Building with Earth
Historical Revision and Improved Characteristics by Adding Supplementary Materials
DECLARATION

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Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials
To the mother, the homeland, the roots, where all my ancestors once lived and now rest in peace, Earth.

To the soul of my grandfather, Abi, Driss El Houari. A humble man who has taught me the love and appreciation of our culture, our heritage and the motherland, Fes. Without these seeds he has planted in me, and in my father before me, this work wouldn't have come to an end.

Through myself and this work, a modest contribution, a simple knot in a larger net, I transfer those seeds to the future generation, which I trust with our heritage to preserve and sustain.
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Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials
ABSTRACT

Earth is the basic material of construction in nearly a third of the world. Not only the built architecture, but also the knowledge that arises from the construction techniques, are a great heritage to be preserved and sustained.

Many reinforcement techniques were developed throughout the centuries, to enhance the properties of the earth material, and adapt the architecture to its environment. These techniques, nevertheless, have failed to answer modern environmental, economical and structural demands.

Therefore, there was a need to revise the historical construction techniques to understand their specificities, and then to provide an affordable, environmental friendly and sustainable alternative upgrade and reinforcement techniques of stabilization, to improve the mechanical properties and durability of the earth material.

In the scope of this thesis, an experimental program was defined, which included the characterization of the raw earth. This was followed by the study of the mechanical behavior of unstabilized loam blocks, and then stabilized loam with different dosage rates of stabilizers, including, coal mining waste, Portland Cement, Calcium Aluminate Cement, algae (Posidonia Oceanica) and lime. The aim was to compare the mechanical performance of different mixtures, under a compressive strength test, to study the effect of those stabilizers on the raw loam behavior.

Finally, a comprehensive conclusions were drawn from the testing results, to define adequate reinforcement solutions to enhance the loam material mechanical properties in terms of compressive strength and durability.
RESUMEN

La tierra es un material básico de construcción utilizado en casi una tercera parte del mundo. No sólo la arquitectura construida, sino también el conocimiento que surge de las técnicas de construcción empleadas, son un gran patrimonio para ser preservado y mantenido.

Muchas técnicas de refuerzo han sido desarrolladas a lo largo de los siglos, cuyo objetivo es mejorar las propiedades de la tierra y adaptar la arquitectura a su entorno. Estas técnicas, sin embargo, no han podido responder en ocasiones a las demandas ambientales, económicas y estructurales modernas. En este sentido, ha sido necesario revisar las técnicas tradicionales de construcción para entender sus especificidades y, a continuación, proporcionar una alternativa económica, ecológica y sostenible, así como el refuerzo de técnicas de estabilización, para mejorar las propiedades mecánicas y la durabilidad del material.

En el marco de esta tesis, se definió un programa experimental que incluyó la caracterización de la tierra cruda. Se siguió el estudio del comportamiento mecánico de bloques no estabilizados, y estabilizados con diferentes tasas de dosificación de estabilizadores, incluyendo residuos de minería de carbón, cemento Portland, cemento de aluminato de calcio, algas (Posidonia oceánica) y cal. El objetivo fue comparar el desempeño mecánico de diferentes mezclas, bajo la prueba de resistencia a la compresión, para estudiar el efecto de estos estabilizadores en el comportamiento resistente de la tierra cruda.

Finalmente, se extraen algunas conclusiones a partir de los resultados de estos ensayos, para definir las soluciones de refuerzo más adecuadas y mejorar las propiedades mecánicas de la tierra cruda en términos de resistencia a la compresión.
RESUM

La terra és el material bàsic de construcció en gairebé un terç del món. No només l'arquitectura construïda, sinó també el coneixement que sorgeix de les tècniques de construcció, són un gran patrimoni a ser preservat i sostingut.

Moltes tècniques de reforç han estat desenvolupades al llarg dels segles, per millorar les propietats del material de la terra i adaptar l'arquitectura al seu entorn. Aquestes tècniques, però, no van poder respondre a les demandes ambientals, econòmiques i estructurals modernes. En aquest sentit, hi va haver la necessitat de revisar les tècniques tradicionals de construcció per entendre les seves especificitats i, a continuació, proporcionar una alternativa econòmica, ecològica i sostenible, així com el reforç de tècniques d'estabilització, per millorar les propietats mecàniques i la durabilitat del material.

En el marc d'aquesta tesi, es va definir un programa experimental que va incloure la caracterització de la terra crua. Es va seguir l'estudi del comportament mecànic de blocs no estabilitzats, i estabilitzats amb diferents taxes de dosificació d'estabilitzadors, incloent residus de mineria de carbó, ciment Portland, ciment d'aluminat de calci, algues (Posidònia oceànica) i calç. L'objectiu va ser comparar l'acompliment mecànic de diferents mescles, sota la prova de resistència a la compressió, per estudiar l'efecte d'aquests estabilitzadors en el comportament de la terra crua.

Finalment, algunes conclusións van estar exposades a partir dels resultats de le proves, per definir les solucions de reforç més adequades per millorar les propietats mecàniques de la terra crua en termes de resistència a la compressió.
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials
RESUMO

A terra é o material básico de construção em quase um terço do mundo. Não só a arquitetura construída, mas também o conhecimento que surge das técnicas de construção, são um grande patrimônio a ser preservado e sustentado.

Muitas técnicas de reforço foram desenvolvidas ao longo dos séculos, para melhorar as propriedades do material da terra e adaptar a arquitetura ao seu ambiente. Essas técnicas, no entanto, não conseguiram responder às demandas ambientais, econômicas e estruturais modernas. Neste sentido, houve a necessidade de rever as técnicas tradicionais de construção para entender suas especificidades e, em seguida, fornecer uma alternativa econômica, ecológica e sustentável bem como o reforço de técnicas de estabilização, para melhorar as propriedades mecânicas e a durabilidade do material.

No âmbito desta tese, definiu-se um programa experimental que incluiu a caracterização da terra crua. Seguiu-se o estudo do comportamento mecânico de blocos não estabilizados, e estabilizados com diferentes taxas de dosagem de estabilizadores, incluindo resíduos de mineração de carvão, cimento Portland, cimento de aluminato de cálcio, algas (Posidonia oceânica) e cal. O objetivo foi comparar o desempenho mecânico de diferentes misturas, sob o teste de resistência à compressão, para estudar o efeito desses estabilizadores no comportamento da terra crua.

Finalmente, uma conclusão abrangente foi desenhada a partir dos resultados do teste, para definir as soluções de reforço mais adequadas para melhorar as propriedades mecânicas da terra crua em termos de resistência à compressão.
البناء بالتربة. مراجعة تاريخية وتحسين الخصائص عن طريق إضافة مواد معد تدويرها.

تعتبر التربة مادة أساسية للبناء، في ما يقارب ثلث بناء العالم. و تجد الإشارة إلى أن العمارة بالطين، تعتبر خصائص و إرثا معمرا من جهة، و موروثا معرفيا نابعا من على و تطور تقنيات البناء.

تم تطوير و تعزيز هذه التقنيات على مر القرون، عن طريق تحسين خصائص المادة الخام، و تكيف تقنية العمارنة مع بيتها. إلا أن هذه التقنيات فشلت في الاستجابة لاحتياجات البيئة و الاقتصادية الحديثة.

ولذلك، تأتي نادل من مراجعة تقنيات البناء التاريخية لفهم خصائصها، ومن ثم تقديم تقنيات بدلة ومستدامة صديقة للبيئة، بأسعار معقولة لتعزيز الخواص الميكانيكية و متانة التربة.

في نطاق هذه الأطروة، تم تعريف برنامج تجريبي، والذي تضمن توصيف التربة الخام. تعزز ذلك دراسة السلوك الميكانيكي لعينات التربة غرب المبحث، ثم العينات المثبتة بمعدلات جرعات مختلفة من المثبتات، بما في ذلك نفايات عدين الفحم، أليف طحالب بحرية، أسمت بورنالد، أسمت اليمينات الكالسوم والجزر. كان الهدف هو مقارنة الأداء الميكانيكي للخلائط المختلفة، تحت اختبار قوة الانضغاط، لدراسة تأثير تلك المثبتات على سلوك التربة الخام.

أخيراً، تم التوصل إلى خلاصة شاملة من نتائج الاختبار، لتحديد حلول التنسيق الأكثر ملاءمة لتعزيز الخواص الميكانيكية للتربة من حيث قوة الانضغاط.
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1. INTRODUCTION

1.1 Motivation

In times governed by economical and environmental crisis, there is an increasing urge to reconsider the way we live, consume, and build. It is necessary to make an halt, and look back into our built heritage not only as an architecture in decay, that needs to be preserved, but as a standing example of traditional building techniques, sustainable by definition, integrated in the landscape, energy efficient, and perfectly translating the balance between the man and his environment. The same heritage that is a guardian of the memory and history, is also a way to learn from an ancestral process of empirical knowledge transmission, from master (maâlem) to apprentice (mtaâlem), and from generation to another. This said, a part of preserving and conserving the built heritage is to learn from historic construction techniques, understand them, revitalize them and finally upgrade them to sustain the knowledge.

Earthen architecture, has for so long been marginalized, unfairly considered in many situations as the architecture for the poor, and commonly linked to popular/vernacular architecture. It carries nevertheless, a construction knowledge that has been improved for centuries, of taming the properties of a widely available material, soil, to the needs of populations in the most arid environments, which makes the architecture of earth the perfect sustainable solution to translate the balance between the human and the environment.

The present dissertation comes as a reconciliation with, and re-appropriation of earthen architecture, It is born of an increasing scientific and academic interest in upgrading earthen architecture from one side, and developing a comprehensive set of regulations from the other.

1.2 Scope

Earth has undoubtedly been one of the most widely used construction materials in the world. Ever since humans have learnt to build, 10 000 years ago, they have developed techniques with the use of earth as a material, that allowed them to construct stronger, safer, and to finally settle and create the earliest civilizations.

There is hardly an inhabited continent, and perhaps not even a country, which does not have a heritage of buildings in unbaked earth. At the end of the 1980s, more than a third of all humanity was estimated to be living in a home built of earth. (Houben and Guillaud, 1989).

The earth architecture is also a type of sustainable architecture. It is based on localized needs and building materials, and reflects the local traditions. For thousands of years, earth has been the most tried and tested natural construction materials. This makes buildings made with earth economical, energy-saving, eco-friendly and sustainable.
Earth buildings include adobe, cob, straw and rammed earth blocks and walls. Worldwide, traditional earth construction techniques are known by various names such as cob, rammed earth, pisé de terre, adobe, clay lump and mud, loam, etc. The earth used in various construction techniques could also be stabilized with cement, lime or bitumen. (Niroumand, Zain and Jamil, 2013) It is possible to analyze the ancestral practices used to protect the Earth material from the harsh environmental conditions, in order to understand how the old earthen buildings were preserved over the centuries. Among these techniques are: the incorporation of biopolymers (such as oils or fats from animal or vegetable origin); the addition of some minerals. However, this knowledge seems to be forgotten, probably due to the prejudice related to earthen constructions, which several times are associated with a poor building. (Eires, Camões and Jalali, 2014)

This research focuses on the study of alternative solutions of earth stabilization with waste and recycled materials, adapting the ancient knowledge to improve the mechanical properties and durability of the earth constructions. An upgrade of earth construction techniques with the use of sustainable reinforcement and stabilization alternatives, would in fact allow reducing energy consumption and the emission of pollutants during the production of construction materials and their transportation to the construction site.

This thesis comes as a response to statistics and studies (Niroumand, Zain and Jamil, 2013), that have shown that the race for a better implementation of the earthen architecture is taking two speeds. In countries like Iran, India and Malaysia, the most important concern is to offer an affordable solution with earthen construction technique, which will be carrying out the same tradition, of vernacular architecture, with its abundance and availability, while enhancing the mechanical properties of the material to provide structural minimal safety rate for the inhabitants.(Figure 1)

![Figure 1](image)

**Figure 1 Distribution of economic reasons supporting earth architecture and earth buildings (Niroumand, Zain and Jamil, 2013)**

<table>
<thead>
<tr>
<th>Option</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lower operating costs</td>
</tr>
<tr>
<td>B</td>
<td>Lower lifetime costs</td>
</tr>
<tr>
<td>C</td>
<td>Higher building value</td>
</tr>
<tr>
<td>D</td>
<td>Enhanced marketability</td>
</tr>
<tr>
<td>E</td>
<td>Helping to transform the market</td>
</tr>
<tr>
<td>F</td>
<td>Increase staff productivity and retention</td>
</tr>
</tbody>
</table>
Whereas in countries like USA, UK and Australia, the economical motive doesn't seem to be of an importance, compared to the aim to have an environmental friendly and sustainable construction material. (Figure 2)

![Figure 2 Distribution of environmental reasons supporting earth architecture and earth buildings (Niroumand, Zain and Jamil, 2013)](image)

<table>
<thead>
<tr>
<th>Option</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Protection of the environment</td>
</tr>
<tr>
<td>B</td>
<td>Reducing climate change and emissions</td>
</tr>
<tr>
<td>C</td>
<td>Minimizing ecological impact of buildings</td>
</tr>
<tr>
<td>D</td>
<td>Scarcity of natural resources</td>
</tr>
<tr>
<td>E</td>
<td>Improving indoor environment quality</td>
</tr>
<tr>
<td>F</td>
<td>Waste reduction</td>
</tr>
</tbody>
</table>

It is believed that by reducing the ecological footprint of the construction life cycle and allowing lower life cycle cost, a principal target of modern construction will be covered.

### 1.3 Objectives

This work aims at exploring the huge potential earth architecture has, by revising earth historic construction techniques, understanding the specificities of the material, to contribute in proposing alternative solutions for the upgrade of its mechanical properties, in order to respond to the economical and environmental problematic.

To this aim, the second chapter will be making an inventory and detailing the common historic construction techniques, focused on the categorization of examples from Spain and Morocco.

In the third chapter, a study was conducted to point out of the main challenges that face Earth architecture in a modern context, and to find solutions for the re-appropriation of this construction technique as a sustainable and affordable alternative.

The forth chapter includes a state of the art to the general properties of the unstabilized soil as a material of construction, as well as an overview of the stabilizing techniques used in history and a
proposal of alternative stabilizers using recycled materials, by upgrading the mechanical properties and durability of the soil, for a modern application that allows the sustainability.

The fifth chapter introduces the multiple experimental produces taken to characterize the properties of the materials, raw soil and admixtures, as well as the experimental set up to define the compressive strength of the tested samples.

The sixth chapter exposes the results of the experiments and the interpretation from the comparison of different dosages of the proposed admixtures.

Finally, the last chapter will be discussing the possible application and the further testing to be done to assess the durability characteristics of the stabilized blocks.

This present work, however, opens to further research in the field of reinforcement of earth with recycled materials. Further investigation could be carried out to study the durability of the reinforced earth in contact with specific environmental and climatic conditions.
2. EARTH, A HISTORICAL CONSTRUCTION TECHNIQUE

Earthen architecture is a great example of how human beings, for centuries, have managed to put their environments under their mercy, sculpting the raw materials into various creations. Humans around the globe have developed ingenious techniques to turn the four elements that were in their disposition to reshape their environment, and transit from a nomadic life to a more sedentary one.

Archaeological excavations have unveiled evidences of millennium cities that were entirely built with earth, going from the earliest found human settlement Göbeklitepe (Turkey), to Çatal Höyük (Turkey), Jericho (Palestine), Babylonia (Iraq), Bam (Iran). Figure 4 shows an excavated site from Göbeklitepe in Turkey. It is considered to as one of the first human settlements from the Neolithic period.

Through earthen architecture, our ancestors were able to get the inspiration from natural caves and other structures, to build shelters and dwellings that were more secure and stable. And thus have started the first human civilizations.
Early civilizations have created not only simple dwellings, but also granaries, citadels, palaces and fortresses, religious buildings, urban centers and cultural landscapes. Figure 5 showcases an example of citadels made completely with earth, the citadel of Bam, in Iran, listed as the largest adobe building in the world. It was nevertheless destroyed after an earthquake in 2003.

Figure 5 UNESCO World Heritage Site, Bam citadel, Iran.
Earthen architecture, in fact, plays a distinctive role in revealing the local identities and in ensuring the sustainability of construction techniques and their aim to unleash a powerful cultural and artistic expression.

Figure 6 UNESCO World Heritage Site, Kasbah Ait Ben Haddou, Pre-Saharan region, Morocco
Figure 6, represents one the most renowned examples of earthen architecture from Pre-Saharan Morocco. Aït Ben Haddou is an outstanding example of a southern Moroccan ksar illustrating the main types of construction to be observed in the valleys of Dra, Todgha, Dades and Sous. Not only is this fortress a witness of an ancestral knowledge in earth construction techniques, but it is also a guardian of the culture and the community spirit it encloses, as it celebrates the tolerance and art of living together, gathering Muslims and Jewish, Arabs, Amazighs and Sub Saharan Africans, in one single sanctuary.

It is therefore by understanding the specificities of the local building techniques with earth as a raw material, that it is possible to contribute into the social and cultural development, with respect to the environment and with a focus on the sustainable development.

An inventory effectuated by CRAterre-ENSAG under the supervision of UNESCO (CRAterre-ENSAG, 2012), suggests that in 29% of the constructions around the world, earth material constitutes more than three quarters of the construction. In Africa and the Arab World, this proportion is respectively of 40 and 35%, while proportions of 15, 22 and 25% respectively are in the region of Latin America, Pacific Asia, Europe and North America.

Figure 7 and Figure 8 show respectively the actual distribution and typologies of earthen historic constructions in Europe, and then in Middle East and North Africa.

These building typologies and techniques vary from a region to another due to climatic and environmental factors, but they are generally in both cases buildings with rammed earth or adobe.

Other techniques might be included, but they depend on the specificities of each region, the materials available, the stabilization techniques, and are not generalized.

![Figure 7 Distribution and typologies of earthen historic constructions in Europe (CRAterre-ENSAG, 2012)](image-url)
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials

Erasmus Mundus Programme

ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

For 24% of those buildings, earth material represents less than a quarter of the construction. This situation is the most frequent in Europe and North America (50%) but also in Latin America (35%). This shows construction typologies that are using other complementary materials, and that are widespread in the mentioned regions.

2.1 Etymology and terminologies

2.1.1. History and origins

The building of shelters became around the same time around the world. But even in earlier stages of the human civilizations', the development was tightly linked to the social evolution. It is based on archaeological findings that researchers could base their assumptions, even if those are limited to remains of virtually indestructible stone tools. This takes us back to a time when the nomadic life style was predominant, when hunting and living to the mercy of the nature and environment were the only ways for survival.

It is by adopting a progressive sedentary nature, that the earliest-known shelters have developed. From seasonal shelters solely made of wood and brush, but covered with mud for waterproofing, that were primarily used during inclement weather conditions and to protect against wild animals and hostile neighbors. However, as the importance of agriculture and its knowledge in humans increased, there increased a need to move away from the hunter-gatherer phase to the more intensive cultivation of fixed locations. With this has finally grown the need for more stable shelters. (Niroumand et al., 2013)

It is also important, at this point, to put a highlight on who started the use of earth, which is a material widespread in the Saharan environment, as a material of construction. According to Waziri (2004), the Latin terminology “pisé de terre”, was first used in Lyon, France, in 1562, and refers to the construction technique of walls with a thickness not less than 50cm, through compaction of clayey soil, in parallel wooden moulds. However, Ibn Khaldoun, a Muslim North African scientist and sociologist (1332-
1406), has mentioned, in his book Muqaddimah (1377), the use of this same technique in Pre-Saharan regions of North Western Africa. We quote 'and of it building with earth for constructing walls, is made through taking two panels of wood with an estimated length and width, while taking into consideration the difference in the estimation, with four-arm in the depth, (...), and connects them with layers of wood, connecting them with ropes. The open parts are then closed with two other small plates, and then the earth mixed with lime is poured, and is compacted with an adequate tool, so that there is a better compaction of better homogeneity with calcareous admixture. The mixture is added two and three times more, until filling the space between the wooden. Then the plates are rearranged as in the first step, and the mixture is also compacted until all the panels are lined up on a line, and until the whole wall is one piece, as if it one monolithic, and it is called the "at-tabiahi" (and the makers are called "at-tawabûn"). Therefore the word 'tapia' that commonly indicates the rammed earth technique in Latin languages, takes its origin from the Arabic "at-tabiahi", and is of the same root as "at-tûb" that refers to 'bricks', and that was introduced to Latin languages as 'adobe' later on, in the mid 18th century.

By observing the different construction examples, it is concluded that the earthen constructions of southern Morocco are rightly celebrated. In fact, they represent a particular family of pre-Saharan architecture, which is common to all countries of the Great Maghreb, Mauritania and Libya. It is not certain that the introduction of these striking constructions dates back to Islamization and to the foundation of Sijilmassa in 757, but it is possible that their structure and technique were propagated from a very early time in Djebel and in the valleys of the south. The typology of this traditional habitat is extremely diversified. Large houses, called tighremt in Amazigh and dar or kasba in Arabic, bring together, around a central rectangular courtyard, four tall fortified wings, topped by angle towers.

2.1.2. Problematics aspects

Although Earth is the most widespread and common construction material, the knowledge related to it has been for so long marginalized. There hasn't been over the centuries a proper documentation and uniformizing of its properties and specificities. Unlike stone masonry that was employed in the construction of edifices of a high historical, economical and cultural value.

Earth is a noble material. It is the support of terrestrial life. But for many reasons, its architecture is unfairly referred to as the "architecture of the poor". This doesn't only limit to the nuclear scale of a community, a society or a country, but extends to a general misconception that has limited earthen architecture to its relation with under developed countries.

This same marginalization has led to a lack of available detailed resources in the academic and scientific publications that study this architecture. Subsequently, earthen architecture being more common in Africa, Middle East, South Western Europe, South Asia and South America, has led to the English language being not inclusive of the terminology to describe the earth construction. It has in fact failed to give ample information about the detailed building process.
There is also a lack of historical evidence and documented information that can give reference to the origins and reasons behind this type of constructions. It is mainly through oral narration that it could be possible to document several historic sites with earthen architecture and trace back in time the origin of their construction. (Roger, 1996)

In this case, it was needed to review documents and collect data not only in English, but to dig more to find information in Arabic, Spanish, French, to draw a more comprehensive table of the used terminology and to understand the particularities of each different technique.

### 2.2 Techniques of construction in Iberian Peninsula and Morocco

The Iberian Peninsula is a rich mine for examples of earthen architecture. The availability of a wide range of adequate soils, as well as the climatic conditions of South Western Europe has made Portugal and Spain notable for the large number of ancient monuments, churches, fortresses but also examples of vernacular architecture in urban and rural settlements. (Mileto and Vegas, 2017)

In Morocco, on the other hand, an ancestral knowledge of earth construction has been developing for centuries, and has been carried out from master (maâlem) to apprentice (mtaâlem). The techniques translate the balance between the man and his environment. It is by using the available elements: earth, water, fire and plants, together in an homogeneous way, that Moroccans have been able to create shelters that face the adversity of the climate.

It is also notable that the cross cultural influence between North Africa and the Iberian Peninsula has enabled the enriching of a panoply of techniques in earth construction, that are now characteristic of these regions.

The same examples of molded adobe blocks, for instance, found in the imperial cities of Fes and Marrakech, are also present in the Andalusian cities of Granada and Seville. The same goes for the rest of the different building techniques, that will be detailed in the following chapter.

In order to catalogue them, these techniques are classified in Figure 9 according to the way in which the earth is used in construction.

These techniques are explained, illustrated and located respectively. (Mileto and Vegas, 2017)

More focus will be given, however, to adobe and rammed earth construction techniques as they are the most widespread in the Iberian Peninsula and North Africa, and as they will be the major interest of the further studies and experiments throughout this thesis.
Building with Earth. Historical Revision and Improved Characteristics by Adding Recycled Materials

Figure 9 Earth construction techniques’ categories

For the case of Morocco, the examples presented are mainly focused on the monumental architecture rather than the vernacular one. This is mainly due to the fact that monumental architecture is better documented and preserved. Although the use of earth construction is most present in regions like Morocco as vernacular architecture, it is through the study of monuments that is possible to examine them on a larger scale, as more efficient structural solutions are employed and better results are reached.

2.2.1. Construction by removal

This technique is considered as the oldest, and consists of digging and removing the earth to create underground or semi-underground spaces. Using the properties of the earth material and its insulating nature, it allows a constant temperature and a regulated level of humidity. It has been used as a widespread dwelling typology for a huge variety of cultures throughout history. It has also been used for auxiliary spaces as wine cellars, ice pits, and spaces for growing mushrooms, curing certain cheeses, etc. These underground spaces can be found throughout Spain, in particular in Andalusia, Castile-León, Navarre, Aragon and a broad strip of the east of the peninsula, including some notable sites in Castile-La Mancha. (Figure 10 Erreur ! Source du renvoi introuvable.)

Examples of these techniques can also be found in the Pre-Saharan region of south and south east Morocco. It is common to find this construction technique in the Anti Atlas mountains. The built spaces, in this case, are generally dedicated for collective granaries to store the goods all over the year. They are referred to as Agadir, Igherm or more specifically matmoura, which literally means "burried". (Figure 11)
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials

2.2.2. Construction by addition

Unlike the previous case, this is a vertical construction method above the ground created by progressively layering earth using a wide range of variants and methods that are outlined and grouped as follows:

Earth used as aggregate

Broken-up earth obtained by excavation or extraction and transported from other places, used almost loose, without compacting or with only slight pressure and very different from compacted earth. It has been used since prehistoric times to make dykes, barriers, hillocks, burial mounds and terracing, as well as for making commemorative landmarks.

The well-known way of building defensive enclosures with piled earth after digging a moat has been written about by many classical authors in their descriptions of the Murus Terreus Carinarum, or simply the Murus Terreus, and is very different from the technique of using a frame or formwork and then compacting or ramming. Nor should earth as aggregate be confused with piled earth because the former is not deliberately dampened nor worked or even finished with some kind of cob process, or shaping by hand.

Earth as aggregate was also used for military purposes to create embankments at the foot of a wall or at the foot of a bastion, provisional fortifications constructed with baskets and wicker gabions filled with earth as a barrier to be filled in later with bundles interspersed with the earth, or as a high-sided protection, etc. (Figure 12)
Stacked earth

A deliberate accumulation of earth to form a wall which can later be either shaped by hand or with a tool, or not be subjected to any further work.

Cob or stacked earth with subsequent shaping:

A wall that is made by piling earth with subsequent reworking of the sides. The first step in achieving this technique is to build up the earth on a foundation made with boulders, masonry, ashlers or bricks. This base has a major role in preventing the dampness caused by capillary action and also prevents from the damages causing erosion in the base of the walls (Figure 13). The nature of the used soil defines the amount of material to put in place each day, in small portions, to create the wall.

To prevent shrinkage that leads to cracks, it is common to add fibers of organic origin (cereal stalks, horse hair, vine shoots). The compaction of the outer side also helps in preserving the integrity of the wall and upgrading its mechanical properties.

If necessary, the verticality and the desired thickness are obtained by vertically cutting the wall, when it is finished, with a special tool with sharp edges. It is an ancient technique, often used in prehistoric times, commonly found at archaeological excavations of Iberian settlements, and which is often confused with rammed earth walls and even adobe. It is rarely found nowadays, but the odd example can still be seen in auxiliary constructions in Castile-León, in the oldest barracas or thatched huts in Valencian agricultural fields, in an auxiliary way as a filling for half-timber in the valley of Liébana (Cantabria), etc. (Figure 14).

Figure 13 Types of foundation (Baglioni et al., 2013)

Figure 14 Piled earth in Molezuela de la Carballeda, Zamora (J. Font)
Piled earth with no subsequent shaping

The wall is created by simply piling the earth. The piling done each day is set by the ability to withstand the weight of the new layers of the previous lift. The degree of consistency that it shows, after partial drying, determines whether the wall can continue to be built higher. Used to construct small walls, temporary shelters and other structures of little importance, it is also quite commonly used to finish copings or the tops of walls, thus avoiding the need to erect formwork for the wall; it is also used to fill half-timbered structures by simply filling the voids with cob. In Spanish it is called pared de montón. (Figure 15)

Figure 16 Process of realizing the Cob construction technique.

Earth piled in blocks

Traditionally, this was done using pieces of earth with very varied shapes using different procedures, which are described below.

Cut blocks without grass roots

Blocks obtained when cutting the ground, generally lateritic soil, although not always, that is easily extracted thanks to its softness but that becomes extraordinarily hard when dried. A technique that is commonly used in different places because it allows the blocks to be arranged as if they were ashlers. There is no lateritic soil in Spain, but occasionally examples of irregular blocks without plant fibres called terrones or tabones (marls) can be found. In Latin America, this technique is more common and is called terrón, tepetate, tacurú, asperón, cancahua or caliche (Figure 17).

Figure 17 Detail of a wall of rammed earth between brick buttresses and courses where the rammed earth blocks are made up of marls and lime mortar in Tordesillas, Salamanca (J. Font).

Cut blocks with grass roots

Blocks obtained when cutting ground with plant fibres; grass, moss, heather or peat. This technique has been used in many cultures, so its various names in several languages are well known. It is often
cited in treatises on fortification since it was commonly used to build fortresses, castles and defensive enclosures. In Spain these blocks are called tepes, céspedes or cespedones and tapines (turf). Tapines, which are less thick, are often used as roofing and to top stone walls.

In the past these blocks were very commonly used all over Spain to build dykes, small walls and defensive embankments. In traditional architecture the technique was more common in the northern part of the peninsula (Asturias, León, Zamora, Palencia, Burgos, Galicia). (Figure 18, Figure 19 and Figure 20)

Figure 18 Cut grass and straw mixed with earth, South Morocco

Figure 19 Turf walls in Lavandeira, Ourense (Vegas and Mileto)

Figure 20 Blocks of turf above a lintel in Molezuela de la Carballeda, Zamora (J. Font)

Hand-shaped blocks

These are the so-called ‘clay lumps’ (glebas). In fact, the agglomerated earth was known as glebas and loose earth as ‘dust’ (polvo). They are made without a mould, simply shaped by hand. The type of earth used, the place and type of building where they were set, together with the expertise of the builder, gave rise to a variety of shapes, sizes and colours, from the massive Andean ticas to the cones, cylinders or ‘buns’ used by the world’s oldest cultures.

The blocks found at Jericho or at Catal-Huyuk are clay lumps, sometimes very regular, and often moulded to create slight depressions that helped to set them better with the clay mortar, although this could have been omitted as often the blocks were used while still in a malleable state. In the context of the Iberian Peninsula and North Africa, this technique is found mainly at archaeological excavations, although these remains are frequently confused with cob due to the erosion suffered.

In order to avoid this error, it is necessary to analyze the level of moisture in the wall when it was made and whether or not the process was compacted or rammed in some way (Figure 21).
Moulded blocks

These are made with a mould that can be larger or smaller in size and a manufacturing process that varies depending on the type of earth used, the amount of water used in the kneading, the advantage of using stabilisers or binders, fibres or other elements.

Adobe. Adobes or sundried bricks are moulded pieces, usually straight rectangular parallelepipeds (Figure 23), although they can also be cubic or trapezoidal in shape and used for making ovens, vaults or domes, as well as flattened to make eaves, ogees or springing blocks. Firstly, it must be determined whether the clay mass needs the addition of fibres (cereal stalks, horse hair, etc.) to avoid cracking during the drying process. Next, the earth or the mixture is kneaded with the required amount of water, the moulds are filled, the pieces are levelled and then the blocks are unmolded and left to dry in the open air, preferably in the shade. (Figure 22)

Adobe blocks are generally laid with mortars. In most cases, they are rendered with earth and lime mud and straw, gypsum or with a simple lime and gypsum mortar. In Morocco, and in addition to those techniques, the interior walls and surfaces are generally covered with "tadellakt", a lime putty that is...
homogeneously layered and rendered with black olive soap to enhance the impermeability and allow the surface to breath.

In Spanish the adobe is called adobe, gasson, adoba, arrobero, de cabeza, menguao, chiquito, adogue, zabaleta. Nevertheless the terms adobe or adoba themselves are originated from the arabic "at-ᵗūb" or "at-ᵗūba" which literally translates to block or brick.

Another technique similar to the adobe is compressed earth, which follows the same process but is applied to blocks on a larger scale.

Figure 26 Process of realizing the compressed earth construction technique.

_Poured earth._ Walls that are moulded but not compacted or rammed. These walls are very cheap to make as they are not rammed, and the services of a master rammer are thus not required. Once the mould, or large frame – similar to that for formwork – has been assembled, the earth, mixed with straw and water, and whose consistency should be plastic enough to properly fill the corners, is poured in. It was necessary to wait a few days before removing the wooden boards that covered the wall, but the cost and way of making it could be done by anyone, even someone inexperienced, and it was used to make enclosures, shelters and very simple structures (Figure 27)

Figure 27 Poured earth wall with alternating courses of adobe in Rivas de Campos.
*Rammed earth.* Moulded walls where the earth, held in shape by formwork, is rammed with a tamper. It is a very useful technique that leads to structures that are almost indestructible. The tapia (rammed earth) is the technique, while the tapial (formwork) is the mould used to hold the earth, although sometimes the latter is used incorrectly to describe this procedure.

‘Moreover, are there not in Africa and Spain walls made of earth that are called framed walls, because they are made by packing a frame enclosed between two boards, one on each side, and so are stuffed rather than built, and do they not last for ages, undamaged by rain, wind and fire, and stronger than quarry stone? Spain still sees the watchtowers of Hannibal and turrets of earth placed on mountain ridges’ (Pliny and Healy, 1991).

Not all earths are suitable for this technique as they must have the right amounts of clay, silt, sand and gravel. Earth, gypsum, charcoal, crushed shells and other substances can be used and rammed inside the formwork. There are different types of rammed earth, beginning with so – called, ‘plain’ rammed earth, where just earth is used. Once it has been rammed, the earth becomes as hard as stone. It is used mainly for normal dwellings, but also for palaces, castles, monasteries and convents, dovecotes, stables, beehives, tiled roofs, etc.

In Morocco, the wall consists of the successive compaction of layers of earth moistened in temporary wooden formworks (tapiales or tabut) of 245 x 85 cm for the side tables (tafraout), with a width between them 40 or 50 cm up to 1 meter in fortress walls. The earth suitable for the tapial is obtained from soils with a coarse texture, in some cases even with stones. Water is added to the mixture and it is allowed to cure a few days before its use without adding any type of additive. During the compaction process, the tapial is directly supported on the wall by placing two transverse pieces (needles or shkal), which, when removed, produce the distinctive pattern of the wall on the surface of the wall. The stripping is done immediately after the compaction, and the construction of the wall continues in horizontal rows.

It can be found all over Spain but also in Morocco. There are some exceptional cases of gypsum-crusted rammed earth found in areas where there are large deposits of gypsum stone, as in Teruel and Zaragoza. Rammed earth walls may also have a lime rendering applied after the formwork has been removed.
Brick-faced rammed earth, also called Valencian rammed earth, is commonly found on the eastern Mediterranean coast of Spain, and includes bricks that are placed against the formwork as the layers are rammed. Subsequent ramming causes the earth to penetrate so deeply into the cracks and spaces between the bricks that the wall is often confused with brickwork (Figure 29).

Figure 29 Brick faced Valencian rammed earth wall at the Palace of Aarcon in Jativa, Valencia (L. Garcia).

Figure 30 Process of realizing the Rammed Earth construction technique.

Other rammed earth techniques, peculiar to Spain, appeared over the centuries given the need to create dwellings for people who settled on land that was reclaimed as the Reconquest advanced. In this technique, the rammed earth units are placed between vertical buttresses and frequently levelled by horizontal brick courses that serve as a base for the formwork of the following upper unit. The sections of earth, called blocks or panels, often not very heavily rammed, are protected by the sides of the buttresses, which are either straight or toothed.

In order to raise rammed earth walls, it is necessary to support the formwork on putlogs that are inserted into putlog holes, the spaced left by which are usually grouted afterwards. These kinds of rammed earth walls can be seen in the miniatures that Alfonso X the Wise ordered to be included in his Cantigas (Figure 31). This technique, especially with brick buttresses and courses but also built with ashlers or adobe, can be found in most parts of Spain.

Figure 31 Rammed earth wall depicted in the 12th century Cantigos of Alfonso X the Wise.
It is thought that the use of rammed earth has increased with the growth of the Muslim Almoravid and Almohade, that are Amazigh (Berber) dynasties that have ruled North Africa and the Iberian Peninsula. Not only is the technique of rammed earth spread in the Sahara from which these dynasties are originated, but is spread in other notorious imperial cities of Morocco and Spain.

Figure 32 Process of rammed earth construction in Morocco

Figure 33 Ruins of Badi palace, Marrakesh, Morocco.
Building with Earth. Historical Revision and Improved Characteristics by Adding Recycled Materials

Figure 34 Rammed earth ramparts and gate, Marrakesh, Morocco.
The famous Kasbahs in the Draa and Dades valleys of Aït Ben Haddou (Figure 6) and Tamnougalt are now World Heritage Sites. In Marrakesh, the city walls (Figure 34) and the El Badi Palace (Figure 33), constructed in 1578 are constructed mainly in rammed earth. (Jaquin, 2008)

Figure 35 Examples of rammed earth construction in Pre-Saharan region, Morocco. From left to right are residential settlements and a religious building. (Terrachidia)
As for Iberia, it is argued that rammed earth was introduced as early as the 9th century. The first rammed earth to have been recorded dates back to 874 A.D., and is the castle of Badajoz, of which nothing now remains.

It is during the 800 years of the Muslim rule over the Iberian Peninsula that there was an intensive use of rammed earth for the fortifications. It was perceived as a speedy and durable method of construction, and has led to the edification of many city murals and citadels in Morocco (Marrakesh, Fes, and later with the same technique Sale, Rabat and Meknes) and in Spain (Granada, Cordoba, Sevilla, etc) (Figure 36).
Moses Maimonides, a Jewish writer and philosopher, born in Cordoba in 1135, and living in Morocco, Egypt and Palestine, commented about rammed earth building techniques:

‘The builders take two boards, about six cubits long and two cubits high and place them parallel to each other on their edges, as far apart as the thickness of the wall they wish to build; they steady these boards with pieces of wood fastened with cords. The space between the boards is then filled with earth, which is beaten down firmly with hammers or stampers; this is continued until the wall reaches the requisite height and the boards are withdrawn’. (Moses Maimonides).

The custom of alternating horizontal lime joints between rammed earth lifts can be found in diverse regions. On the other hand, this tradition of inserting horizontal lime joints to level the support for the upper lift of a rammed earth wall and cover the putlog holes can be seen in both Castile-La Mancha and Castile-León, and also in many dwelling in cities of Morocco like Fes, Meknes or Marrakech, but with courses of adobe, stone or brick. The main aim of this structural element, called “Imtari” in Moroccan dialect, is to allow the equal transfer of the loads through the bricks from the top of the wall to the foundations.

Finally, we must highlight the traditional role that wood has had as a supplementary connection in historical defensive walls from Islamic times onwards, especially in corners, where logs were inserted and alternated with the layers of earth to improve their connection. In the area of Monforte de Lemos, it is possible to find rammed earth walls with wooden boards inserted either between layers or lifts or in the corners to strengthen the bonds. (Mileto and Vegas, 2017)

2.3 Vulnerability of historic traditional earth construction techniques

In order to take better preservation measures for the conservation of historic and traditional earthen architecture, it is important to understand its weaknesses and observe the factors that lead to its deterioration. This step is important in targeting the necessary material parameters and properties that need to be upgraded in the earth constructions and structures.
Building with Earth. Historical Revision and Improved Characteristics by Adding Recycled Materials

The following is summary, from various references, and from the observation of earthen constructions, to the principal factors that cause damages in earthen structures. These are mainly attributed to construction deficiencies, natural factors.

It is to note, nevertheless, that different factors can simultaneously be causes for the degradation. An anthropogenic factor for example, generally leads to the acceleration process of further natural factors.

2.3.1. Construction deficiencies

Material deficiency

These are principally related to the texture of the soil that is selected for the construction, or to the composition of the earth mixture.

A soil with a high content of stones and gravel, but a low content of clay, has an effect in the mechanical properties of the earthen material. It will have a low compressive strength and water resistance.

A soil with a high content of clay will cause cracking due to shrinkage.

Although adding different traditional admixtures to upgrade the properties of the soil, these can sometimes have a negative effect. Adding straw, for example, enhances the tensile strength of the mixture, but is prone to drying and decompositions. This leaves void in the structure, which lowers its mechanical performance.

Structural defects

The lack of a proper design that is generally incorrect or even inexistent, due to the empirical and intuitive nature of the construction methods of earthen architecture, lead to major structural defects that cause severe damage to rammed earth or other construction techniques.

For example, timber A-frame trusses are often used as support structure of the roof of rammed earth constructions, but if incorrectly designed they may transmit horizontal thrusts that cannot be absorbed by the walls, resulting into cracking and leaning (Keefe 2005).

This said, the thoughtful design of the earthen structures, regarding the depth of the walls and the use of the adequate materials, is important to have better structural performances.

Foundation problems

Having a foundation that is not adequate for the type of construction, where it doesn’t have the necessary bearing capacity to transfer the loads, causes major damages to the structural integrity. These are mainly noticed in severe cracks and even collapse.
2.3.2. Natural factors

Direct action of rain water

Observing earthen constructions suggests that rain water attacks their unprotected parts, mainly the top and base of the walls. Erosion also occurs on the vertical direction of façade surfaces (this decay is accelerated by the wind action and the effects of the oceanic climate). (Figure 38)

Figure 38 Erosion on the top (a) and on the façade (b) of rammed earth walls in Morocco.

Punctual erosion

Some parts of the earthen building are vulnerable to the erosion. These weak points are where the leaking of water converges.
Water settlement and infiltration

Rain water is generally confined in localizations where there was a previous collapse of a wall, a loss of material due to water leakage (Figure 39 and Figure 40), or because of waste deposit which blocks the natural way for the water drainage. Errors in the design and construction such as the lack of a proper roofing system, with no adequate slope, can also cause water settlement.

![Figure 39 Erosion by water infiltration on the roof (a) and at the base of walls (b).](image)

Figure 39 Erosion by water infiltration on the roof (a) and at the base of walls (b).

Figure 40 Lack of a proper drainage, as well as further anthropogenic actions, cause water settlement problems which leads to the humidification of the structure and therefore its deformation.

Thermal movements

It is generally thought that the softness and pliability of earthen structures gives them immunity to problems of thermal (Warren, J. 1999). However, this is not true. These movements cause vertical cracks, found through the walls length (spaced in regular intervals) and at walls junctions. As a result, the monolithic behavior and stiffness of the all is affected.

Biological activity

In conditions with a high moisture content, it is possible to see signs of biological colonization. This results in the growth of plants that cause cracking in the structure due to the tensile stress caused by the expansion. The biological activity is not only linked to the flora, but is also manifested in the
colonization of animals and insects that drill tunnels within the structure and feed from the organic matter in it. (Warren, J. 1999)

**Natural disasters**

Earthquakes and floods are all responsible for severe damages and may even need to collapse of the earth constructions. In particular, earthquakes inflict the highest catastrophic effect. This is both a consequence of the fact that earth constructions are usually built on places with moderate to high seismic hazard, and that these constructions present high seismic vulnerability. (Da Silva, 2013)

In fact, the seismic performance of earth constructions is very deficient when compared with contemporary structures, due to their low strength and high deadweight. The deficient constructive dispositions also greatly contribute for the poor seismic behavior of earth constructions. Such deficiencies are typically related with the lack of connection between structural elements (walls, arches, domes, vaults, roof frames, etc.) composing the earth construction. Therefore, a strong earthquake may lead them to collapse or may inflict severe structural damage, by originating harsh cracks and reducing the overall structural stiffness (Tolles et al. 2002).

**Wind action**

Wind has mainly an erosive action over earth constructions. However, it can also affect other decay agents, like shrinkage or rain.
3. EARTH CONSTRUCTION, A REVALORIZATION OF THE TECHNIQUE

Raw earth is one of the first building materials used in humanity. It is widespread across the globe with nearly 30 percent of the Earth population living in earthen construction. Earth as a building material has also proven its efficiency throughout the centuries, by adapting to the most arid climates, translating the balance between the man and his environment.

However, in an era governed by the industrialization of the construction sector, the challenges are raising, to build higher, stronger, cheaper and more energy efficient. There is in fact a clear gap nowadays between the needs of the populations, the performance of earth as a building material, and the codes and regulations that are normalizing earth construction.

The following chapter presents the reasons why traditional earth construction techniques are becoming obsolete, proposes solutions to upgrade the earth first as a material of construction, and as a building technique, and finally possibilities to insert earth construction techniques in a modern context.

3.1 Earth construction techniques in a modern context

3.1.1 Difficult standardization

In the ancient times, the earth construction was a mere result of empirical constatatations, applying an ancestral knowledge based on expeditious experiments and highly intuitive procedures in the selection of the raw material that was locally available, and the other admixtures.

However, the modern trend tends to subjugate these materials to norms and codes of construction that require reaching higher performances and better results. Experts are therefore seeking to adapt the earth material to build in structures that are adequate with the modern norms.

Nevertheless, the variable composition of the soils makes it difficult for the modern adaptation, normalization and uniformization of the earth construction. This comes from the fact that around the world, and given the properties of each soil in different regions, each type of soil is adequate to a specific building typology that was developed locally, and was thought to translate the needs of the environment in terms of climate and properties of the building material in that specific geographical and geological context.

It is in fact of a real challenge to rethink the earth material, and convert it from a material that is resulting from the diversity, to standardize it and adapt it in a uniform way to diverse contexts.
3.1.2. Misconceptions related to earth construction

Earth is this material that is omnipresent and accessible to all, abundant and affordable, if not free. It generally one of the only materials available on a local scale, making it possible for everyone, whether in emergency situations or not, to build easier and faster without needing a prior experience.

This explains why the third of the population on the planet finds refuge in earthen constructions. The abundance of this material and its availability in multiple contexts allows a notable diversity in the technique and culture of the construction.

These properties have nevertheless a major drawback. The earth construction is unfairly perceived by actors in the building sector as a poor material with no value. Earth architecture is therefore synonymous of poverty. This material of no apparent aesthetic and that lacks an evolution in the techniques of construction, is proper to the vernacular architectures of countries with allow index of development, and where the industrialization was late. (Figure 41)

Although there are various edifices that attest of the high potential of earth as a material of construction, and that are holder of a great heritage, cultural and architectural value, such as citadels and fortresses from the Islam era in Andalusia, or impressive religious edifices that have faced the most harsh weather conditions over centuries, and are witnesses of an ingenuity in using the earth material like the Great Mosque of Djenné in Mali.(Figure 42)
3.1.3. Lack of comprehensive norms and regulations

Another step of the literature review was to revise the standard codes for earthen construction, with the study and analysis of the most relevant aspects, such as stabilization, soil selections, the requisites of the products and the existent test, comparing the diverse normative. In Table 1 is a list of different building codes around the world, the techniques they focus on and their application fields. (Cid, Mazarrón and Cañas, 2011)

Table 1 Selected norms and regulations and their content

<table>
<thead>
<tr>
<th>Country</th>
<th>Norm</th>
<th>REF.</th>
<th>Technique</th>
<th>Application field</th>
<th>Selection of soils</th>
<th>Required products</th>
<th>Experiments</th>
<th>Manufacturing</th>
<th>Construction</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>NMAC, 14.7.4, 2004</td>
<td>21</td>
<td>Adobe, Compressed earth blocks, rammed earth</td>
<td>Construction regulation</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASTM E2392 M-10</td>
<td>22</td>
<td>Adobe, rammed earth</td>
<td>Guide of construction for earthen systems</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>UNE 41410:208</td>
<td>23</td>
<td>Compressed earth blocks</td>
<td>Definition, specifications and testing methods</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>XP P13-901, 2001</td>
<td>24</td>
<td>Compressed earth blocks</td>
<td>Terminology, dimensions and testing methods</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>NZS 4297, 1998</td>
<td>32</td>
<td>Adobe, Compressed earth blocks, poured earth, rammed earth</td>
<td>Structural design and sustainability of earthen buildings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>NZS 4298, 1998</td>
<td>33</td>
<td>Compressed earth blocks, poured earth, rammed earth</td>
<td>Material characterization and construction specification for the use of raw earth. Testing procedures</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After reviewing the different codes regarding earthen construction techniques and application, it was noticed that there is a lack of coherence between the stated codes and regulations and the understanding of the concerned population. These texts being in discord with their economical context, makes it harder for a more comprehensive understanding, mastering and application.

However, there have been efforts to regulate the earthen construction, so that it reaches a credibility in the modern construction sector. The CRATerre laboratory, and many other entities, whether academic or scientific, have been working on the elaboration of documents that detail the characteristics and properties of the earth material and that regulate its applicability, by respect to the norms of security and sustainability. Another measure taken was to realize an inventory of the different techniques of construction using raw earth.

Nevertheless, even if there is an evolution in the field related to the earth construction, the applicability of the various regulations is of a high complexity. This difficulty is linked to the multiplicity of the techniques, and the need to make an empirical traditional construction knowledge evolve.

### 3.1.4. Evolution of the traditional techniques

It is not until 1973, with the oil crisis, that there was an overall consciousness about the scarcity of natural resources. And in these circumstances, the rammed earth technique was reappropriated around the 70s and 80s of the last century, with trials to adapt it to the new technologies.

In this modern context, there was a possibility to construct either in-situ or prefabricated earth walls. The manual mixing of the earth was substituted by mechanical mixers. The earth was then compacted...
in larger moulds, using a pneumatic compacter that uses compacted air, with an impact frequency of 700 hits/minutes. Adopting this force of compaction required a reinforcement of the moulds, which became metallic, so as to resist to the lateral thrusts during compaction. After the unmolding, the outcome is a wall with a smooth surface, resulting from the high pressure that was used for the compaction.

3.2 Discussions

It is clear, that there is a direct correlation between the life cycle environmental footprint and the energetic consumption resulting from the industrialization of construction materials. Therefore the environmental impact is consequently reduced with the reduction of the energy consumption.

The economical system that is mainly based on a consumption cycle, causes the industries to produce materials with a limited life span, that are meant to be replace at the end of the products' life cycle. This economical pattern omits the possibility for recycling and urges the user to buy more, and the industries to produce more.

These two issues, create a vicious circle of intermittent production, which triggers an economical crisis from one side, because the user's purchasing power becomes limited, and an environmental crisis from the other, where the sustainability as well as the natural resources' availability are threatened.

This general ascertainment becomes a serious problematic in the construction field, and the earth material, being widely available, affordable, environmental friendly and sustainable by nature, seems like the holy grail that would solve these recurrent issues.

Now that the reconsideration of earth as a material of construction has been place to research for the past 45 years, many reinforcement techniques were developed. The most notable is the stabilization. We refer here to the physico-chemical stabilization, where the additives used are lime or cement. The stabilization of the earth material has been considered for the past years as the basic method for the upgrade of construction techniques with earth. It is nevertheless, important to highlight its advantages and drawbacks, to understand its mechanisms and to draw conclusions about the extent of its applicability.
4. **EARTH, A CONSTRUCTION MATERIAL**

4.1 **Earth as a raw material**

Beyond fairly general definition, earth is nothing more than an accumulation (usually natural, although it can be artificial) and arrangement, of elementary particles of the soils. They therefore consist of fractions of mineral grains that vary in sizes, called aggregates. They range from gravel to silt and clays.

![Figure 43 Earth sample extracted from la Meuse by BC architects & studies.](image)

Petrologically, the components of a non-cohesive sediment are classified according to their size in the following groups and according to their measurements, although the ranges offered vary slightly according to the bibliographic source consulted:

- **Gravel:** Is constituted of relatively hard rock pieces, coming from an initial rock with a particle size between 2 and 20 mm (over 5mm according to Mileto and Vegas (2017)). It is a component of the sand in the soil. Mechanic properties of the gravel are not affected by the presence of water.

- **Sand:** Mineral grains with a particle size between 60 microns and 2 mm (between 0.5 and 5 mm according to Mileto and Vegas (2017)). It is mainly composed of quartz and silica. It is a component of the sand in the soil. In the dry state, sand presents no cohesion but a high degree of internal frictions. When the sand is humid, the water contained in the interstitial voids between the grains gives an apparent cohesion.

- **Silt:** Their particle size is comprised between 2 and 60 microns (between 5 and 500 microns according to Mileto and Vegas (2017)). In the dry state, the silts have no cohesion. Their friction resistance relative to the movement of their particles (internal friction) is lower than the one of sands. With the addition of water, silts present a good cohesion. Their volume varies depending on the water content and the volume of the material.

- **Clay:** Colloids are the finest components of the soil, with a particle size lower than 2 microns (lower than 5 microns according to Mileto and Vegas (2017)). The main colloids in the soil are the clays. Their composition doesn't have the same characteristics as the other granulates, as they are resulting from the chemical alteration of silicate minerals. Anger and Fonraine (2005) add that these particles are distinguished by their fine size, and their lamellar facies that subject them to capillary forces, more important than the grains.
The soil raw material is the result of the alteration of the parent rock. This process occurs either through mechanical, physical, chemical or biological actions. The resulting material undergoes further transformation as it is continuously transported, deposited, compressed, and/or chemically modified (Houben & Guillaud, 1989).

The mineral composition of the soil used in Earth construction is not as relevant as the particle size distribution. The mechanical properties of unstabilized soils essentially depend upon the grain size of their constituents rather than to their chemical composition or the type of alteration. The different particle-size, as well as the possible admixtures to stabilize it, also plays an important role in the stability, durability and behavior of earthen architecture.

Given the large geography covered by earthen constructions, and specificities of the raw material in each region, the classification of soils differs. Despite the variability of compositions, and the particle size distribution of the soils used in buildings constructed with earth being vast, it is accepted that the composition of a suitable material for earthen construction must fall within this range (Figure 44).

In this case the most common distribution of the fractions consists of:

- clay from 5 to 25%;
- silt from 10 to 30%;
- sand from 40 to 50% and
- gravel between 0 and 15%.

![Figure 44 PSD curves for different earth construction techniques (Jaquin and Augarde, 2012)](image-url)
Below are characteristic properties that define Earth as a material and as a structure (Figure 45 and Figure 46)

The dry density or volumetric mass ($\rho$) of the earth material is the relation between its mass and its volume, and is measured at the dry state after oven drying the earth sample. This property depends on many parameters, principally the particle size distribution, the water content for workability, and the energy related to the workability.

![Figure 45 Density of Earth material suitable for each construction technique compared to concrete and plaster.](image)

The parameters that contribute to a high compressive strength of the earth material are:

- a high volumetric mass;
- a low water content;
- a high content of clay and silt;
- existence of expandable clays;
- a good homogeneity;
- fine grains

It is nevertheless impossible to predict the compressive strength of earth without experimental interventions. Determining the density and the water content of the soil are not enough. Many parameters are taken into considerations when it comes to the cohesion of the earth, and that define its strength. The link between the microstructure of earth and its mechanical properties is extremely complex.

Another parameter that makes it difficult to define a precise compressive strength for the earth material, is the lack of a comprehensive experimental protocol and set of normalizations that are specific to the complexity of the raw earth. The results are therefore generally influenced by the direct projection of codes and regulations concerning concrete and cement on earth, which doesn't take into consideration the disparities between the mechanical properties of those materials.
Effect of the water content

When it comes to using earth as a construction material, it doesn't need much transformations. Reaching an optimal water content provides the adequate consistency. It is then by drying and loosing the water content, and after molding, that earth acquires its cohesive properties. This gives a sustainable characteristic to the earth construction, as it is possible to reuse the same raw earth sample after its destruction and only by adding an adequate amount of water.

Earth as a construction material has a life cycle where the main variable is water, which plays an important role in the softening and reaching the plastic and liquid state of the earth, and finally evaporates to allow the drying of the blocks. Water also allows the earth to adjust its consistency. A dry earth has no cohesion, as much as a humid earth allows the forming of clumps that agglomerate when compressed. Adding a higher amount of water, however, decreases the workability of the earth that reaches its plastic limit (PL). The more water added, the more the earth reaches its viscose states and gains less resistance. This is when it meets its liquid limit (LL) and becomes impossible to mould. The plastic (PL) and liquid (LL) limits vary from one earth to the other. The further they are, the higher the plasticity index is (PI=LL-PL).
After the addition of the adequate amount of water, the earth is left to dry to allow its hardening. During this phase, important quantities of water evaporate.

After the drying phase, the earth reaches a state where its mass remains relatively constant. The material is therefore in equilibrium with its environment and balances its water content according to the ambient humidity.

Earth is a porous and hygroscopic material. Therefore, the amount of water contained in the ambient air can be absorbed by the accessible porous surfaces, and then condensed by the pores through capillary condensation. The more porous the material is and the more its pores are fine, the more can the earth absorb humidity.

![Manufacturing process of an earth block, hardening phase.](image)

**Figure 48** Manufacturing process of an earth block, hardening phase.

### 4.3 Earth and admixtures

#### 4.3.1 Traditional stabilizers

A review of the past construction techniques has revealed a subsequent amount of ancient procedures that were used to enhance the performance of the Earth as a building material. In spite of all the potential Earth has as a building material, these ancestral practices were aware of its limitations. Clay has a low structural behavior, and is vulnerable to harsh weather conditions. These techniques could manifest of a great potential to protect the Earth material and improve its mechanical properties and durability. (Eires, Camões and Jalali, 2014)

The most common stabilizers are listed in Table 2 below:

<table>
<thead>
<tr>
<th>Mineral Origin</th>
<th>Lime</th>
<th>Syrian Asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials

Bitumen of Judea

Animal Origin

Horse Hair
Bristles
Excrements

Plant Origin

Fibers
Straw
Branches
Sap

In parallel with the compaction that adds to the cohesion of the Earth particles and improves the mechanical performance, soil stabilization is also a measure to enhance the durability of the material. It doesn't only improve the mechanical strength, but also increases its durability to avoid its vulnerability to harsh climatic conditions such as erosion and freeze and thaw cycles.

Presented below (Table 3) are the materials, mainly biopolymers, that have been used throughout history, and different regions of the world, and their effect on the performance of Earth material:

<table>
<thead>
<tr>
<th>Geographic location</th>
<th>Biopolymer(s)</th>
<th>Techniques/ Materials/ Obtained properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>Cow dung or urine</td>
<td>“Gohber” - plaster technique, used mainly to fill up surface cracks. Mixture: 1 part of cow dung and 5 parts of earth (in mass). It improves the cohesion and plasticity of soil with low clay content. Another practice is the addition of horse urine, that acts as a hardener and improves waterproofing and impact resistance.</td>
</tr>
<tr>
<td>North of Gana</td>
<td>Dung and carob tree pods</td>
<td>Paint - waterproof effect and hardener of walls and floors in laterite.</td>
</tr>
<tr>
<td>Egypt and Sudan</td>
<td>Straw and dung with fermentation</td>
<td>Adobe and plaster - hydrophobic properties and enhanced resistance.</td>
</tr>
<tr>
<td>México and pre-Columbian people</td>
<td>Nopal - cactus</td>
<td>Used in manufacture of lime based paints. The nopal is still used as waterproof materials for protection against rain to allow the addition of other decoration materials in earth walls.</td>
</tr>
<tr>
<td>México and southwest</td>
<td>Agave - cactus</td>
<td>Used in mortars - the gum is boiled and the</td>
</tr>
</tbody>
</table>
Building with Earth. Historical Revision and Improved Characteristics by Adding Recycled Materials

<table>
<thead>
<tr>
<th>Location</th>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td><em>Leuchtenbergia principis,</em></td>
<td>Extract is kept for two or three weeks before to mix in the clay mortar.</td>
</tr>
<tr>
<td></td>
<td><em>Lophanta, Caeruslens</em> or</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Lechuguilla</em></td>
<td></td>
</tr>
<tr>
<td>South America, especially Peru</td>
<td><em>Tuna</em> - cactus</td>
<td>Soil stabilizer for walls and plasters. Acts as consolidative, more water resistant combined with the surface polish technique.</td>
</tr>
<tr>
<td></td>
<td><em>Opuntia Ficus Indica</em></td>
<td></td>
</tr>
<tr>
<td>South America and Africa</td>
<td><em>Látex</em> - natural resin</td>
<td>Paints - Waterproof effect.</td>
</tr>
<tr>
<td></td>
<td><em>Hevea Euphorbiacex</em></td>
<td></td>
</tr>
<tr>
<td>South America and Africa</td>
<td><em>Banana</em> - stems and leaves</td>
<td>Use of these components boiled for mortars, and paints (only leaves). Waterproof effect.</td>
</tr>
<tr>
<td>Malaya, Indonesia and East India</td>
<td><em>Dammar</em> - natural resin</td>
<td>Mortars - Waterproof effect</td>
</tr>
<tr>
<td></td>
<td><em>Diopteroxycarpaceae family</em></td>
<td></td>
</tr>
<tr>
<td>Asia Minor</td>
<td><em>Animal blood</em></td>
<td>Technique that fell into disuse, which was used as stabilizer for soil or mortars with or without lime. Improves the water resistance and the compressive strength. But presents a high risk of fungi growth.</td>
</tr>
<tr>
<td>Babylonia (5th century B.C.)</td>
<td><em>Natural bitumen</em> - resultant from natural decomposition of vegetable or animals</td>
<td>Soil stabilizer. More effective in soils with little clay. It produces a waterproofing film that prevents the ingress of water</td>
</tr>
</tbody>
</table>

4.3.2. Alternative stabilizers from literature review

In the modern applications and in contemporary upgrade of the vernacular earth constructions, cement is the stabilizer broadly used.

It is not recommended, nevertheless, due to problems connected to leaching and consequent formation of salts or alkaline silicates. This drastically increases the cohesion between the particles and thus, alters the construction’s mechanical properties.

In times governed by economical and environmental crisis, it is necessary to look back into the history, and get the inspiration from the traditional building techniques, to propose environmental friendly alternatives.

The objective of this research is to revise the traditional earth construction technologies, and propose affordable and sustainable alternatives to the stabilization techniques to enhance the material properties of earth.
Several researches have been developed, in fact, to use investigate binding properties of pozzolanic materials, as well as the biopolymers, to upgrade the loam as a raw material, and make it adequate for modern applications, in compliance with building codes and regulations.

In the following Table 4 is a list of the tested admixtures for the upgrade of loam in earth constructions, for each construction technique:

<table>
<thead>
<tr>
<th>Table 4 Alternative stabilizers found from literature review.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane ash</td>
</tr>
<tr>
<td>(Salim, Ndambuki and Adedokun, 2014)</td>
</tr>
<tr>
<td>Seaweed biopolymers</td>
</tr>
<tr>
<td>(Dove, Bradley and Patwardhan, 2016)</td>
</tr>
<tr>
<td>Plant aggregates</td>
</tr>
<tr>
<td>(Ph et al., 2018)</td>
</tr>
<tr>
<td>Cement and pozzolanic reactions</td>
</tr>
<tr>
<td>(Karin, Johansson and Andersson, 2002)</td>
</tr>
</tbody>
</table>

4.3.3. Alternative stabilizers used for the research

In the scope of this paper, the proposed admixtures are the result of waste materials from the mining industry such as coal mining waste or are natural non synthesized fibres such as the mediterranean algae Posidonia Oceanica (Table 5).

<table>
<thead>
<tr>
<th>Table 5 List of proposed stabilizers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral Origin</td>
</tr>
<tr>
<td>Lime</td>
</tr>
<tr>
<td>Coal Mining waste</td>
</tr>
<tr>
<td>Portland cement</td>
</tr>
<tr>
<td>CAC (calcium aluminate cement)</td>
</tr>
<tr>
<td>Plant Origin</td>
</tr>
<tr>
<td>Posidonia Oceanica</td>
</tr>
</tbody>
</table>

4.3.4. Effect of stabilizers

The addition of stabilizers to the soil leads various reactions, by which the soil is bound together and its strength is increased. Adding different stabilizers results in having different effects on the mechanical properties. The stabilizers discussed in connection with mass stabilization are divided into the following groups:
- binders: cement and quicklime
- latent hydraulic admixtures, e.g. ground granulated blast furnace slag
- pozzolanic admixtures, e.g. fly ash
- fillers, e.g. fine sand

The group to which a stabilizer belongs depends, in simple terms, on its CaO:SiO$_2$ ratio, its general mineralogical composition, and its particle size and shape. (Table 6) (Karin, Johansson and Andersson, 2002)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Chemical composition</th>
<th>Mineralogical</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binders</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland cement</td>
<td>~3</td>
<td>Crystalline</td>
<td>~300 - 500 m$^2$/kg</td>
</tr>
<tr>
<td>Lime</td>
<td>&gt;40</td>
<td></td>
<td>0 - 0.1 mm</td>
</tr>
<tr>
<td><strong>Latent hydraulic additives</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground granulated blast furnace slag</td>
<td>~1</td>
<td>Amorphous</td>
<td>~400 - 600 m$^2$/kg</td>
</tr>
<tr>
<td><strong>Pozzolanic additives</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal fly ash</td>
<td>~0.1 - 0.5</td>
<td>Amorphous/crystalline</td>
<td>~300 - 500 m$^2$/kg</td>
</tr>
<tr>
<td><strong>Fillers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine sand</td>
<td>≪0.1</td>
<td>crystalline</td>
<td>0.006 - 0.002 mm</td>
</tr>
</tbody>
</table>

**Lime**

Lime, Ca(OH)$_2$, has been used since ancient times as a stabilizer for earthen architecture. Ca(OH)$_2$ provokes pozzolanic reactions at high pH (> 12) at which clay minerals or other aluminosilicates are partially dissolved and transformed into calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH) and/or zeolite-like phases. These phases have been recognized in antique roman mortars. They can act as cementing agents and improve the durability and mechanical strength of earthen architecture. This is demonstrated by the soundness and resistance of ancient lime-amended rammed earth structures such as the Alhambra fortress (Elert, Pardo and Rodriguez-navarro, 2015)
Lime is produced by burning limestone. A reaction occurs when it enters in contact with water in the soil to form slaked or calcium hydroxide \((\text{Ca(OH)}_2)\). The reaction generates heat and an increase of the pH value to 12.5 approximately. This favours the pozzolanic reactions, where clay particles in the soil react with the calcium hydroxide forming strength enhancing products. Therefore, lime reacts with medium, moderately fine, and fine-grained soils to produce decreased plasticity, increased workability, and increased strength.

The first phase of the chemical reaction involves immediate changes in soil texture and soil properties caused by cation exchange. The free calcium of the lime exchanges with the adsorbed cations of the clay mineral, resulting in reduction in size of the diffused water layer surrounding the clay particles. This reduction in the diffused water layer allows the clay particles to come into closer contact with one another, causing flocculation/agglomeration of the clay particles, which transforms the clay into a more silt-like or sand-like material. Overall, the flocculation and agglomeration phase of lime stabilization results in a soil that is more readily mixable, workable, and, ultimately, compactable. According to Eades and Grim (1960), practically all fine-grained soils undergo this rapid cation exchange and flocculation/agglomeration reactions when treated with lime in the presence of water.

The second phase of the chemical reaction involves pozzolanic reactions within the lime-soil mixture, resulting in strength gain over time. When lime is combined with a clay soil, the pH of the pore water increases. When the pH reaches 12.4, the silica and alumina from the clay become soluble and are released from the clay mineral. In turn, the released silica and alumina react with the calcium from the lime to form cement, which strengthens in a gradual process that continues for several years (Eades and Grim, 1960). As long as there is sufficient calcium from the lime to combine with the soluble silica and alumina, the pozzolanic reaction will continue as long as the pH remains high enough to maintain the solubility of the silica and alumina (Little, 1995). Strength gain also largely depends on the amount of silica and alumina available from the clay itself; thus, it has been found that lime stabilization is more effective for montmorillonitic soils than for kaolinitic soils (Lees et. al, 1982).

In addition to pozzolanic reactions, carbonation can also lead to long-term strength increases for soils stabilized with lime. Carbonation occurs when lime reacts with carbon dioxide from the atmosphere to produce a relatively insoluble calcium carbonate. This can be advantageous since after mixing, the slow process of carbonation and formation of cementitious products can lead to long-term strength increases (Arman and Munfakh, 1970). However, prior to mixing, exposure of lime to air should be avoided through proper handling methods and expedited construction procedures in order to avoid premature carbonation of the lime (Chou, 1987).

Cement

Numerous minerals compose the cement, which is principally manufactured by combining cement clinker (a sintered material of limestone and clay) and gypsum. Mixing cement with water enhances the formation of calcium silicate hydrate and calcium hydroxide \((\text{Ca(OH)}_2)\).
With lime stabilization, the silica is provided when the clay particle is broken down. With cement stabilization, the cement already contains the silica without needing to break down the clay mineral. Thus, unlike lime stabilization, cement stabilization is fairly independent of the soil properties; the only requirement is that the soil contains some water for the hydration process to begin.

Similar to lime stabilization, carbonation can also occur when using cement stabilization. When cement is exposed to air, the cement will react with carbon dioxide from the atmosphere to produce a relatively insoluble calcium carbonate. Thus, similar to lime, proper handling methods and expedited construction procedures should be employed to avoid premature carbonation of cement through exposure to air.

Coal mining waste

In the case of coal mining, according to the studies by Haibin and Zhening (Haibin and Zhenling, 2010), mining waste represents a major environmental concern in China, since from 2007 a production of 315 million tons per year is estimated, and around 4.5 billion tons are stored in pits. In Spain, for every 11 million coal production, waste production amounts to 2 million tons. There are 175 million tons of wastes accumulated in landfills throughout the European Union, with the consequent negative economic, social and environmental impact.

The coal mining has consequently a negative effect on the environment as it generates a great amount of coal mining waste. In this direction, the main objective was to think of alternative uses for this material, and include them in the recycling process.

These wastes are composed mainly by kaolinite, illite and quartz. This composition is very interesting and only by a low thermal activation they are converted in methakaolin: a based pozzolan.

Further papers (Frias et al., 2018), have investigated the use of coal mining waste in the mechanical properties of the Portland cement, as it enhances the pozzolanic properties of Portland Cement through thermal activation. It was proven that that coal mining waste has an active role in enhancing the compressive strength values in blended Portland cement, with the carbonation time being accelerated and the pores in cement reduced.

In this research, and through the use of coal mining waste as an additive in the stabilization of loam, an investigation will be carried out on how the coal mining waste affects the mechanical performance of the earth blocks. This shall be proven by experimenting the addition of Coal mining waste as a main stabilizer with raw loam, and then with the alternation of Portland Cement, Calcium Aluminate Cement, and fibres from the Mediterranean algae Posidonia Oceanica.

The use of different other stabilizers along with the coal mining waste is due to the fact that it doesn't react by itself during stabilization, but they can form strength enhancing materials very slowly on addition of water and some form of calcium hydroxide (Ca(OH)₂). Calcium hydroxide is normally added
in the form of Portland cement in order to obtain faster “normal” strength enhancement. (Karin, Johansson and Andersson, 2002).

**Filler materials**

To increase the number of solid particles a filler, such as fine sand, may be added in soil stabilization. The filler itself does not react but increases the strength of the soil by acting as a “stiffener”.

The filler material will be of greatest relevance in the stabilization of peat and mud, as these soils often require large quantities of stabilizers. Replacing part of the stabilizer with inexpensive filler can save costs. The filler may also be expected to fill any voids formed during stabilization.

In practice, fillers do differ in effectiveness since no filler is completely inert. Thus, for example, high-silica sand is likely to have a greater effect than limestone filler. However, the effect of fillers of whatever type is considerably less than that of the same quantity of binder. (Karin, Johansson and Andersson, 2002)

**Algae (Posidonia Oceanica)**

Through literature review, it was possible to make an inventory of many traditional techniques that use natural fibers as admixtures to improve the mechanical behavior of brittle materials. In the scope of this research, the purpose is to use waste obtained by renewable sources and with potential biodegradability, to replace less efficient materials, to get better mechanical performance results, and from the other side to replace the sustainable fibers so as to reduce the overall environmental impact.

In general, fibers used as stabilizers have a lower dry density, a lower thermal conductivity and a high water absorption, which has consequences on the workability such as the loss of fluidity, slowing the hydraulic binders such as cement, and finally the hygroscopic behavior in the use of other materials (better relative humidity regulation and high latent inertia).

When stabilizing the soil with the use of fibers, the aim is to maximize the porosity of the fine materials. When in a classical earth block, the grains are dense and don't take part in the water absorption, the fibers tend to replace the hygroscopic and porous grains, by fiber particles.

Posidonia Oceanica is a type of marine phanerogam found on both the Atlantic and the Mediterranean coasts. In the latter, the extensive meadows of Posidonia Oceanica are vital to the marine ecosystem, are a good indicator of water quality, and have been used as a parameter for beach classification. However, these plants lose a high amount of leaves that are transported to the coast and accumulate on shores.
Figure 49 Geographical distribution of Posidonia Oceanica.

This spontaneous accumulation requires a specific waste disposal with negative consequences to beach qualities, especially in touristic areas such Spain, Morocco or Tunisia. Besides, further usage as energy source is difficult due to its low combustible behavior under fire. Therefore, the valorization of Posidonia oceanica as a reinforcement in building industry would serve both for mechanical and waste recycling purposes. (Maciá et al., 2016)
5. EXPERIMENTAL ASSESSMENT OF STABILIZED AND UNSTABILIZED LOAM CONSTRUCTION MATERIAL

5.1 Methodology

The assessment of the properties of the available soil was an important step to outline the specificities of the soil like its texture, consistency, organic content, binding force and compactness. These are determined through expeditious and laboratory tests, as presented in Figure 50:

![Figure 50 Experimental testing methodology](image)

5.2 Material characterization

The assessment of the used loam as well as the characterization of material properties was carried out both by means of expeditious tests and laboratory tests.

Information was nevertheless provided about other characteristics of the loam and the stabilizers by the material suppliers.

5.2.1 Selection of the raw materials

Loam

The selected loam, Can Botella, was supplied by "Suministros de Arcilla", and extracted from a quarry located in the north west of Barcelona, Spain.

The supplier indicates it is an illitic clay-limestone with montmorillonite. It presents little contraction giving rise to a porous ceramic. It says to be a plastic clay with a very good behavior for extrusion, and an adequate particle size with reddish color.
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials

Figure 51 "Can Botella" soil collection from the quarry of "Suministros de Arcilla".

A previous analysis was done in the University of Barcelona to determine the chemical mineralogical properties of the studied loam. Those properties are given in Table 7 and Table 8:

Table 7 Mineralogical composition of "Can Botella" (minerals)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Montmorillonite</th>
<th>Chlorite</th>
<th>Illite</th>
<th>Kaolinite</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Plagioclase</th>
<th>Goethite</th>
<th>Hematites</th>
<th>Calcite</th>
<th>Dolomite</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>3</td>
<td>2</td>
<td>24</td>
<td>9</td>
<td>43</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8 Chemical composition of "Can Botella" (oxides)

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>K₂O</th>
<th>CaO</th>
<th>TiO₂</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>LoI*</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.34</td>
<td>2.52</td>
<td>18.13</td>
<td>55.22</td>
<td>0.14</td>
<td>3.59</td>
<td>4.62</td>
<td>0.75</td>
<td>0.00</td>
<td>6.20</td>
<td>8.50</td>
</tr>
</tbody>
</table>

*loss of ignition

Further data were provided to determine the particle size distribution (PSD) and Atterberg limits. This information will be provided in the next chapters along with the relative normative.

Sand

Sand with 1 mm particle size and a dry density of 2.60 g/cm³ was used along with the rest of the mixtures. According to the classification parameters of Atterberg, it has a liquid limit of 33.46%, a plastic limit of 21.82%, a plasticity index of 11.64, and a dry density of 2.63 g/cm³ with an average size of 23.71 lm. (González-lópez et al., 2017)Table 8
Lime

The used hydrated lime in this experiment is a manufactured Calcium Hydroxide native, powder QP (Ca(OH)$_2$), from Panreac Quimica, Castellar del Vallès, Barcelona.

Figure 52 Hydrated lime sample

Cement

Two categories of cement were used in this paper. Calcium aluminate cement and Portland cement. They were provided by the supplier 'Cemento Molins', located in the outskirts of Barcelona.

Figure 53 a) CAC b) Portland cement

The chemical compositions of the Portland cement are given in Table 9 and Table 10, and of the Calcium Aluminate cement in Table 11:

<table>
<thead>
<tr>
<th>Majority Oxide</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>K$_2$O</th>
<th>TiO$_2$</th>
<th>MgO</th>
<th>SO$_3$</th>
<th>Na$_2$O</th>
<th>P$_2$O$_5$</th>
<th>MnO</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>21.22</td>
<td>6.39</td>
<td>3.19</td>
<td>61.38</td>
<td>1.67</td>
<td>0.17</td>
<td>1.97</td>
<td>0.42</td>
<td>0.87</td>
<td>0.20</td>
<td>0.04</td>
<td>2.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minor Elements</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
<th>Zn</th>
<th>Pb</th>
<th>Cl</th>
<th>Co</th>
<th>F</th>
<th>Sr</th>
<th>Y</th>
<th>Mo</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>ppm</td>
<td>117</td>
<td>76</td>
<td>149</td>
<td>54</td>
<td>36</td>
<td>14</td>
<td>237</td>
<td>19</td>
<td>929</td>
<td>392</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Coal Mining Waste

The coal mining waste used was supplied by Hullera Vasco-Leonesa, Sociedad Anónima, miners operating out of Santa Lucía in the Spanish province of León.

This waste was activated in a laboratory furnace for 2 h at 600 °C, the optimal temperature from the standpoint of both pozzolanicity and economic and energy efficiency. (Frias et al., 2018)

The material obtained was substantially more reactive with portlandite than other types of inorganic waste.

The chemical compositions of the coal mining waste are given in Table 13 and Table 14:

**Table 11 Chemical characteristics of Calcium Aluminate cement**

<table>
<thead>
<tr>
<th>Component</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>42.90</td>
</tr>
<tr>
<td>CaO</td>
<td>36.10</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>11.40</td>
</tr>
<tr>
<td>FeO</td>
<td>4.50</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>2.90</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>0.01</td>
</tr>
<tr>
<td>S$^{2-}$</td>
<td>0.03</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.10</td>
</tr>
<tr>
<td>Alkalies</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**Figure 54 Coal mining waste sample**

The material obtained was substantially more reactive with portlandite than other types of inorganic waste. (Frias et al., 2018)

**Table 12 Chemical composition of coal mining waste (majority oxides)**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>K$_2$O</th>
<th>TiO$_2$</th>
<th>MgO</th>
<th>SO$_3$</th>
<th>NaO</th>
<th>P2O5</th>
<th>MnO</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>52.63</td>
<td>25.29</td>
<td>4.64</td>
<td>4.20</td>
<td>3.09</td>
<td>1.17</td>
<td>0.77</td>
<td>0.27</td>
<td>0.17</td>
<td>0.14</td>
<td>0.08</td>
<td>3.09</td>
</tr>
</tbody>
</table>

**Table 13 Chemical composition of coal mining waste (minor elements)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
<th>Zn</th>
<th>Pb</th>
<th>Cl</th>
<th>Co</th>
<th>F</th>
<th>Sr</th>
<th>Y</th>
<th>Mo</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>ppm</td>
<td>-</td>
<td>65</td>
<td>210</td>
<td>162</td>
<td>25</td>
<td>4</td>
<td>46</td>
<td>24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21</td>
<td>2</td>
</tr>
</tbody>
</table>
Posidonia Oceanica

The used Algae (Posidonia Oceanica) was provided by the Instituto Ecologia Litoral, and was collected from Alicante, South Western Spain.

Figure 56 below presents the testing results of the scanning electron microscopy of Posidonia Oceanica leaves (SEM).

Figure 56 SEM results and stress-strain curve of PO (Scaffaro, Lopresti and Botta, 2018)

a) SEM image of the surface and the cross section of Posidonia Oceanica leaf; b)SEM image of Posidonia Oceanica leaf cross section at a higher magnification; c) Stress-strain of Posidonia Oceanica dead leaves.

5.2.2. Pre-treatment

The first step of the material preparation was the grinding of the material (Figure 57) to increase its workability and allow a better use for the further steps including material property determination and sample compacting and testing.

Figure 57 Manual grinding of the raw "Can Botla"
The second step was to separate the samples (Figure 58), following the method for reducing laboratory samples (UNE-EN 932-2).

The aim of this procedure is to reduce the material to a representative sample of 5 kg (then also divided to 2.5 kg), so as to perform the different laboratory tests.

![Figure 58 Sample reduction of the raw "Can Botela"](image)

**5.2.3. Expedious test**

Apart from the laboratory tests that are usually long and costly, and might require higher expertise, the in situ tests help to identify some characteristics of the studied soil. They can be performed by anybody with sensitive analyses.

The results are nevertheless qualitative and informative on the small fraction tested. Therefore, they are not always enough, and need to be verified with more advanced quantitative laboratory tests.

With these preliminary tests, the main points to examine are:

- Grain size distribution, to know the quantity of each grain size.
- Plasticity characteristics, to know the quality and properties of the binders (clays and silts).
- Compressibility, to know the optimum moisture content, which will require the minimum compaction energy for the maximum density.
- Cohesion, to know how the binders bind the inert grains. (Satprem Maïni, 2005)

**Manual / visual inspection**

This test consists in manually grinding a sample of the soil after removing all the gravel, and this both in the dry and humid state, and then perceiving its consistency by moving the sample between the fingers.
- If the soil is sandy: large grains and rough.
- If the soil is silty: fine grains, smooth and adhesive.
- If the soil is clayey: hard to grind, not soluble in water, highly adhesive and very smooth.

Cohesion test - Experiment 1

Preparing a sample of the tested soil and letting it rest for more than an hour (so as to allow the clay to react with water), then sculpting a cigar shape from the paste.

The paste shouldn't stain the hands.

On a plate, form a 3 cm diameter and 20 cm long cigar.

Slowly pressing the cigar towards the edge of the plate.

Measuring the broken part.

Repeating the procedure three times and measuring the average length of the broken part.

If the broken part is:

- Between 10 to 15 cm, then the sample is appropriate for the construction.
- Less than 5 cm, the soil is highly sandy.
- Longer than 15 cm, the percentage of clay in the soil is too high.

Cohesion test - Experiment 2 (Ribbon test)

A 12 mm diameter cigar shaped sample is formed from the fine soil.

The paste shouldn't stain the hands, and should be shaped until forming a 3 mm diameter continuous ribbon.

The ribbon is then held on the palm of the hand, and pressed between the index finger and the thumb.

The pressing should continue from one of the extremities until reaching the highest length.

The length of the ribbon is measured right after the detachment from the original sample.

- If the broken ribbon is between 25 to 30 cm, the sample contains a high percentage of clay.
- If the broken ribbon is between 5 to 10 cm, the sample contains a low percentage of clay
- If it is impossible to create the ribbon, then the sample doesn't contain clay, or the percentage of clay is extremely low.

**Dry test**

Small discs are made from a [terre molle]

The discs are left to dry by exposing them to sun or by drying them in the oven.

The discs are pressed between the index finger and the thumb.

The pressing should continue until the discs are turned to powder.

The properties of the earth sample are then driven according to the following results:

- If the sample disc is very strong and hard to break, or if it broken, it is impossible to turn it to powder, then it is a quasi pure clay (a)
- If the sample is easy to break and turns to powder when pressure is applied, then it is a silty or sandy soil, with a low percentage of clay

**Consistency test**

From a mixture of fine soil, small balls with diameters between 2 and 3 cm are prepared.

The ball is moisturized until it reaches a good degree of cohesion.

The ball is modeled on an even clean surface, until getting a rope like shape.

If the rope is cut before reaching 3 mm of diameter, then the soil sample is very dry, and needs to be further moisturized.

A good result is having a continuous rope until reaching 3 mm of diameter.

After the rope is cut, a small ball is modeled from the
same sample, a then pressed between the index finger and the thumb.

The properties of the earth sample are then driven according to the following results:

- If the rope is hard, then the soil of the shaped ball is hard to break, doesn't crack, and is indivisible, which implies it contains a high amount of clay.

- If the rope is fragile, the shaped ball is not shaped without breakage or division, this implies the soil is silty and sandy and contains a low amount of clay.

- If the rope is soft and spongy, then the soil of the shaped ball is soft and spongy, elastic and not hard, which implies it is an organic soil.

5.2.4. Laboratory tests

Determination of the particle size distribution - Sieving method (UNE-EN 933-1, April 1998)

In a sieve analysis, a sample of dry aggregate of known weight is separated through a series of sieves with progressively smaller openings. Once separated, the weight of particles retained on each sieve is measured and compared to the total sample weight. Particle size distribution is then expressed as a percent retained by weight on each sieve size. Results are usually expressed in tabular or graphical format.

The test consists of dividing up and separating, by means of series of sieves, a material into several particle size classification of decreasing sizes. The aperture sizes and the number of sieves are selected in accordance with the nature of the sample and the accuracy required. The mass of the particles retained on the various sieves is related to the initial mass of the material. The cumulative percentages passing each sieve are reported in numerical form or in graphical form.

**Individual retained** – the mass or percentage retained on one sieve after test.

**Cumulative retained** – sum of the mass or percentages retained on the sieve and on all coarser sieves.

**Cumulative passing** – sum of the mass or percentage passing the sieve (e.g. sum of the retained on all finer sieves and pan).

**Test sieves** – set of sieves with given aperture sizes and shape.

The basic series of sieves are: 0.063 mm; 0.125 mm; 0.250 mm; 0.500 mm; 1 mm; 2 mm; 4 mm; 8 mm; 16 mm; 31.5 mm; 63 mm; 125 mm

Sieves with aperture size of 4 mm and above are perforated plate with square holes and sieves below 4 mm are from woven wire.
**Test portions** - depends on maximum aggregate size and is specified in (Table 14)

### Table 14 Test proportions for each aggregate size

<table>
<thead>
<tr>
<th>Maximum aggregate size $D$ [mm]</th>
<th>Minimum aggregate mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>40</td>
</tr>
<tr>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>2.6</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
</tr>
<tr>
<td>≤4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Pour the washed and dried material (or directly the dry sample) into sieving column. The ideal drying temperature is comprised is ($110 \pm 5$)°C so as to dry the aggregates without causing its particles to break. The column comprises a number of sieves fitted together and arranged, from top to bottom, in order of decreasing aperture sizes with pan and lid.

- Shake the column, manually or mechanically, then remove the sieves one by one, and shake each sieve manually ensuring no material is lost.

- Transfer all the material, which passes each sieve onto the next sieve in the column before continuing the operation with that sieve.

To avoid overloading sieves, the fraction retained at the end of the sieving operation on each sieve shall not exceeded:

$$\frac{A \times \sqrt{d}}{200}$$

Where

- $A$ is the area of the sieve [mm$^2$]
- $d$ is the aperture size of the sieve [mm]

- Weigh the retained material for the sieve with the largest aperture and record its mass as R1. Carry out the same operation for all the sieves......R2, R3, R4....

- Record the various masses on test data sheet as mass of material retained

- Calculate the mass retained on each sieve as percentage of the original dry mass M

- Calculate the cumulative percentage of the original dry mass passing each sieve down

- If the sum of the masses retained $R1 + R2 +$ ...... differs more than 1% from the mass $M$, the test shall be repeated
Determination of the Atterberg limits

Determining the Atterberg limit allows knowing the degree of cohesion and workability of earth in its dry state or in the presence of water.

A dry earth has no cohesion, as much as a humid earth allows the forming of clumps that agglomerate when compressed. Adding a higher amount of water, however, decreases the workability of the earth that reaches its plastic limit (PL). The more water added, the more the earth reaches its viscose states and gains less resistance. This is when it meets its liquid limit (LL) and becomes impossible to mould.

The plastic (PL) and liquid (LL) limits vary from one earth to the other. The further they are, the higher the plasticity index is (PI=LL-PL)

Moisture content

The oven dried method was used to define the initial water content of the raw "Can Botella".

For this, small representative samples were obtained, weighed, and oven dried at 40°C for 24 hours. The samples were then reweighed. The difference determined the weight of the evaporated water loss during the drying process. The difference in weight was divided by the weight of the dry soil, giving the water content on a dry weight basis.

Proctor compaction test

It is important to assess the compaction properties of the soil when it comes to rammed earth construction. There is in fact a direct correlation between the dry density and the compressive strength of the material, as the more the material is compact, the higher is its strength. Compaction is also a major technique in improving the mechanical properties of earth blocks in the earthen construction. (González-lópez et al., 2017)

Figure 59 presents the testing protocol that was conducted for the standard Proctor compaction test, following the instructions sited in the Spanish norms UNE 103-500-94
The first step was to determine the volume of the mould in cm$^3$ (in this case, and according to the given standards, it was a cylindrical mould of 102 mm diameter and 122.4 mm height).

Then determining the mass of the mould with its base and without the upper collar.

In the Proctor test, the soil is first air dried and then separated into 4 samples. The water content of each sample is adjusted by adding water. An increment of 1% percent was added each time, having percentages of 9%, 10%, 11% and 12%.

The soil is then placed and compacted in the Proctor compaction mould in three different layers where each layer receives 26 blows of the standard hammer. Before placing each new layer, the surface of the previous layers is scratched in order to ensure a uniform distribution of the compaction effects.

At the end of the test, after removing and drying of the sample, the dry density and the water content of the sample is determined for each Proctor compaction test. Based on the whole set of results, a curve is plotted for the dry unit weight (or density) as a function of the water content. From this curve, the optimum water content to reach the maximum dry density can be obtained.

5.3 Laboratory methods for preparing and testing the stabilized loam specimens

According to the New Zealand standards for materials and workmanship earth buildings, test specimens shall be made from materials that are representative of the earth material or earth bricks whose characteristic strength is to be determined, and, as far as practicable, using similar techniques and standards of workmanship and under similar conditions to those that are (or will be) applicable for earth walls constructed of that material. NZS 4298-1998 B2.2.2

5.3.1 Mixing of soil and stabilizers

The common way to allow the stabilization of clay in the industry is to add a percentage of cement or lime to the mixtures. In this paper, the aim is to study the different traditional stabilization techniques and propose sustainable and affordable alternatives to improve the durability and strength of loam as construction material.
As the literature review of traditional stabilization techniques could suggest, different biopolymers have been used to improve the strength and durability of clay, most of which being results of organic fibers and wastes.

Many stabilizers can be used. Cement and lime are the most common ones. Others, like chemicals, resins or natural products can be used as well. The selection of a stabilizer will depend upon the soil quality and the project requirements:

- Cement will be preferable for sandy soils and to achieve quickly a higher strength.
- Lime will be rather used for very clayey soil, but will take a longer time to harden and to give strong blocks.

The average stabilizer proportion is rather low:

- Cement stabilization = 5% average.

The minimum is 3% and the maximum is 8% (only for cost reasons).

- Lime stabilization = 6% average.

The minimum is 2% and the maximum is 10% (for technical reason).

No prior preparation was needed for all the stabilizers as they were in a ready to use state. However, the Posidonia Oceanica collected leaves needed a more appropriate preparation (Figure 60).

First, for the cleaning process, all PO was submerged in freshwater to remove salt particles and other organic and inorganic debris, which were also manually removed. Afterwards, the clean Posidonia Oceanica was dried for 2 h at 110 °C in an electric oven. Once the material was clean and dried, it was crushed mechanically allow a better workability. (Macià et al., 2016)

![Figure 60 Preparation process of Posidonia Oceanica](image)

**5.3.2. Dosage rates**

Table 15 summarizes the mix designs of stabilized clay with various percentages of coal mining waste, lime, Portland cement, Calcium Aluminate cement and the algae (Posidonia Oceanica). Three samples were prepared for each dosage rate.
Table 15 Dosage rates (%) of stabilizers used for the sample preparation.

<table>
<thead>
<tr>
<th>Loam</th>
<th>Sand</th>
<th>Coal mining waste</th>
<th>Lime</th>
<th>Portland cement</th>
<th>Calcium Aluminate Cement</th>
<th>Posidonia Oceanica</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>30</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>67</td>
<td>30</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>67</td>
<td>30</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>98</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>68</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>66</td>
<td>30</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>68</td>
<td>30</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.3.3. Mixing procedure

General observations were made regarding the work-ability of the mixture during preparation as well as the quality and homogeneity of the final specimens. Each block was weighed and its dimensions measured. The unit mass (g) and unit volume (cm\(^3\)) were then used to calculate the bulk density (\(\rho\)).

In order to achieve the desired moisture content for the batch, additional water was first blended into the soil and mixed thoroughly until getting an homogeneous mixture.

Given that sand has a different density and water absorption rate than loam, an amount of 1% of the needed mass was added to the sand separately.

After water addition, the appropriate amounts of stabilizer were then added to the mixture and blended manually until getting an homogeneous mixture.

The water and stabilizer were each added slowly to promote uniform blending and to prevent clumping of the soil and/or stabilizer.

5.3.4. Curing

The different mixtures were then molded in the same steel cylindrical moulds that were used in the Standard Proctor Compaction test, with a diameter of 102 mm and a height of 124 mm.

The New Zealand standard for materials and workmanship of earth buildings suggests a height to width ratio of 2:1. Nevertheless, for reasons linked to the availability of materials, the height was limited to 70(\(\pm\) 10) mm.

An aspect ratio factor was used after retrieving the results from the tests to correct for sample height effects.

The density of each of the admixtures and stabilizers was defined, as well as their water content. The given percentage of the dosage rate was mass related.
Three samples of each dosage rate were manufactured for this research, and the compaction was done using a compaction machine with a pressure of 1Mpa(Figure 61 and Figure 62). What was the preassure?

![Figure 61 Compaction machine software interface](image1)

![Figure 62 Compaction machine and first set of compacted samples (100% Loam)](image2)

When the samples were unmolded, they were placed in a chamber with a relative humidity ranging between 65% and 75% in temperature about 20 °C.

The curing periods for the samples were as follows:

14 Days of curing
- Loam 65% Sand 30% Lime 5%
- Loam 98% Posidonia Oceanica 2%
- Loam 68% Sand 30% Posidonia Oceanica 2%
- Loam 66% Sand 30% Posidonia Oceanica 2% Coal mining waste 2%

28 Days of curing
- Loam 100%
- Loam 70% Sand 30%
- Loam 68% Sand 30% Coal mining waste 2%
- Loam 67% Sand 30% Coal mining waste 1% CAC 2%
- Loam 67% Sand 30% Coal mining waste 1% Portland cement 2%

Unlike cement or lime stabilized materials which involve long term pozzolanic reactions, modification with biopolymers relies on more immediate effects such as cross linking. Therefore the effect of longer...
curing times (e.g. 28 and 90 days) typically adopted for conventional stabilisers were not considered relevant in the stabilization with Posidonia Oceanica fibers. (Dove, Bradley and Patwardhan, 2016)

As for the samples stabilized with lime, they were used as observation samples, to justify the none convenience of lime stabilization for the reinforcement in the modern context, as this traditional technique of stabilization requires a longer time to allow the reaction than other stabilizers.

5.3.5. Compressive strength testing

The procedure adopted in performing the compressive strength testing is similar to that used for fired clay and concrete blocks. Individual units are capped and tested directly between platens. Block surfaces are usually sufficiently flat and parallel that only thin membrane sheet capping is necessary. The blocks were tested in the direction in which they have been.

Three samples of each dosage rate were collected for characterization. The test samples were 3 blocks for each dosage rate.

A compression machine, presented in (Figure 63), with 0.05 kN of precision and a loading speed of 2 kN/s is used.

![Figure 63 Compressive strength testing equipment](image)

The compressive strength of is evaluated on the basis of expression:

\[ F_c = \frac{F}{S} \]

Where:

- \( F_c \) is the compressive strength (N/mm\(^2\))
- \( F \) is the failure load (N)
- \( S \) is the area of specimen (mm\(^2\))
6. RESULTS OF THE ASSESMENT

This chapter will be presenting the experimental tests and the results that were driven from the material properties characterization, as well as the results of the compressive strength test.

6.1 Material assessment

6.1.1. Particle Size Distribution test

The granular composition curve of the designed soil mixture is plotted in Figure 65.

As it is shown in Figure 64, the designed mixture fits, for the most part, in the granular composition area that is suggested by Jaquin and Augarde (2012).

![Figure 64 PSD envelope for different earth construction techniques (Jaquin and Augarde, 2012)](image1)

![Figure 65 PSD curve for untreated soil "Can Botella"](image2)
Building With Earth. Historical Revision And Improved Characteristics By Adding Recycled Materials

Table 16 Particle size fractions of untreated soil "Can Botella".

<table>
<thead>
<tr>
<th>&lt;150 μm</th>
<th>&lt;50 μm</th>
<th>&lt;20 μm</th>
<th>&lt;2 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td>86</td>
<td>82</td>
<td>10</td>
</tr>
</tbody>
</table>

The dosage specification suggests in most mixtures with stabilizers, a correction with 30% of fine sand with a grain size between 1 and 2 mm.

This adjustment, and the use of the new curve, is expected to optimize the density of the material and thus its strength performance.

The particle size distribution with the given percentage gives results plotted in Figure 66.

![Figure 66 Correction of the soil "Can Botella" with 30% of sand (1-2 mm)](image)

Table 17 Particle size fractions of soil "Can Botella" 70% with correction of 30% of sand

<table>
<thead>
<tr>
<th>&lt;1000 μm</th>
<th>&lt;150 μm</th>
<th>&lt;50 μm</th>
<th>&lt;20 μm</th>
<th>&lt;2 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>56.4</td>
<td>51.6</td>
<td>49.2</td>
<td>6</td>
</tr>
</tbody>
</table>

### 6.1.2. Atterberg limits

The liquid limit (LL), plastic limit (PL) and plasticity index were previously determined for the studied soil "Can Botella", and the results are presented in (xx). In this case, the test was previously conducted by the loam suppliers.

Although it is common to refer to the Atterberg in earth construction, there are few recommendations that suggest values for the unstabilized rammed earth or adobe. The use of these parameters regards commonly the selection of a stabilization technique (chemical), but they also provide information on the mineralogical properties of the fine fraction, which can have consequences on the performance of the rammed earth.

Houben and Guillaud (2008) propose an envelope of recommended values for PI (plasticity index) and LL (liquid limit) given in Figure 67.
The studied soil "Can Botella" falls slightly outside the suggested envelope.

![Graph of Plasticity Index vs Liquid Limit](image)

**Figure 67** Comparison of the consistency parameters of the soil against the envelope with recommended values by Houben and Guillaud (2008) for unstabilised rammed earth.

In practical terms, this means that rammed earth prepared with soil "Can Botella" may have durability or/and strength problems, whose uncertainty can only be clarified by testing the performance of rammed earth specimens. This will be further investigated by testing the compressive strength of the untreated soil "Can Botella" in comparison with the same soil treated with fillers and stabilized with different dosage rates of admixtures.

**Table 18** Atterberg's limits of the soil "Can Botella"

<table>
<thead>
<tr>
<th></th>
<th>Liquid Limit (LL)</th>
<th>Plastic Limit (PL)</th>
<th>Plasticity index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorada Especial</td>
<td>38.1</td>
<td>26.8</td>
<td>11.26</td>
</tr>
</tbody>
</table>

Given the plasticity index of the soil "Can Botella", it can be classified according to the USCS classification as a clayey sand with gravel (SC).

### 6.1.3. Proctor test

The results of the standard Proctor test are summarized in Table 19, and the compaction curve of the studied soil is presented in Figure 68.

**Table 19** Compaction properties of the soil "Can Botella"

<table>
<thead>
<tr>
<th>Water content (%)</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density (\rho) (g/cm(^3))</td>
<td>1.83</td>
<td>1.91</td>
<td>1.89</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Based on the whole set of results, a curve is plotted for the dry unit weight (or density) as a function of the water content. From this curve, the optimum water content to reach the maximum dry density can be obtained.
The maximum dry density of soil according to the Proctor test result is 1.91 g/cm³, corresponding to an optimal water content of 10%.

An earth with an excellent performance is said to have a maximum dry density between 2.10 g/cm³ and 2.20 g/cm³.

Figure 68 Compaction curve of the studied soil “Can Botela”.

6.1.4. Mechanical performance assessment

The compressive strength of the prepared samples was assessed performing a compressive strength test on 3 blocks from each dosage rate following the procedure in 5.3.5.

Following the guidelines given by NZS 4298 (NZS 1998b), the characteristic compressive strength was determined from a set of tests, in accordance with the design requirements.

This definition of the characteristic compressive strength takes into consideration the height to thickness ratio, which defines an aspect ratio factor $k_a$. The aspect ratio has to be taken into account by applying the equation:

$$f'_{c} = k_a \cdot f_c$$

Where:

- $f'_{c}$ is the adjusted compressive strength
- $k_a$ is the aspect ratio factor
The NZS 4298 (NZS 1998b) suggests an ideal height to thickness ratio of 2:1, while giving a table (Table 20) that limits the aspect ratio factor between 0.5 and 1.

<table>
<thead>
<tr>
<th>Height to thickness ratio</th>
<th>0.4</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0 or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio factor (k_a)</td>
<td>0.50</td>
<td>0.70</td>
<td>0.80</td>
<td>1.0</td>
</tr>
</tbody>
</table>

In the case of this experiment, the height to thickness ratio ranges between 0.68 and 0.84.

It was found by linear interpolation that the corresponding aspect ratio factor for each height to thickness ratio value is as follows in Table 21:

<table>
<thead>
<tr>
<th>Height</th>
<th>70</th>
<th>73</th>
<th>82</th>
<th>86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height to thickness ratio</td>
<td>0.68</td>
<td>0.72</td>
<td>0.8</td>
<td>0.84</td>
</tr>
<tr>
<td>Aspect ratio factor (k_a)</td>
<td>0.5933</td>
<td>0.6067</td>
<td>0.6333</td>
<td>0.6467</td>
</tr>
</tbody>
</table>

The characteristic compressive strength $f_{ck}$ was then computed using the following equation:

$$f_{c,k} = \left(1 - 1.5 \frac{s}{f'_{c}}\right) f'_{c,min}$$

Where:

- $f'_{c}$ is the average adjusted compressive strength.
- $s$ is the respective standard deviation.
- $f'_{c,min}$ is the respective least value.

### 6.2 Results of the assessment

The results adjusted compressive strength of the 3 samples were plotted for each dosage rate.

Following are the graphs for each dosage specification, as well as the failure modes and the average adjusted and characteristic compressive strengths.
6.2.1. Loam 100 %

\[ f_c = 1.24 \text{ N/mm}^2 \]
\[ f'_c = 0.73 \text{ N/mm}^2 \]
\[ f_{c,k} = 0.68 \text{ N/mm}^2 \]

Figure 69 Failure mode for a dosage rate 100% of loam

Figure 70 Compressive strength-strain curve for a dosage rate 100% of loam

6.2.2. Loam 70 % Sand 30 %

\[ f_c = 1.3 \text{ N/mm}^2 \]
\[ f'_c = 0.79 \text{ N/mm}^2 \]
\[ f_{c,k} = 0.70 \text{ N/mm}^2 \]

Figure 71 Failure mode for a dosage rate 70% of loam and 30% of sand

Figure 72 Compressive strength-strain curve for a dosage rate 70% of loam and 30% of sand
6.2.3. Loam 65 % Sand 30 % Lime 5 %

$f_c = 0.54 \text{ N/mm}^2$

$f'_{c} = 0.32 \text{ N/mm}^2$

$f_{c,k} = 0.24 \text{ N/mm}^2$

In this case, all the samples had a very low compressive strength, leading to a complete crushing of the sample.

![Figure 73 Compressive strength-strain curve for a dosage rate 65% of loam, 30% of sand and 5% of lime](image)

6.2.4. Loam 98 % Posidonia Oceanica 2 %

$f_c = 1.27 \text{ N/mm}^2$

$f'_{c} = 0.78 \text{ N/mm}^2$

$f_{c,k} = 0.63 \text{ N/mm}^2$

![Figure 74 Failure mode for a dosage rate 98% of loam and 30% of algae](image)

![Figure 75 Compressive strength-strain curve for a dosage rate 98% of loam and 2% of algae](image)
6.2.5. Loam 68% Sand 30% Posidonia Oceanica 2%

\[ f_c = 0.63 \text{ N/mm}^2 \]
\[ f'_c = 0.39 \text{ N/mm}^2 \]
\[ f_{c,k} = 0.18 \text{ N/mm}^2 \]

Figure 76 Failure mode for a dosage rate 68% of loam, 30% of sand and 2% of algae

6.2.6. Loam 66% Sand 30% Posidonia Oceanica 2% Coal mining waste 2%

\[ f_c = 0.43 \text{ N/mm}^2 \]
\[ f'_c = 0.30 \text{ N/mm}^2 \]
\[ f_{c,k} = 0.17 \text{ N/mm}^2 \]

In this case, all the samples had a very low compressive strength, leading to a complete crushing of the sample.

Figure 78 Compressive strength-strain curve for a dosage rate 66% of loam, 30% of sand, 2% of algae and 2% of coal
6.2.7. Loam 68% Sand 30% Coal mining waste 2%

\( f_c = 0.55 \text{ N/mm}^2 \)

\( f'_{c} = 0.34 \text{ N/mm}^2 \)

\( f_{c,k} = 0.04 \text{ N/mm}^2 \)

![Figure 79 Failure mode for a dosage rate 68% of loam, 30% of sand and 2% of coal mining waste](image)

![Figure 80 Compressive strength-strain curve for a dosage rate 68% of loam, 30% of sand and 2% of coal mining waste](image)

6.2.8. Loam 67% Sand 30% Coal mining waste 1% CAC 2%

\( f_c = 0.33 \text{ N/mm}^2 \)

\( f'_{c} = 0.24 \text{ N/mm}^2 \)

\( f_{c,k} = 0.19 \text{ N/mm}^2 \)

![Figure 81 Failure mode for a dosage rate 67% of loam, 30% of sand, 1% of coal mining waste and 2% of CAC](image)

![Figure 82 Compressive strength-strain curve for a dosage rate 67% of loam, 30% of sand, 1% of coal mining waste and 2% of CAC](image)
6.2.9. Loam 67 % Sand 30 % Coal mining waste 1% Portland cement 2%

\[ f_c = 1.04 \text{ N/mm}^2 \]
\[ f'_{c} = 0.66 \text{ N/mm}^2 \]
\[ f_{c,k} = 0.50 \text{ N/mm}^2 \]

**Figure 83** Failure mode for a dosage rate 67% of loam, 30% of sand, 1% of coal mining waste and 2% of Portland cement

**Figure 84** Compressive strength-strain curve for a dosage rate 67% of loam, 30% of sand, 1% of coal mining waste and 2% of Portland cement

### 6.3 Discussions

The failure of the specimens occurred according to two modes:

- material crushing and consequent disaggregation of the specimen (Figure 76);
- main vertical/diagonal crack formation with spalling of the specimen surface (Figure 83).

The first mode occurred mostly in the specimens with lower compressive strength, while the second occurred mostly in those with a higher compressive strength.
When there are no hydraulic stabilizers involved, the average compressive strength results of all of the tested samples were relatively similar, ranging around 1.2 N/mm². This is applied for the unstabilized loam, the grain size corrected loam as well as loam stabilized with the algae fibers (Posidonia Oceanica).

In this case, the compressive strength with 98% of loam and 2% of Posidonia Oceanica had a performance better than the raw loam but still didn't meet the requirement minimal compressive strength.

However, only the sample with 70% loam with a grain correction using as a filler material 30% of sand (1 mm), met the requirement of minimal compressive strength equal to 1.3 N/mm² set by the New Zealand standard NZS 4298:1998.

An attention should be driven to the fact that, even if the samples with a dosage specification of 70% loam and 30% loam have met the minimum compressive strength suggested by NZS 4298:1998, the addition of 2% of Posidonia Oceanica didn't lead to a positive result. These results can be explained by many hypothesis that might have affected the experimental procedure.

The first would be due to the curing time of 14 days not being enough for the reaction to occur between the raw loam and the admixtures.

Another explanation would be the fact that the fibrous particles of the algae's aim is to maximize the porosity of the fine materials. They tend to lower the density in the mixture and to replace the hygroscopic and porous grains, by fiber particles. Therefore, having sand grains that have a higher particle size doesn't allow a good cohesion between.

Also, due to limited references about Posidonia Oceanica and the limited time accorded to this thesis work, it was difficult to determine all the material characteristics of the algae. Empirical and intuitive
procedures were taken in order to define its water content. In fact, the low density and high water absorption of Posidonia Oceanica require a higher water percentage. In this case the water content of the mixture didn't meet its optimal value, and therefore, the mixture didn't the optimal level of plasticity.

The addition of coal mining waste lowers the performance of the mixture with loam, sand and Posidonia Oceanica. This is mainly due to the fact that coal mining waste only reacts in the presence of another pozzolanic material. It can therefore form strength enhancing materials very slowly on addition of water and some form of calcium hydroxide (Ca(OH)\(_2\)). Calcium hydroxide is normally added in the form of Portland cement in order to obtain faster “normal” strength enhancement (Karin, Johansson and Andersson, 2002). This also justifies the fact that the coal didn’t react when added with loam and sand alone, and gave a lower compressive strength (\(f_c = 0.55\) N/mm\(^2\)), but allowed a better result when added to a dosage specification including Portland cement (\(f_c = 1.04\) N/mm\(^2\)). It is suggested that a longer curing time period or a higher relative humidity would allow better results for the samples stabilized with coal and Portland cement.(Narloch, Woyciechowski and Jęda, 2015)

In the case of the stabilization with lime, which has shown the lowest resulting compressive strength, the result was expected as the pozzolanic reaction between the clay particles and Ca(OH)\(_2\). Lime, Ca(OH)\(_2\) is traditional stabilizer that has proven its efficiency over centuries. This is demonstrated by the soundness and resistance of ancient lime-amended rammed earth structures such as the Alhambra fortress (Elert, Pardo and Rodriguez-navarro, 2015) Nevertheless, it has been proven that unlike cement that needs 28 days for curing, or biopolymers that only require 14 days of curing, lime stabilized materials involve long term pozzolanic reactions, and needs at least 90 days for curing (Dove, Bradley and Patwardhan, 2016)

The samples stabilized with lime were used as observation samples, to justify the none convenience of lime stabilization for the reinforcement in the modern context, as this traditional technique of stabilization requires a longer time to allow the reaction than other stabilizers. It has been proven that they have given lower values of compressive strength than the rest of the stabilizers. Morel, Pkla and Walker, 2007 present other reasons that could affect the compressive strength testing results. In fact, the geometry of test blocks has a significant influence on the value of measured compressive strength using the standard test methodology. The apparent strength enhancement due to platen restraint depends on the ratio of height to thickness (aspect ratio) of the block. As previously outlined one approach adopted is to correct measured strength by a single aspect ratio correction factor. The distinct advantage of this approach is that it enables a variety of different block sizes to be used, but of course it relies on accurate correction factors.

Geometric effects on compressive strength of compressed earth blocks stem not only from platen restraint, but also influence of friction during block manufacture. Density of blocks produced using single acting ram presses is not constant, but reduces with height away from the ram face due to friction along the mould sides. Experimental studies have confirmed that the apparent unconfined compressive strength value is achieved when the aspect ratio reaches 5 . However, beyond an aspect...
ratio of 1.5 the compressed earth block material is unlikely to be homogeneous, due to friction during manufacture.

It should also be noted that in practice the variation in compressed earth block geometry is not as extreme as described above, but it is possible to extend this work to adobe where the variation in block geometry can be even greater.

The compressive strength of compressed earth blocks is strongly related to dry density achieved in compaction. Compressive strength of individual blocks consistently increases as dry density increases. This relationship between strength and density has been consistently proven by test data over the past 20 years.

As a conclusion, it is to note that according to Bui et al. (2009), a traditional rammed earth wall (about 50 cm thick) is loaded by stresses between 0.1 N/mm² and 0.3 N/mm². All the samples tested, which have compressive strengths comprised between 0.24 N/mm² and 0.79 N/mm² (considering the average compressive strength of the specimens) would present the safety factors in (Table 22) for a stress level of 0.3 N/mm².

<table>
<thead>
<tr>
<th>Material Mix</th>
<th>$f'_{c}$</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% loam</td>
<td>0.73</td>
<td>2.45</td>
</tr>
<tr>
<td>70% loam 30% sand</td>
<td>0.79</td>
<td>2.64</td>
</tr>
<tr>
<td>65% loam 30% sand 5% lime</td>
<td>0.33</td>
<td>1.09</td>
</tr>
<tr>
<td>98% loam 2% algae</td>
<td>0.79</td>
<td>2.62</td>
</tr>
<tr>
<td>68% loam 30% sand 2% algae</td>
<td>0.39</td>
<td>1.30</td>
</tr>
<tr>
<td>66% loam 30% sand 2% algae 2% coal</td>
<td>0.31</td>
<td>1.02</td>
</tr>
<tr>
<td>68% loam 30% sand 2% coal</td>
<td>0.35</td>
<td>1.16</td>
</tr>
<tr>
<td>67% loam 30% sand 1% coal 2% CAC</td>
<td>0.25</td>
<td>0.83</td>
</tr>
<tr>
<td>67% loam 30% sand 1% coal 2% Portland</td>
<td>0.66</td>
<td>2.20</td>
</tr>
</tbody>
</table>

In practical terms, this means that a rammed earth dwelling built with any of the dosage specifications tested would not collapse under normal conditions (e.g. in the absence of moisture problems and important seismic events). Only the dosage specification with 1% of coal mining waste and 2% calcium aluminate cement would present a risk of collapse under this condition.

There is nevertheless a standing issue about the application of the same dosage specification for compressed blocks, or for a modern context application, as the design requirement for the design of earth structures in modern application requires a higher minimal compressive strength.
7. CONCLUSION AND FUTURE WORKS

7.1 Main conclusion

This thesis research was deemed to explore the potential earth architecture has. This was done by revising earth historic construction techniques, understanding the specificities of the material, and finally the proposal of alternative solutions for the upgrade of its mechanical properties, in order to respond to the economical and environmental problematic.

In the inventory that was conducted to detail the common historic construction techniques, focused on the categorization of examples from the Iberian Peninsula and Morocco, several categories and subcategories were defined as follows:

- Construction by removal;
- Construction by addition;
- Earth used as aggregate;
- Stacked earth. This category encloses: cob, or stacked earth with subsequent shaping and piled earth with no subsequent shaping.
- Piled earth in blocks. This category encloses: cut blocks without grass roots, cut blocks with grass roots, hand-shaped blocks, and finally moulded blocks (adobe, poured earth and rammed earth).

These categories are common to both mentioned regions, but some of them are only limited to archaeological sites, and are not practiced anymore. There was therefore more focus on the adobe and rammed earth techniques, that are still widespread and used in many rural regions as a vernacular architecture.

With all the positive aspects the earth construction presents, it is perceived as a vulnerable material, and therefore generally unfairly considered as a poor material, and the vernacular architecture that emanates from strictly reserved for the poor. This misconception has led to a loss of interest in the use of the earth material in the modern context.

It is not until the last 45 years that light was shed on the importance of the reconsideration of the earth material, as it is affordable, widely available, and most importantly sustainable. And although this reconsideration came with several norms and regulations, these standards are not exhaustive, and fail to cover all the specificities of the earth material.

Another raised issue is the use of physico-chemical stabilizers with the raw earth, which are not always adequate to the initial material. Although cement and lime, for instance, have positive effects on the mechanical properties' enhancement and he water resistance, which improves the durability of the earthen structures in arid climatic conditions, this stabilization technique presents major drawbacks.
Firstly, this stabilization has a considerable influence on the price of the construction. Moreover, the use of cement and lime make the recycling process of the used composition impossible, and therefore, the possibility for the reuse of the material, which characterizes earth as a sustainable material, is omitted.

The ambitions that contemporary humans have to further stretch the limits of a material, threatens in this case the ecological and environmental interest that the earth material presents.

The conducted research experiments investigate the possibility of using alternative stabilizers, issued from recycled waste materials (coal mining waste) or from non synthesized and non industrialized fibers (algae Posidonia Oceanica). Other additives were nevertheless used, such as calcium aluminate cement ad Portland cement but with lower percentages than the usual applications.

The results have shown that the unstabilized earth blocks, as well as the blocks stabilized with coal mining waste activated with Portland cement and the blocks reinforced with Posidonia Oceanica, have a better performance than those with hydraulic stabilizers. Not only this, but these earth blocks have a lower energy consumption and life cycle environmental footprint.

### 7.2 Future works

A revision of historical earth construction techniques, as well as an experimental investigation of the mechanical behavior of stabilized and unstabilized earth blocks were carried out within the framework of this thesis, but these topics still need further investigation. In addition, a set of questions regarding the development of other types of reinforcement solutions for earth constructions should be addressed in further research. Therefore, a listing of future works is proposed as follows:

- Application of the stabilization of earth material for different construction techniques, such as on large-scale models in laboratory of rammed earth,
- Further investigation on the mechanical behaviors under tensile strength and shear strength, with the same dosage rates;
- Investigation of the behavior of loam stabilized with Posidonia Oceanica with the use of different water content and different dosage rates,
- Investigation of the behavior of loam stabilized with coal mining waste activate with Portland cement, with the use of different water content and different dosage rates,
- Experimental testing to assess the durability of the earth blocks, and resistance to erosion, freeze and thaw effect, using the Geelong test for instance,
- Study of the environmental impact of these stabilized earth blocks and investigate in the possibility of further recycling of the blocks after the end of their life cycle.
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Building with Earth. Historical Revision and Improved Characteristics by Adding Recycled Materials


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