effect on the normal and diagonal compressive strength of the material. The stabilization of rammed earth material with cement and lime provided an increase in the compressive strength. The higher increase has been observed in the case of cement stabilization with 6% gain in the normal to layers compressive strength. On the other hand, the presence of fiber reinforcements in the rammed earth mixture resulted in a gain of the diagonal compressive strength independently on fiber types.

CONCLUSION

The good mechanical behavior and the contribution to increasing environmental sustainability in constructions, has made the earthen constructions 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.

Construction with Rammed Earth material has been found to be sustainable and aesthetically pleasing construction technique, tracing its ancient roots to its modern adaptations. The durability and strength of rammed earth is an important issue to be addressed. Many examples of historical constructions in the world are clear evidence of the durability of this material if properly designed and maintained. Obviously, a better understanding of rammed earth from the mechanical and structural point of view will allow us to master its disadvantages and therefore pursuing advanced studies that will permit to protect our earth heritage and to consider its implementation in modern construction as a sustainable building material for the future application. For rammed earth construction, the granulometry is not a mandatory factor for the suitability of soil and a large variety a soil types can be used. However, the dry density has a considerable effect on the strength of rammed earth. The compressive strength of rammed earth found to be increased with the increase in dry density. Values of the compressive strength found in the literature are about 1 MPa to 2.5MPa. The tension strength was found about 10% of the compressive one and shear strength found to be very low.

The geotechnical properties of the studied rammed earth have been evaluated by the particle size distribution (PSD), optimum moisture content (OMC) and dry density. By performing dry and wet sieving analysis, the particle size greater than 80 µm has been found and plotted on the PSD curve. The sedimentation method using the hydrometer has been carried out later for the particles passing the 80 µm to complete the rest of PSD curve. The final PSD curve indicated a coarse soil containing only 10% of finer particles. The OMC and dry density were evaluated in the next step using the standard proctor test. An OMC and a dry density equal to 12.6% and 1.91 g/cm3, respectively was found at the end of the test. The optimum water content obtained from the proctor test has been used in the mixture of rammed earth specimen prepared for the mechanical characterization tests. The mechanical characterization program has included a test on unstabilized/stabilized and unreinforced/reinforced rammed earth material. The data acquisition and post-processing of the experimental program has been performed using the Digital Image Correlation technique giving a better understanding of the behavior and failure modes of the tested specimens. The normal and diagonal compressive strength of rammed earth material have been found to be influenced by the stabilization and fiber reinforcement. An increase in the normal compressive strength has been highlighted in the case of stabilized specimens up to 6% for cement stabilization. Fiber reinforcement has also a significant influence on the diagonal compressive strength with a gain up to 33% independently on fiber types.

REFERENCES

A Borri , G Castori , M Corradi , E Speranzini . Shear behavior of unreinforced and reinforced masonry panels subjected to in situ diagonal compression tests. Construct Build Mater, 2011, 25(12):4403-4414.

A. Corbin, C. Augarde, Fracture Energy of Stabilised Rammed Earth, Procedia Mater. Sci. 3 (2014) 1675–1680. doi:10.1016/j.mspro.2014.06.270.

A. Corbin, C. Augarde, Investigation Into the Shear Behaviour of Rammed Earth Using Shear Box Tests, in: First Int. Conf. Bio-based Build. Mater., Clermont-Ferrand, France, 2015, pp. 93–98.

A. E. Institute, Building with Earth - Technique overview.

A. Laborel-Préneron, J. E. Aubert, C. Magniont, C. Tribout, A. Bertron, Plant aggre- gates and fibers in earth construction materials: A review, Constr. Build. Mater. 111 (2016) 719–734. doi:10.1016/j.conbuildmat.2016.02.119.

Ademe, “se chauffer au bois,” (2015).

Arslan ME, Emiro Glu M, Yalama A (2017) Structural behavior of rammed earth walls under lateral cyclic loading: a comparative experimental study. Constr Build Mater 133:433–442.

ASTM C136 (2014) Standard test method for sieve analysis of fine and coarse aggregates. ASTM International.

ASTM, D1633-17. Standard Test Methods for Compressive Strength of Molded Soil- Cement Cylinders (2017). doi:10.1520/D1633- 00R07.combine.

ASTMD422 (2011) Standard test method for dispersive characteristics of clay soil by double hydrometer. ASTM International.

ASTM-E519 (2015) Standard test method for diagonal tension (Shear) in masonry assemblages. ASTM Internation.

Ávila, F., Puertas, E., Torrús, C., & Gallego, R. (2024). Influence of crack propagation on the seismic behavior of historic rammed earth buildings: The Tower of Muhammad in the Alhambra (Spain). Engineering Structures, 301, 117365.

B. Bossink, H. Brouwers, Construction waste: quantification and source evaluation, Journal of construction engineering and management 122 (1) (1996) 55–60. doi: 10.1061/(ASCE)0733-9364(1996)122:1(55).

B. Pignal, Terre crue - Techniques de construction et de restauration. Eyrolles, 2005.

B. V. Venkatarama Reddy, P. Prasanna Kumar, Embodied energy in cement stabilised rammed earth walls, Energy Build. 42 (3) (2010) 380–385. doi:10.1016/j.enbuild. 2009.10.005.

BIS, IS:13827-1993 Improving Earthquake Resistance of Earthen Buildings – Guidelines (1993).

BNQ 2501-025 (2013) Sols-Analyse granulométrique des sols inorganiques. Bureau de Normalisation du Québec.

BS 1377-2 (1990) Methods of test for soils for civil engineering purposes—Part 2: Classification tests. British Stand/ards Institution.

Bui QB, Hans S, Morel JC (2007) The compressive strength and pseudo elastic modulus of rammed earth. In: Proceedings of the international symposium on earthen structures, Interline Publishers, Bangalore, India, pp 217–223.

C. G. Da Rocha, N. C. Consoli, A. Dalla Rosa Johann, Greening stabilized rammed earth: Devising more sustainable dosages based on strength controlling equations, J. Clean. Prod. 66 (2014) 19–26. doi:10.1016/j.jclepro.2013.11.041.

C. H. Kouakou, J. C. Morel, Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder, Appl. Clay Sci. 44 (1-2) (2009) 27–34. doi:10.1016/j.clay.2008.12.019.

C. Kouakou, J. Morel, Strength and elasto-plastic properties of non-industrial build- ing materials manufactured with clay as a natural binder, Applied Clay Science 44 (1) (2009) 27 -34. doi:https://doi.org/10.1016/j.clay.2008.12.019.

Celli, B., Fabbri, L., Criner, G., Martinez, F. J., Mannino, D., Vogelmeier, C., ... & Agusti, A. (2022). Definition and nomenclature of chronic obstructive pulmonary disease: time for its revision. American journal of respiratory and critical care medicine, 206(11), 1317-1325.

Cheah JSJ, Walker P, Heath A, Morgan TKKB (2012) Evaluating shear test methods for stabilised rammed earth. Proc Inst Civ Eng Constr Mater 165 (6):325–334.

D. Alex, Recognition of a heritage in danger: Rammed-earth architecture in Lyon city, France, IOP Conf. Ser. Earth Environ. Sci. 143 (1) (2018). doi:10.1088/1755-1315/ 143/1/012054.

D. Ciancio, P. Jaquin, P. Walker, Advances on the assessment of soil suitability for rammed earth, Constr. Build. Mater. 42 (2013) 40–47. doi:10.1016/j.conbuildmat. 2012.12.049.

D. Ciancio, P. Jaquin, P. Walker, Advances on the assessment of soil suitability for rammed earth, Construction and Building Materials 42 (2013) 40 – 47. doi:https: //doi.org/10.1016/j.conbuildmat.2012.12.049.

D. D. Tripura, K. D. Singh, Characteristic properties of cement-stabilized rammed earth blocks, J. Mater. Civ. Eng. 27 (7) (2015) 04014214. doi:10.1061/(ASCE)MT.1943-5533. 0001170.

D. Gallipoli, A. Bruno, C. Perlot, N. Salmon, Raw earth construction: is there a role for unsaturated soil mechanics, Proceedings of Unsaturated Soils: Research & Applications (2014) 55–62.

Easton D (1982) The rammed Earth experience. Blue Mountain Press, Wilseyville, California, USA Easton D (2008) The industrialisation of monolithic Earth walling for first world applications.

El-Nabouch, R., Bui, Q. B., Plé, O., & Perrotin, P. (2017). Assessing the in-plane seismic performance of rammed earth walls by using horizontal loading tests. Engineering Structures, 145, 153-161.

ENISO14688-1 (2018) Geotechnical investigation and testing – Identification and classification of soil - Part 1: Identification and description. European Committee for Standardization.

ENISO17892-4 (2018) Geotechnical investigation and testing – Laboratory testing of soil - Part 4: Determination of particle size distribution. European Committee for Standardization.

F. Champiré, A. Fabbri, J. C. Morel, H. Wong, F. McGregor, Impact of relative hu- midity on the mechanical behavior of compacted earth as a building material, Con- struction and Building Materials 110 (2016) 70–78. doi:10.1016/j.conbuildmat. 2016.01.027.

F. Loccarini, G. Ranocchiai, T. Rotunno, M. Fagone, Experimental and numerical anal- yses of strengthened rammed earth masonry arches, Comput. Struct. 239 (2020) 106329. doi:10.1016/j.compstruc.2020.106329.

G. Bauluz del Río, P. Bárcena Barrios, Bases para el diseño y construcción con tapial, Tech. rep., Ministerio de Obras Públicas y Transportes (MOPT), Madrid, Spain (1992).

G. Minke, Building with earth: Design and Technology of a Sustainable Architecture, Birkhäuser – Publishers for Architecture, Basel, Switzerland, 2006.

G. Minke, Building with earth: design and technology of a sustainable architecture (2004).

G. Minke, Building with earth: Design and Technology of a Sustainable Architecture, Birkhäuser – Publishers for Architecture, Basel, Switzerland, 2006.

G. Minke, Building with earth: Design and Technology of a Sustainable Architecture, Birkhäuser – Publishers for Architecture, Basel, Switzerland, 2006.

H. Houben and H. Guillaud, Earth Construction: A Comprehensive Guide. London, United Kingdom: CRATerre – EAG, Intermediate Technology Publication, 2008.

H. Houben, H. Guillaud, CRAterre, Intermediate Technology Publications, Earth con- struction: a comprehensive guide, Intermediate Technology Publications, London, UK, 1994.

H. Houben, H. Guillaud, Earth construction: a comprehensive guide, bcin.ca.

H. Morris, New Zealand: Aseismic Performance-Based Standards, Earth Construction, Research, and Opportunities, Getty Seismic Adobe Project 2006 Colloquium, Los Angeles, US (Best 1974) (2003) 52–66.

H. Nowamooz, C. Chazallon, Finite element modelling of a rammed earth wall, Constr. Build. Mater. 25 (4) (2011) 2112–2121. doi:10.1016/j.conbuildmat.2010.11.021.

Hall M (2002) Rammed Earth: traditional methods, modern techniques, sustainable future. Build Eng 77(11), pp 22–24.

Hall MR, Swaney W (2012) Soil stabilisation and earth construction materials, properties and techniques. In: Hall MR, Lindsay R, Krayenhoff M (eds) Modern earth buildings: materials, engineering, construction and applications. Woodhead Publishing Ltd., UK, pp 650–687. ISBN 978-0-85709-026-3

Houben H, Guillaud H (2003) Earth construction: a comprehensive guide. Intermediate Technology Publications/CRATerra-EAG, London.

J. E. Aubert, A. Marcom, P. Oliva, P. Segui, Chequered earth construction in south- western France, J. Cult. Herit. 16 (3) (2015) 293–298. doi:10.1016/j.culher.2014.07. 002.

J. Keable, Rammed earth structures. A code of practice, Intermediate Technology, Lon- don, UK, 1996.

J. Kennedy, Building Without Borders, New Society Publishers, Gabriola Island, BC, Canada, 2004.

J. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Building and Environment 36 (10) (2001) 1119–1126. doi:10.1016/s0360-1323(00)00054-8.

J. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Building and Environment 36 (10) (2001) 1119–1126. doi:10.1016/s0360-1323(00)00054-8.

J. Ruzicka, F. Havlik, J. Richter, K. Stanek, Advanced prefabricated rammed earth structures—mechanical, building physical and environmental properties, Proc. 1st Int. Conf. Rammed Earth Constr. ICREC 2015 (July) (2015) 139–143. doi:10.1201/ b18046- 29.

J.-C. Morel, A. Pkla, P. Walker, Compressive strength testing of compressed earth blocks, Construction and Building Materials 21 (2) (2001) 303 – 309. doi:https: //doi.org/10.1016/j.conbuildmat.2005.08.021.

Jaquin PA, Augarde CE, Gerrard CM (2006) Analysis of historic rammed earth construction. In: Proceedings of the 5th international conference on structural analysis of historical constructions, New Delhi, India, pp 1091–1098.

Jayasinghe C (2007) Shrinkage characteristics of cement stabilised rammed earth. In: Proceeding of international symposium on earthen structures, Bangalore, India, pp 212–216. ISBN 81-7296- 051-4.

Jayasinghe C, Kamaladasa N (2007) Compressive strength characteristics of cement stabilised rammed earth walls. Constr Build Mater 21(11):1971–1976.

Kapfinger O, Sauer M (2015) Martin Rauch refined Earth construction and design with rammed Earth, Eberl Print GmbH. Immenstadt, Germany.

Kumar, S., Chauhan, P., & Jain, N. (2021). Photoredox halogenation of quinolones: the dual role of halo-fluorescein dyes. Organic & Biomolecular Chemistry, 19(20), 4585-4592.

L. Miccoli, U. Müller, P. Fontana, Mechanical behaviour of earthen materials: A com- parison between earth block masonry, rammed earth and cob, Constr. Build. Mater. 61 (2014) 327–339. doi:10.1016/j.conbuildmat.2014.03.009.

L. Soudani, Modelling and experimental validation of the hygrothermal performances of earth as a building material, Ph.d. thesis, Université de Lyon, France (2016).

Lepakshi R (2017) Studies on characteristics of cement stabilised rammed Earth and flex- ural behaviour of plain and reinforced rammed Earth. PhD thesis, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

Lepakshi R (2017) Studies on characteristics of cement stabilised rammed earth and flexural behaviour of plain and reinforced rammed earth. PhD thesis, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

Lepakshi R, Reddy BVV (2018) Influence of layer thickness and plasticisers on the characteristics of cement stabilised rammed Earth. J Mater Civil Eng 30(12):04018314,1–10. https://doi.org/10. 1061/(ASCE)MT.1943-5533.0002539.

Lindsay R (2012) Australian modern Earth construction. In: Hal MR, Lindsay R, Krayenhoff M (eds) Modern Earth buildings: materials, engineering, construction and applications. Woodhead Publishing Ltd. Cambridge, UK, pp 609–649.

M. Hall, Y. Djerbib, Rammed earth sample production: Context, recommendations and consistency, Constr. Build. Mater. 18 (4) (2004) 281–286. doi:10.1016/j.conbuildmat. 2003.11.001.

M. Hall, Y. Djerbib, Rammed earth sample production: context, recommendations and consistency, Construction and Building Materials 18 (4) (2004) 281 – 286. doi: https://doi.org/10.1016/j.conbuildmat.2003.11.001.

M. I. Gomes, T. D. Gonçalves, P. Faria, Unstabilized rammed earth: Characterization of material collected from old constructions in south portugal and comparison to normative requirements, Int. J. Archit. Herit. 8 (2) (2014) 185–212. doi:10.1080/15583058.2012. 683133.

M. Kosarimovahhed, V. Toufigh, Sustainable usage of waste materials as stabilizer in rammed earth structures, J. Clean. Prod. 277 (2020) 123279. doi:10.1016/j.jclepro. 2020.123279.

M. Krayenhoff, Techno-economic analysis and environmental assessment of stabi- lized insulated rammed earth (sirewall) building, in: Modern Earth Buildings, El- sevier, 2012, pp. 735–748.

New Zealand Standard, NZS 4297:1998. Engineering design of earth buildings (1998). URL https://www.standards.govt.nz/sponsored- standards/building- standards/ nzs4297/.

P. Jaquin, 12 - History of earth building techniques, in: M. R. Hall, R. Lindsay, M. Krayenhoff (Eds.), Mod. Earth Build., Woodhead Publishing Series in Energy, 2012, Ch. III, pp. 307–323.

P. Taylor, R. J. Fuller, M. B. Luther, Evaluating rammed earth walls: A case study, Energy Build. 40 (2008) 793–800. doi::10.1016/j.enbuild.2007.05.013.

P. Vacher, S. Dumoulin, F. Morestin, S. Mguil-Touchal, Bidimentional strain measurement using digital images. In: Proceedings of the Institution of Mechanical Engineering, Part C: Journal of Mechanical Engineering Science, 213(8), 1999, pp. 811-817.

P. Walker, R. Keable, J. Martin, V. Maniatidis, Rammed earth : design and construction guidelines, 2005.

Pavan GS, Ullas SN, Nanjunda Rao KS (2020a) Interfacial behavior of cement stabilized rammed earth: experimental and numerical study. Const Build Mater 257:119327.

Pavan GS, Ullas SN, Nanjunda Rao KS (2020b) Shear behavior of cement stabilized rammed earth assemblages. J Build Eng 27:100966.

Q. B. Bui, J. C. Morel, Assessing the anisotropy of rammed earth, Constr. Build. Mater. 23 (9) (2009) 3005–3011. doi:10.1016/j.conbuildmat.2009.04.011.

Q. B. Bui, T. T. Bui, M. P. Tran, T. L. Bui, H. A. Le, Assessing the seismic behavior of Rammed earth walls with an L-Form cross-section, Sustain. 11 (5) (2019). doi: 10.3390/su11051296.

Q. B. Bui, T. T. Bui, R. El-Nabouch, D. K. Thai, Vertical Rods as a Seismic Reinforce- ment Technique for Rammed Earth Walls: An Assessment, Adv. Civ. Eng. 2019 (2019). doi:10.1155/2019/1285937.

R. A. Silva, D. V. Oliveira, L. Miccoli, L. Schueremans, Modelling of Rammed Earth Under Shear Loading, SAHC2014 - 9th Int. Conf. Struct. Anal. Hist. Constr. (October) (2014) 14–17.

R. A. Silva, D. V. Oliveira, L. Schueremans, P. B. Lourenço, T. Miranda, Modelling the structural behaviour of rammed earth components, Civil-Comp Proc. 106 (September) (2014). doi:10.4203/ccp.106.112.

R. El Nabouch, Q. B. Bui, O. Plé, P. Perrotin, Assessing the in-plane seismic perfor- mance of rammed earth walls by using horizontal loading tests, Eng. Struct. 145 (2017) 153–161. doi:10.1016/j.engstruct.2017.05.027.

Rao KSN, Venkatarama Reddy BV, Gade MR (2011) Strength and elastic properties of cement stabilized rammed earth. In: National conference on recent developments in civil engineering, VIET, Mysore, Karnataka.

Rathod, R. S. B., & Reddy, B. V. (2022). Behaviour of plain and fibre reinforced cement stabilised rammed earth under compression, tension and shear. Construction and Building Materials, 344, 128125.

Reddy BVV, Kumar PP (2009) Compressive strength and elastic properties of stabilised rammed earth and masonry. Mason Int 22(2):39.

Reddy BVV, Kumar PP (2011) Cement stabilised rammed Earth—Part A: compaction characteris- tics and physical properties of compacted cement stabilised soils. Mater Struct 44(3):681–694.

Reddy BVV, Kumar PP (2011) Structural behaviour of story-high cement-stabilised rammed earth walls under compression. J Mater Civ Eng 23(3):240–247.

S. Lenci, F. Clementi, T. Sadowski, Experimental determination of the fracture prop- erties of unfired dry earth, Eng. Fract. Mech. 87 (2012) 62–72. doi:10.1016/j. engfracmech.2012.03.005.

S. M. Sajad Hussaini, V. Toufigh, Strength and fracture behavior of rammed-earth materials, J. Mater. Civ. Eng. 31 (10) (2019) 1–13. doi:10.1061/(ASCE)MT.1943-5533. 0002876.

S. N. Zealand, NZS 4297:1998 Engineering design of earth buildings 4297 (1998) 60.

S. Raj, A. K. Sharma, K. B. Anand, Performance appraisal of coal ash stabilized rammed earth, J. Build. Eng. 18 (March) (2018) 51–57. doi:10.1016/j.jobe.2018.03.001.

S. Serrano, C. Barreneche, L. Rincón, D. Boer, L. F. Cabeza, Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA, Constr. Build. Mater. 47 (2013) 872–878. doi:10.1016/j. conbuildmat.2013.05.018.

S. Siddiqua, P. N. Barreto, Chemical stabilization of rammed earth using calcium car- bide residue and fly ash, Constr. Build. Mater. 169 (2018) 364–371. doi:10.1016/j. conbuildmat.2018.02.209.

SADCSTAN, SADC ZW HS 983:2014 Rammed Earth Structures – Code of Practice (2014).

T. Bui, Q. B. Bui, A. Limam, J. C. Morel, Modeling rammed earth wall using dis- crete element method, Contin. Mech. Thermodyn. 28 (2016) 523–538. doi:10.1007/ s00161- 015- 0460- 3.

T. Graham, ―Wattle and daub: craft, conservation and Wiltshire case study,‖ Master thesis, University of Bath, United Kingdom, 2004.

T. T. Bui, Q. B. Bui, A. Limam, S. Maximilien, Failure of rammed earth walls: From observations to quantifications, Constr. Build. Mater. 51 (2014) 295–302. doi:10.1016/ j.conbuildmat.2013.10.053.

T. T. Bui, Q. B. Bui, A. Limam, S. Maximilien, Failure of rammed earth walls: From observations to quantifications, Constr. Build. Mater. 51 (2014) 295–302. doi:10.1016/ j.conbuildmat.2013.10.053.

Tejas K (2007) Constructing cement stabilised rammed Earth houses in Gujarat after 2001 Bhuj earthquake. In: Proceedings of international symposium on earthen structures, Interline Publishers, Bangalore, pp 62–71.

URL http://www.earth- auroville.com/world{_}techniques{_}introduction{_}en Php.
URL http://www.ibpsa.org/proceedings/BS2009/BS09{_}1530{_}1537.pdf.
URL https://hal.inria.fr/tel- 01585348/.
URL https://ia600905.us.archive.org/2/items/gov.in.is.13827.1993/is.13827. 1993.pdf.

V. Soebarto, Analysis of indoor performance of houses using rammed earth walls, in: IBPSA 2009 - Elev. Int. Build. Perform. Simul. Assoc. Conf., Glasgow, UK, 2009, pp. 1530–1537.

Venkataramu, V., & Venkatarama Reddy, B. V. (2022). Characteristics of mortars and masonry using granulated blast furnace slag as fine aggregate. Journal of Materials in Civil Engineering, 34(5), 04022060.

Venkataramu, V., & Venkatarama Reddy, B. V. (2022). Characteristics of mortars and masonry using granulated blast furnace slag as fine aggregate. Journal of Materials in Civil Engineering, 34(5), 04022060.

Verma PL, Mehra SR (1950) Use of soil-cement in house construction in the Punjab. Indian Concr J 24(4), pp 91–96.

Walker P, Keable R, Martin J, Maniatidis V (2005) Rammed Earth: design and construction guidelines. BRE Bookshop, Watford.

Walker P, Keable R, Martin J, Maniatidis V (2005) Rammed earth: design and construction guidelines. BRE Bookshop, Watford, UK.

Windstorm B, Schmidt A (2013) A report of contemporary rammed Earth construction and research in North America. Sustainability 5(2), pp 400–416.