RAMMED EARTH: FEASIBILITY OF A GLOBAL CONCEPT APPLIED LOCALLY

CONSTRUÇÃO EM TAIPA: VIABILIDADE DE UM CONCEITO GLOBAL APLICADO LOCALMENTE

Silva, Rui A.; University of Minho, Civil Engineering Department*, Guimarães, Portugal, ruisilva@civil.uminho.pt*

Oliveira, Daniel V.; University of Minho, Civil Engineering Department, Guimarães, Portugal, *danvco@civil.uminho.pt*

Miranda, Tiago F.; University of Minho, Civil Engineering Department*, Guimarães, Portugal, tmiranda@civil.uminho.pt*

Escobar, M. Carolina; University of Minho, Civil Engineering Department, Guimarães, Portugal, *mcescobars@gmail.com*

Cristelo, Nuno M.; University of *Trás-os-Montes e Alto Douro*, Sciences and Technology School*, Vila Real, Portugal, ncristel@utad.pt*

ABSTRACT

Rammed earth is an ancient building technique that has been continuously reinvented in the dynamic movement of people all over the world, where it has been used to build from dwellings to enormous fortresses and city walls. In the particular case of Portugal, the inhabitants have been closely related to earth construction. From one region to another, rammed earth, adobe and wattle-and-daub buildings are frequently found. The rammed earth construction is mainly found in the southern part of Portugal and is almost absent from the north. However, the relatively low seismic hazard of the north of Portugal plus the sustainability of earth as a building material encourages the development of this technique in the region. The suitability of the typical granite residual soils from the Minho region for rammed earth construction was assessed by means of an experimental program, in which three representative soils were subjected to expeditious and laboratory tests that evaluated the characteristics of the soils and the performance of rammed earth built with them. The results showed that the granite residual soils tested fulfil most of the requirements needed for rammed earth construction, being the low compressive strength its main limitation. In this way, an innovative and sustainable stabilization technique based on alkaline activation of fly ash is proposed.

RESUMO

A taipa é uma técnica de construção antiga que tem sido continuamente reinventada pelo movimento dinâmico de pessoas por todo o mundo, onde tem sido utilizada para construir desde habitações até grandes fortes e muralhas. No caso particular de Portugal, os habitantes têm uma relação direta com a construção em terra. De uma região para outra, são encontrados frequentemente construções em taipa, adobe e tabique. A taipa é maioritariamente encontrada no sul de Portugal e está praticamente ausente do norte. Porém, a relativamente baixa perigosidade sísmica do norte de Portugal, associada à sustentabilidade da terra como material de construção encorajam o desenvolvimento desta técnica na região. A adequabilidade dos típicos solos residuais graníticos da região do Minho para a construção em terra foi analisada num programa experimental, no qual três solos representativos foram sujeitos a ensaios expeditos e laboratoriais, que avaliaram características dos solos e o desempenho de taipa construída com estes. Os resultados mostraram que solos residuais graníticos testados cumprem muitos dos requisitos necessários para a sua utilização na construção em taipa, sendo a principal limitação a sua reduzida resistência à compressão. Neste sentido, propõe-se uma técnica de estabilização inovadora e sustentável baseada na ativação alcalina de cinzas volantes.

1 - INTRODUCTION

Building with earth can be considered as one of the most popular solutions to the issue of shelter and housing. In fact, 30% of the World's population live in a house built with raw earth (Houben and Guillaud, 2006). In developed countries the practice of building with earth has fallen in disuse over the past century, as a consequence of the technological development and extensive use of modern building materials (concrete and steel). However, the recent environmental concerns have been recalling earth construction as a modern building solution mostly due to its recognized sustainability and benefits.

The earth construction concept includes several building techniques that have different constructive features, which depend mostly on local limitations related with the properties of the available soil. Buildings made of raw earth are common and are widespread in Portugal, where the most common building techniques are: rammed earth (*"taipa"*), adobe and wattle-and-daub ("*tabique*"). Rammed earth, which consists in compacting moist soil by layers between a removable formwork to build monolithic walls, is found almost exclusively in the south of Portugal, namely in Alentejo and Algarve. On the other hand, the traditional building stock of the north of Portugal consists of granite masonry, whose construction was supported by the great availability of this stone. But this building solution also felt the takeover by the building solutions incorporating modern materials, resulting in the fact that, nowadays, the construction of new houses with stone masonry is not common. Regarding rammed earth construction, this technique is almost absent from the region. However, it can be looked as a path for promoting sustainable construction, which raises the question of the region´s typical and abundant granite residual soils being suitable or not for this purpose. Ideally, one should look for a solution where no stabilization is required, minimizing financial cost and environmental impact (Houben and Guillaud, 2006).

Having in mind this motivation, an experimental program was carried out on three representative soils from the north of Portugal in order to conclude on the suitability of the local soils. The experimental program was divided in two different approaches: one based on simple expeditious tests; and the other on more elaborate laboratory tests. Finally, and as consequence of the results achieved, an innovative soil stabilization technique, based on alkaline activation of fly ash, is briefly presented. The results of a preliminary set of tests that support the proposed technique are also addressed.

2 - RAMMED EARTH CONSTRUCTION

2.1 - Concept of earth construction

Building with earth is a solution for housing globally known since ancient times, whose success resides on a material that can be found everywhere in adequate quantities. However, not all the soils are suitable for earth construction. For example, an earthen material prepared with a soil with very low clay content does not gain enough cohesion, since the clay is not enough to accomplish its function of binding the coarse particles. Thus, it is necessary to identify the characteristics of a given soil in order to evaluate the quality of the earthen materials to be produced or to choose the most suitable building technique. There are several techniques for building with earth that reflect not only differences between soils of different regions but also the local identity and culture. According to Houben and Guillaud (2008), 12 main techniques of using earth as a building material can be recognized, from which seven are commonly used:

- Rammed earth: moist earth is compacted by layers in between a removable formwork to build monolithic walls;
- Adobe: handmade bricks or adobes are composed by moist earth to which straw is often added. Wood or metal moulds are used to mould the adobes that are then sundried. The adobes are used to build masonry walls, arches, vaults or domes, using in general an earth mortar;
- Straw-clay: high clay content soil is mixed with water to form a greasy slip which is then added to the straw, where the role of the earth is to bind the straw together. This mix is then used to shape the bearing elements;
- Wattle-and-daub: a wooden bearing structure consisting of a grid that is covered and filled by a daub layer, i.e. a combination of moist soil and straw;
- Compressed earth blocks (CEB): blocks are produced by mechanically compacting in a press a mix of moist earth with low clay content, to which binders are frequently added. The blocks after curing are used to make masonry walls. This is the most standardized from all the techniques;
- Cob: earth, straw and water are mixed and thick monolithic walls are built by piling up balls of this material on top of one another;
- Direct shaping: earth and water are mixed to produce a plastic mix that makes possible to mould the elements without formwork by using only the hands of the builder.

Building with these techniques requires shaping, filling, moulding, stacking or compacting an earth mix. For each one it is required a different consistency of the mixes, which is function of the water content as can be seen in Figure 1 Despite of the diversity of earth building techniques, nowadays the most widespread are the adobe, rammed earth and CEB.

The option for building with earth brings several advantages that put this building solution ahead of current building solutions. Such advantages include:

- Good thermal performance: soil's good thermal inertia properties and the typical thick walls of earth constructions result in the capacity to damp and delay thermal variations and external thermal inflows. This is particularly valuable in regions characterized by high daily thermal variations, where this particular behaviour results in an interior temperature that is relatively constant and comfortable (Houben and Guillaud, 2008);

- Good noise insulation: the typical thick and dense walls of earth constructions promote a quiet ambient inside;
- Promotion of an healthy and comfortable interior ambient: The capacity of earthen materials to quickly absorb and desorb the air humidity balances the interior moisture and keeps it constant at values that create a comfortable and healthy ambient (Minke, 2006);
- Very low environmental impact of the construction: building in rammed earth requires very low CO_2 emissions when compared with other building materials, since the presence of the material in the local does not requires transportation and the earth processing requires little energy. If one thinks that 5% of the global CO_2 emissions are from the cement industry, this reveals to be a great feature of earth construction, especially if no stabilization is required. Moreover, the earth can be reused or can be simply returned to the nature;
- Fire-resistant: Earth does not burn;
- Simple building process: in general all the earth construction techniques do not require specialized manpower, which allows anyone to build a house with resource to simple tools.

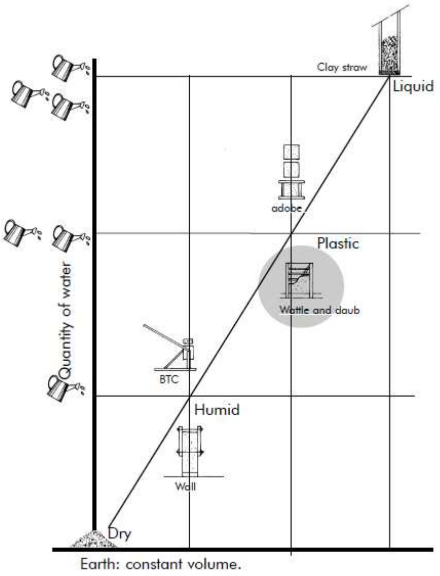


Figure 1 – Water content of the earth mixes as function of the building technique (Aedo and Olmos, 2003).

The main disadvantage of building with earth is that this is not a standardized material and there are no regulation and design codes in the majority of the countries. Other disadvantages can be mentioned:

- Low mechanical properties of the earthen materials: in general, unstabilized earthen materials present low strength (especially in what regards to the tensile strength) and brittle behaviour, which confers to these buildings high seismic vulnerability, limiting the construction to 1 or 2 storeys in regions of moderate seismic hazard;
- Drying shrinkage: the drying of the earthen materials causes shrinkage which results in cracking, diminishing the strength of the earthen materials. Soils with excessive swelling clays should be avoided and the building technique should be chosen according to shrinkage level of the soil;
- Low water resistance: in general, the earthen materials present low resistance to water, requiring very often stabilization by binder addition (lime, cement or bitumen) when, for example, rain constitutes a problem;
- Maintenance demanding: earth constructions require maintenance more frequently than constructions built with modern materials. No maintenance measures or maintenance measures with inadequate periodicity result in fast decay rates.

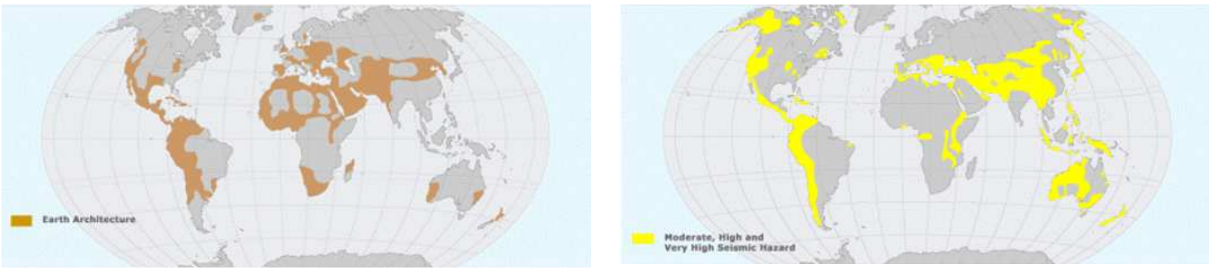
2.2 - History and geographical distribution

From the history of all earth construction techniques, rammed earth is relatively recent (Fernandes, 2008) and its origin is not consensual. According to Houben and Guillaud (2008) this technique was first developed in its “true” form in China during the Three Kingdoms period (221-581 AD). On the other hand, Jaquin *et al.* (2008) argue that the technique had two independent origin focuses: in China and around the Mediterranean. First it appeared in China, where Jest *et al.* (1990) claim that remnants of rammed earth walls and houses found in Qinghai, Tsaidam (between Tibet and Central Asia) date from the Muomhong period (2000–500 BC). The rammed earth around the Mediterranean was first used by Phoenicians in their settlements (800 BC).

In the Iberian Peninsula, the rammed earth technique is documented in several Arabic documents from 8th century AD in military constructions of settlements and in *alcazavas* such as that of Badajoz. However, the presence of rammed earth in the region is thought to be previous to this date, since there are older documents reporting earthen walls. However, there are uncertainties about the building process, which might have consisted in pouring earth between formwork or compacting earth between formwork ("real" rammed earth) (Fernandes, 2008).

In the 16th century AD, the rammed earth technique was introduced in South America by the Portuguese and Spanish settlers and later on (18th and 19th centuries) it was introduced in North America and Oceania by the European colonization. The publication of construction manuals of François Cointeraux in 1791 (Cointeraux, 1791) marked and stimulated rammed earth construction in Europe, which was re-introduced as a fireproof solution alternative to the typical timber constructions of that period. Then, with the invention of Portland cement in the 19th century, rammed earth construction fell in disuse. However, in Germany, this technique was extensively used to solve the housing problem generated after the end of World War II (Fernandes, 2008), but since then it has been substituted by modern materials. More recently, there has been a growing interest on earth construction (including rammed earth) which led to, for example, the creation of the CRATerre group by University of Grenoble, one of the most important international centres concerning earth construction. Nowadays, rammed earth technique is commonly used in Australia and New Zealand, where solid recommendations and standards to regulate earth construction were developed.

This short overview on the history of rammed earth shows that this technique is worldwide spread. Figure 2 shows that earth constructions (where rammed earth is included) are present in all 5 inhabited continents. Moreover, it is shown that the geographical distribution of earth construction is almost coincident with zones of moderate to very high seismic hazard. This distribution combined with the seismic vulnerability of earth constructions has led to several catastrophes, such is the case of the 2003 earthquake in Iran, which completely destroyed Bam citadel (UNESCO world heritage site), see Figure 3.



(a) (b)

Figure 2 – World's Geographical distribution of (a) earth construction and of (b) zones of moderate to very high seismic hazard (De Sensi, 2003).

Before **After**

Figure 3 – Bam citadel before and after the 2003 earthquake.

2.3 - Recommendations and standards

In most of the countries raw earth is a non-standard material in the building industry. However, some countries already developed or are developing documents to regulate earth construction. These documents are in general dedicated to three main building techniques: compressed earth blocks (CEB), adobe and rammed earth. According to Delgado and Guerrero (2007), the documents can be divided in three groups: (i) standards and regulations; (ii) normative documents such as rules and guidelines; and (iii) general bibliography on technical aspects of earth construction. A list of the most important documents for rammed earth construction is presented in Table 1. The design methodology of new rammed earth constructions included in the documents dedicated to this technique is, in general, very simple, and it is based on codes for unreinforced masonry. However, they consider larger safety factors that account for the uncertainties of earthen materials. This is a consequence of the lack of material testing and of studies to understand and to develop knowledge on these materials (Jaquin, 2008).

Table 1 – List of the most important documents regulating rammed earth construction.

Group	Country	Document	Technique
Standards and regulations	USA	NMAC 14.7.4 (2000)	CEB, Adobe and rammed earth
	New Zealand	NZS 4297 (1998)	CEB, Adobe and rammed
		NZS 4298 (1998)	CEB, Adobe and rammed
		NZS 4299 (1998)	CEB, Adobe and rammed
	Zimbabwe	SAZS 724 (2001)	Rammed earth
Normative	Germany	Lehmbau Regeln (2000)	CEB, Adobe and rammed earth
	Australia	HB 195 (2002)	CEB, Adobe and rammed earth
	Spain	MOPT (1992)	CEB, Adobe and rammed earth
Technical documents		Houben and Guillaud (2008)	CEB, Adobe and rammed
		OIA (1970)	CEB, Adobe and rammed
		Minke (2006)	CEB, Adobe and rammed

The evaluation of the soil suitability for rammed earth construction takes an important part in these documents, which also consider the possibility of improving the soils that cannot be used in their natural state by stabilization with addition of binders. The evaluation of soil suitability can be carried out according to two approaches: based on the evaluation of the properties of the soil or based on the properties of the final earthen material. The first approach is in general more usual, whereas properties such as texture, plasticity, organic content, binding force and compactability are assessed. In the second approach, the evaluated properties of earthen materials are basically the compressive strength (mechanic) and the resistance to erosion by water (durability). A broader review on the aforementioned documents and on their particular recommended/standard properties can be found in Maniatidis and Walker (2003).

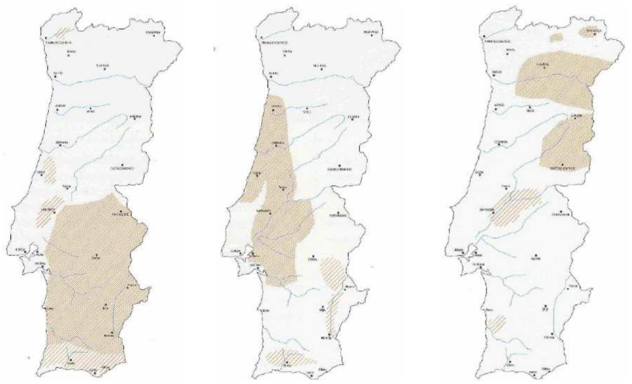
2.4 - Rammed earth in Portugal

Rammed earth construction in Portugal was extensively used during the period of Islamic domination. In this period, the technique was used both to build military and civil constructions. The military constructions are mainly constituted by fortresses, which were firstly built between the 7th and 9th centuries. There are fortresses that survived until nowadays with more than 800 years old, such is the case of the Silves and Paderne castles. Comparing the military with the civil constructions, the first are stronger and more durable, since in general there was used earth enriched with lime and natural pozzolanas (Correia, 2004).

Until the nineteen fifties, rammed earth was the main building technique used in the south of Portugal (Correia and Merten, 2005), which includes the Regions of Ribatejo, Alentejo and Algarve, see Figure 4. In opposition, the traditional construction in the north of Portugal is dominated by stone masonry. From the earth construction techniques, the wattle-and-daub is the most commonly found in traditional buildings. Rammed earth constructions are not common in this region; where just few cases are reported in Viana do Castelo (Correia and Merten, 2005).

The almost nonexistence of rammed earth constructions in the north of Portugal can be explained by several factors, such as: historical, cultural and climatic reasons, usage of other abundant resource of the region (granite stone) or possible unsuitability of the local soil. The historical and cultural reasons may be related with the absence of a real Islamic domination in the region, which took place during several centuries in the south, thus integrating the rammed earth technique in the culture of the population. However, this technique is not strange to the northern neighbouring region of Galicia (Tellado, 1998).

The typical soils from the north of Portugal are saprolitic residual soils from granite rocks; which are weathered by high precipitations that make possible the solubility and hydrolysis of minerals and by temperatures that favour higher rates of the chemical reactions (Viana da Fonseca, 1996). In general, these soils are well graded in grain size distribution and have low plasticity indexes, and thus are usually classified as silty sands (SM) and clayey sands (SC). The colour of these soils is typically grey, white and rose. Mineralogically speaking, granite residual soils are mainly composed by silicates in more than 65%, whereas the main minerals are quartz, which is very slowly affected by weathering processes, and feldspars, which is transformed into kaolinite and mica. According to Correia and Merten (2005), the rammed earth houses from Alentejo built with soils resulting from the weathering of schist are those that present better mechanical properties, where the flat and elongated shape of the coarse grains of schist is the main factor contributing to this fact. Examples of such constructions are found, for instance, in Reguengos de Monsaraz or in Serpa. On the other hand, constructions that were built with soils with high content of round shaped quartz grains show more tendency to disaggregate. This is eventually a drawback of the typical residual soils of the north of Portugal, when regarding rammed earth construction.



Rammed earth **Adobe** **Wattle-and-daub**

Figure 4 – Distribution of earth constructions in Portugal (Rocha, 2005).

The climate of a region is another factor that may limit the local rammed earth construction, as there is a relation between the climate and the durability of these constructions; the rainfall and wind force erodes the earthen materials. The north of Portugal, and in particular the Minho region, is known by its high rainfall when compared with the south of Portugal. Table 2 compares the average annual rainfall in Minho against other regions where earth construction is common. While Frankfut and Boscombe Down present lower rainfall values, similar rainfall values are found in São Paulo. This means that the high rainfall of the north of Portugal should not be regarded to as an obstacle to build in rammed earth in the region.

Table 2 – Annual precipitation average (sources: *www.meteo.pt; www.dwd.de; www.inmet.gov.br* and *www. metoffice.gov.uk*).

Region	Average annual rainfall (mm)
Minho, Portugal	1465.7
Alentejo, Portugal	571.8
Frankfurt, Germany	620.1
São Paulo, Brasil	1445.0
Boscombe Down, UK	735.7

Another limiting factor of rammed earth construction is the seismic hazard. As previously mentioned, earth constructions are known for having high seismic vulnerability, whereby it is not recommended to build with earth on regions of moderate to high seismic hazard. In Portugal, rammed earth constructions are concentrated in the regions of higher seismic hazard (south of Portugal), which constitutes a risk factor for the local population. On the other hand, the north of Portugal is included in the regions of lower seismic hazard, and therefore building in rammed earth is not so problematic. Moreover, there are several constructive measures that can be adopted to reduce the seismic vulnerability of new rammed earth constructions (Oliveira *et. al.,* 2010).

3 - SUITABILITY OF GRANITE RESIDUAL SOILS FOR RAMMED EARTH

3.1 - Methodology

In order to investigate the possibility of performing unstabilized rammed earth using residual granite soils from the north of Portugal, three soil samples were collected from different locations in Minho. The soils S1 (Azurém) and S2 (Pencelo) were collected from the municipality of Guimarães, while S3 (Barqueiros) was collected from the municipality of Barcelos. All the samples were collected superficially (between 5 cm and 20 cm deep).

One of the approaches to assess the suitability of the soils for earth construction consists in assessing their properties, namely texture, plasticity, organic content, binding force and compactability. The other approach consists in assessing the properties of the produced earthen materials, namely their mechanical strength and durability. There are several tests that can be carried out to achieve this goal, which, depending on their complexity, are grouped into two categories: expeditious tests and laboratory tests.

The expeditious tests are very simple test that can be carried out on site using simple and common tools. These tests are essentially focused in evaluating the properties of soil in a qualitative way, while giving indication of the quality of the soil for earth construction. Table 3 presents the expeditious tests carried out within the experimental program. It should be noted that one should look at the reference provided for the complete procedure of the tests and respective interpretation.

Table 3 – Expeditious tests carried out within the experimental program.

Test	Property	Reference
Visual description	Texture/organic matter	ASTM D 2488 (2006)
Jar test	Texture	HB 195 (2002)
Ribbon test	Texture/binding force	HB 195 (2002)
Dropping ball test	Compaction/texture	NZS 4298 (1998)
Dry strength test	Texture	Houben and Guillaud (2008)

The laboratory tests are in general more accurate and rigorous than those expeditious, and give quantitative results. However, performing them requires more resources (tools, equipment, funding, etc.), which not always are available. These tests include the traditional geotechnical tests for soil characterization and those tests for the characterization of the earthen materials. The laboratory tests carried out within the experimental program are listed in Table 4. Finally, Table 5 gives the fraction limits traditionally adopted in earth construction, which were also adopted in the paper.

Table 4 – Laboratory tests carried out within the experimental program.

Test	Property	Reference
Particle size distribution	Texture	LNEC E 196 (1966)
Atterberg limits	Plasticity	NP 143 (1969) ASTM D 4943 (1995)
Density of particles	Physical/compaction	NP 84 (1965)
Standard Proctor	Compaction	LNEC E 197 (1967)
Compression test	Compressive strength	Escobar (2011)
Water drip test (Geelong)	Durability to water erosion	NZS 4298 (1998)

Table 5 – Fractions traditionally adopted in earth construction.

Fraction	Particles dimensions
Clay	≤0.002 mm
Silt	0.002 mm to 0.06 mm
Sand	0.06 mm to 2 mm
Gravel	2 mm to 20 mm
pebbles	≥20 mm

3.2 - Expeditious tests

3.2.1 - Visual inspection

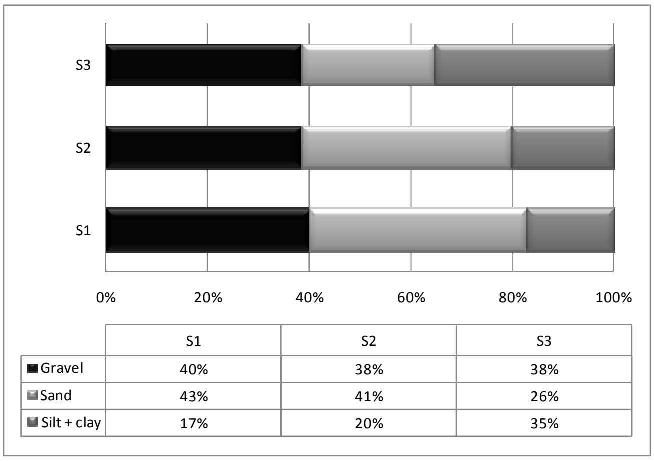
The visual inspection of the soils samples was carried out resorting to ASTM D 2488 (2006). The soil S1 has coarse particles (>2 mm) that are mainly sub-angular (see Figure 5), and the shape is neither elongated nor flat. The colour of the dry soil is light grey, whereas it can be observed white and black coarse grains. The soil also does not evidence any odour related to the presence of organic matter, even after some wetting and drying cycles. Soil S2 is similar to S1 in terms of angularity and shape of the grains. This soil has a light colour and has no odour evidencing the presence of organic matter. On the other hand, the coarse particles of soil S3 are sub-rounded to rounded, but are also not elongated or flat. The colour of this soil is light yellow and no evidences of organic matter were found through odour. As expected, the coarse grains of these soils have not the elongated and flat shape of the schist soils previously mentioned, whereby rammed earth specimens of lower characteristics are expected.

S1 **S2** **S3**

Figure 5 – Coarse particles of the assessed soils.

3.2.2 - Jar test

After letting the particles of the soils settling in their respective flask, the fractions were identified visually and the thickness of the corresponding layer was measured. Since it is impossible to distinguish by naked eye the transition between clay and silt, these fractions were considered as constituting a single layer (clay + silt). Then the proportions between fractions were computed and the results are presented in Figure 6. Soil S1 has lesser fines content (clay + silt) than S2 and S3, whereas S3 shows a much higher content than the other two soils. However, the observed flocculation of the clay particles seems to affect this result in a great extent, giving higher fine content than that really owned by the soils. This is a great limitation of the jar test. Later on, these results are compared with the particle size distribution.



	S1	S2	S3
■ Gravel	40%	38%	38%
■ Sand	43%	41%	26%
■ Silt + clay	17%	20%	35%

Figure 6 – Jar tests results.

3.2.3 - Ribbon test

The ribbon test was carried out on all soils. However, it was impossible to roll the soils S1 and S2 to the shape of a sausage (see see Figure 7a). This is explained by the low fine content (especially the clay content) of these soils, which is not enough to provide the required cohesion (binding) to the material. Eventually this shows that these soils have insufficient clay to produce an earthen material with adequate strength and durability, nevertheless, it is not possible to conclude on the suitability of these soils, just based on this test. In the case of S3, which has a larger fine content, the sausage could be shaped and the test was carried out on three specimens, see Figure 7b. An average length of 45 mm was obtained, which according to HB 195 (2002), allows to conclude that this soil is suitable for stabilized CEB and for rammed earth construction.

(a) (b)

Figure 7 – Ribbon test of soil S1 (a) and ribbon test of soil S3 (b).

3.2.4 - Dropping ball test

This test is usually carried out on site during the mixture of the earth with water to determine if adequate quantity of water was added to start compacting rammed earth. Therefore, this requires several trials while adjusting the water content of the mixture to obtain the correct state of the ball after impact with the ground. Figure 8 presents the 3 possible states occurring within the tests. After obtaining a successful trial (i.e. the ball crumbled partly with minor cracks) the water content of the ball was measured and the results are given in Table 6. It should be mentioned that moulding the ball was difficult for soils S1 and S2 due to their very low clay content.

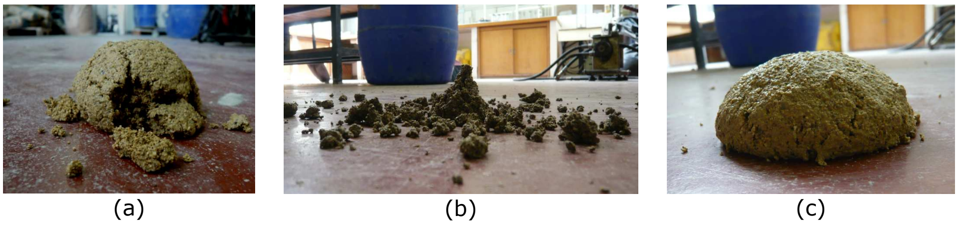

(a) (b) (c)

Figure 8 – Possible states of the ball after impact: (a) crumble partly with minor cracks, (b) completely crumbled and (c) flattened.

Table 6 – Compaction water content obtained from the dropping ball test.

Soil	Water content (%)
S1	18
S2	18
S3	10

3.2.5 - Dry strength test

Three pats with 4 cm diameter and 1 cm thickness were prepared for each soil (using a plastic mixture prepared with the fraction below 0.425 mm) and the effort required to break them manually (see Figure 9) was evaluated according to the qualitative scale presented in Table 7. S1 and S2 pats were easy to break, while S3 pats required moderate effort. This test shows that the fines of soils S1 and S2 are poor on clay, and thus are mainly constituted by silt and fine sand. The higher effort required for breaking the pats of soil S3 evidences greater clay content when compared with the remaining soils, which is in agreement with the previous test results.

Figure 9 – Dry strength test.

Table 7 – Interpretation of the dry strength test (Houben and Guillaud, 2008).

Effort required	Description
High	The dry pat is very difficult to break. When it does, it breaks with a snap, like a dry biscuit. The soil cannot be crushed between thumb and forefinger; it can merely be crumbled, though without reducing it to dust: almost pure clay.
Moderate	The pat is not too difficult to break. It can be crushed to powder between thumb and forefinger after a little effort: silty or sandy clay.
Low	The pat can be easily broken and can be reduced to powder between thumb and forefinger without any difficulty at all: silt or fine sand, low clay content.

3.3 - Laboratory tests

3.3.1 - Particle size distribution

In order to quantify all the fractions composing the soils, both sieving and sedimentation analyses were carried out. The gain size distribution curves were determined and compared with the envelope of typical residual soils from the north of Portugal given by Viana da Fonseca (1996), see Figure 10. As it can be seen, the soils can be denominated as typical residual soils from the north of Portugal. Moreover, the particle size distribution curves show that all the soils are well graded and that soils S1 and S2 have very low clay content (see Table 8), which is in agreement with the expeditious tests. On the other hand, soil S3 presents a clay content that is twice as large as that of the other two soils.

Comparing the obtained fractions with those from the jar test in Figure 11, it can be seen that the fine content is significantly larger in the jar tests due to the flocculation of the clay particles. This effect is more important in soil S3, whose clay content is larger.

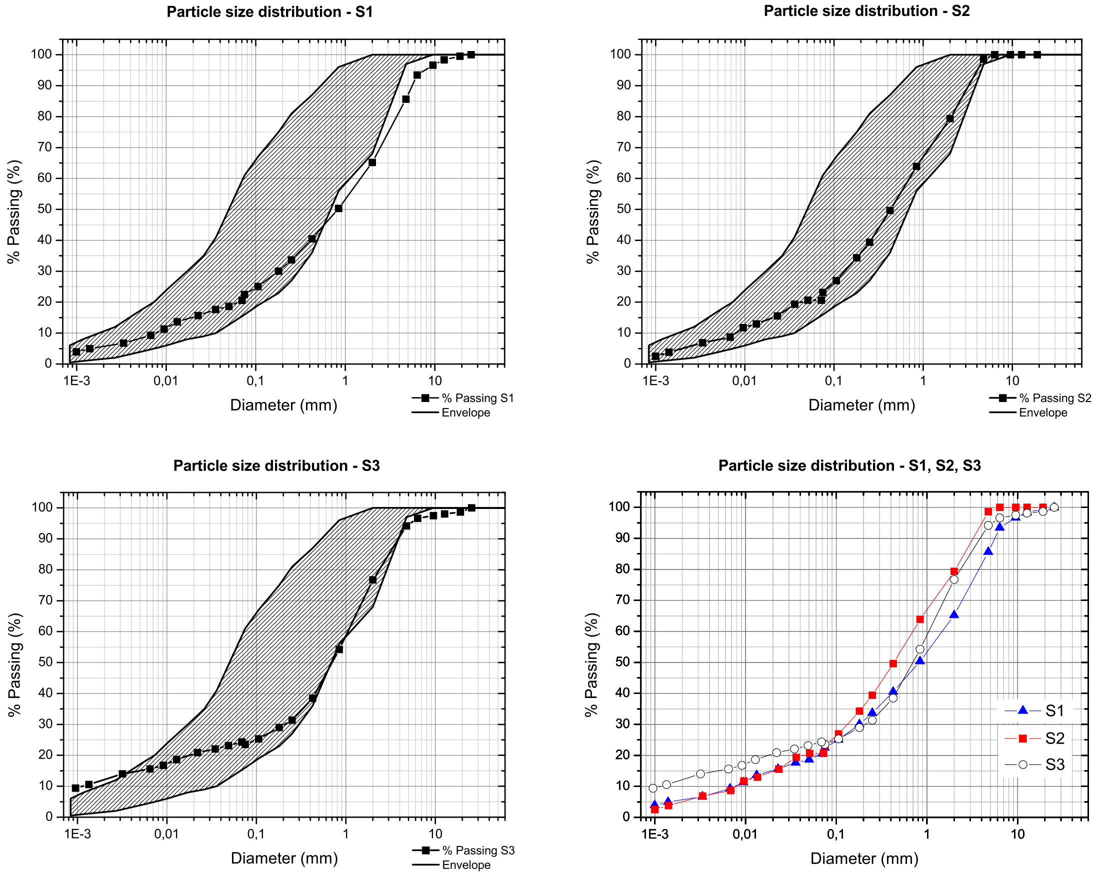
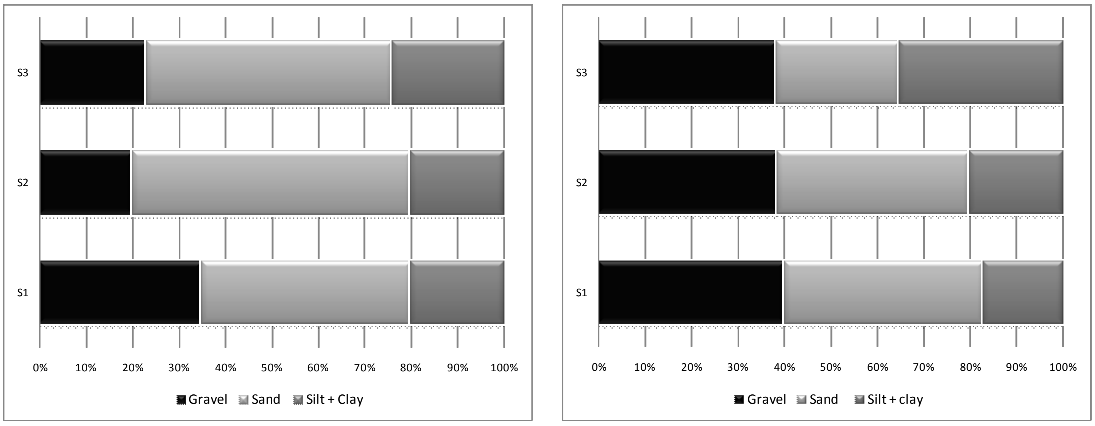


Figure 10 – Particle size distribution of the soils S1, S2 and S3.



Particle size distribution **Jar test**

Figure 11 – Comparison between the particle size distribution and the results of the jar test.

Table 8 – Size fractions of the soils determined from the particle size distribution.

Fraction	S1	S2	S3
Clay	6%	5%	13%
Silt	14%	15%	11%
Sand	45%	60%	53%
Gravel	35%	20%	23%
Pebbles	0%	0%	0%

3.3.2 - Atterberg limits

The plastic limit (PL), liquid limit (LL) and shrinkage limit (SL) were determined for each soil and the results are presented in Table 9. It should be noted that the PL test could not be carried out for the soils S1 and S2 due to their low clay content, therefore these soils are non-plastic. Soil S3, on the other hand, is considered to be a medium cohesive soil. Moreover and according to the USCS (Unified Soil

Classification System) (ASTM D 2487) the soils are classified as follows: S1 – silty sand (SM); S2 - silty sand (SM); S3 - clayey sand (SC). The low values obtained for the shrinkage index (SI) of the soils indicates that these have low shrinkage/swelling characteristics.

Table 9 – Atterberg's limits of the soils.

Soil	LL (%)	PL (%)	PI (%)	SL (%)	SI (%)
S1	34	-	-	27	7
S2	27	-	-	23	4
S3	30	19	11	22	8

3.3.3 - Standard Proctor test

The compaction properties of the soil are very important in rammed earth construction because there is a direct relationship between dry density and compressive strength of the material. The more compact the material is, the higher is its strength. The standard Proctor is in general preferred to the modified Proctor, since the compaction energy of traditional rammed earth is closer to that of the first test (Houben and Guillaud, 2008). The compaction curves are plotted in Figure 12 and the results of the test are summarized in Table 10.

Even though soils S1 and S2 have the same optimum water content (OWC), S1 achieves higher dry density under the same compaction conditions. Soil S3 has the highest dry density and the lowest optimum water content. When comparing the OWC with the water content obtained from the dropping ball test, the later test gives a good approximation of the OWC for the soil S3, but not in the case of soils S1 and S2. The low clay content and the fact that the balls for the test were hardly moulded may be the reason behind this large difference.

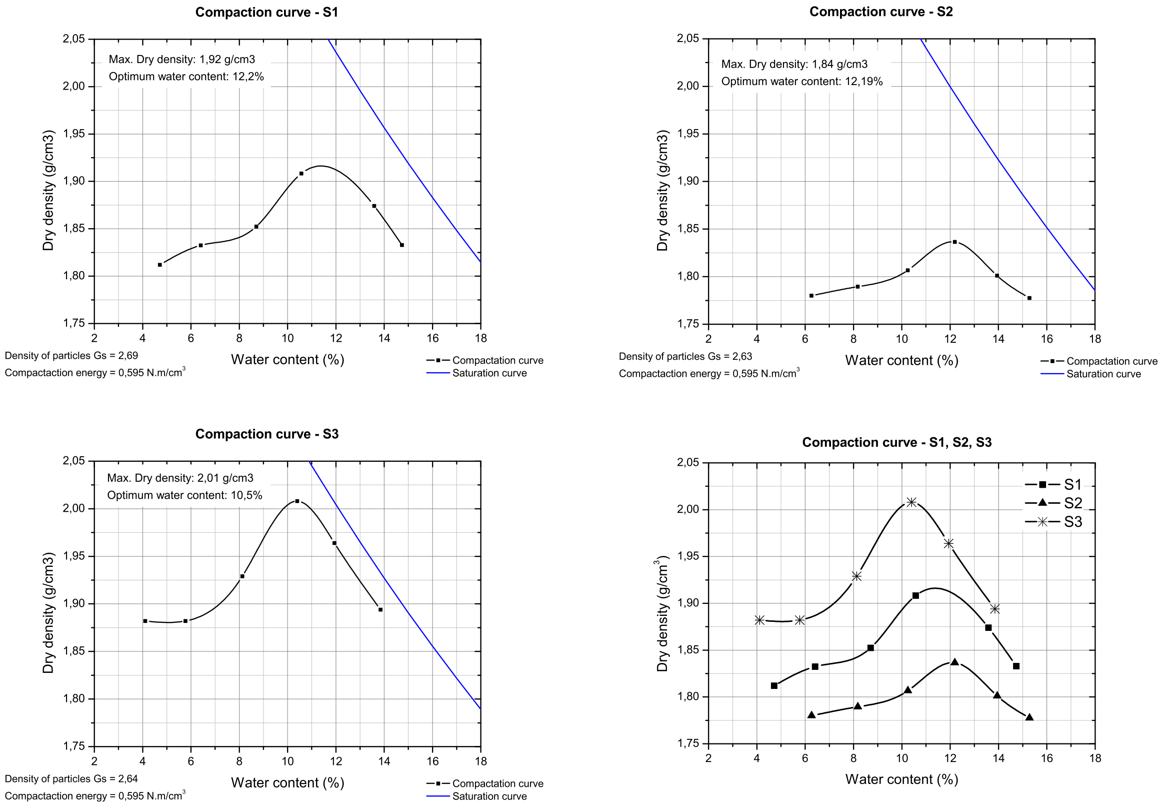


Figure 12 – Compaction curves of the soils.

Table 10 – Compaction properties of the soils.

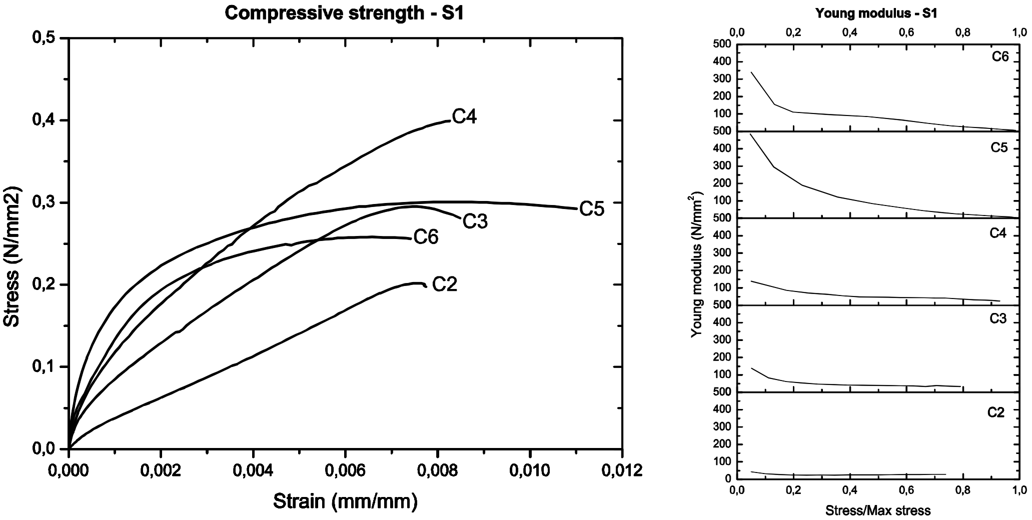
Soil	γ_d (g/cm^3))	OWC (%)	G_s
S1	1.92	12	2.69
S2	1.84	12	2.63
S3	2.01	10	2.64

3.3.4 - Compression test

According to NZS 4298 (1998), the moisture content to compact rammed earth should never be 3% below or 5% above the optimum water content. There are rammed earth practitioners defending that the compaction should be carried out in the dry side to facilitate the demoulding, while others defend the wet side, since it promotes higher strength (Minke, 2006). In order to investigate the influence of the water content (and consequently of the material density) on the strength of rammed earth, a set of 6 specimens were prepared per soil type, representing each a point of the respective compaction curve. The specimens were three-layered cylinders with dimensions 100 mm diameter and 200 mm height and were tested after achieving their equilibrium water content at 20ºC temperature and 57.5% relative humidity (drying period between 27 and 35 days). The vertical deformations at the middle third of each specimen were measured by means of three LVDTs radially-disposed and tests were carried out in displacement control at a rate of 3μm/s, applied monotonically (see Figure 13). It should be mentioned that most of the first specimens, corresponding to the first points of the compaction curve, had not enough cohesion and started disaggregating after demolding, whereby they were not tested.

Figure 14a exemplifies the stress-strain curves of S1 soil specimens, where C2 is the cylinder compacted with the second lowest water content and C6 is the cylinder compacted with the highest water content. The high difference in deformability among specimens is a consequence of the different densities of the cylinders. Figure 15 represents the dry density, Young modulus and compressive strength as a function of the water content. The Young modulus was computed between 5% and 30% of the compressive strength of each cylinder, by linear fitting of the stress-strain curve. The compressive strength and compaction curves present the same trend for all soils, i.e., dry density seems to be a parameter directly related to the strength of these soils. Regarding the Young modulus, there is no clear tendency or it may be masked by the dependency of this parameter on the stress state (or strain state), see also Figure 14b. Two typical failure modes were observed: the cylinders with lowest water content tended to desegregate, while those with highest water content presented a well-defined cracking pattern, see Figure 16.

Figure 13 – Compression tests.



(a) (b)

Figure 14 – Stress – strain (a) and Young modulus – normalized stress (b) curves of the soil S1 specimens. The water content of compaction increases from C2 to C6.

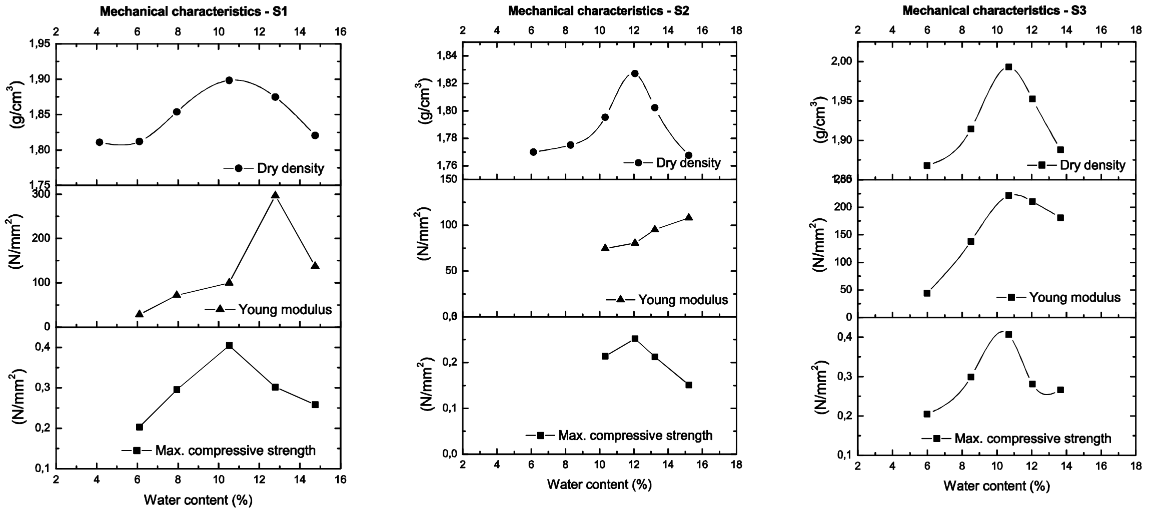


Figure 15 – Results of the compression tests.


C2 **C3** **C4** **C5** **C6**

Figure 16 – Failure mode of the soil S1 specimens.

3.3.5 - Durability (Geelong test)

Durability of unstabilized earthen materials is in general measured by its resistance to water erosion, which can be done by the water drip test (known by Geelong test). This test was carried out on one specimen of each soil. The specimens were prepared with the maximum density and OWC (compacted in three layers) and had the geometry of a cube with dimensions 150x150x150 mm^3 (see Figure 17). The specimens were dried under controlled ambient (T=20ºC and RH=57.5%) and were tested after 21 days. In each test the pitting depth and depth of moisture penetration were measured, as can be seen in Figure 18.

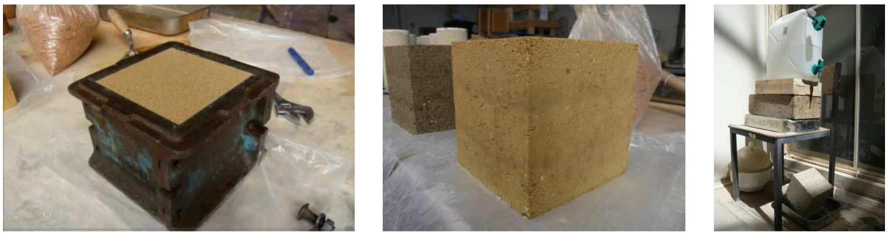


Figure 17 – Geelong test.

Figure 18 – Pitting depth and depth of moisture penetration.

According to NZS 4298 (1998), the pitting depth is classified as an erodibility index (see Table 11) and the depth of moisture penetration is acceptable if lower than 120 mm. The results are given in Table 12, whereas it can be seen that the soils cannot be fully disregarded by durability reasons. However, their application is limited to situations that require erodibility indexes higher or equal to 3 (in the case of S1 and S2) and to 2 (in the case of S3), see NZS 4297 (1998). The soil S3 shows better durability performance due to its higher clay content.

Table 11 – Geelong test interpretation according to NZS 4298 (1998).

Pitting depth (*D*)	Erodibility index
0<*D*<5 mm	2
5≤*D*<10 mm	3
10≤*D*<15 mm	4
D≥	5 (Fail)

Table 12 – Results of the Geelong test.

Soil	Pitting depth (mm)	Erodibility index	Depth of moisture penetration (mm)
S1	6	3	51
S2	9	3	58
S3	3	2	20

3.4 - Discussion

There are no strict instructions to follow for determining if a given soil is suitable for unstabilized rammed earth construction. The ideal situation is to test the final material (rammed earth) before employing it on site, which is not always possible in the majority of the countries. Although, there are several recommendations to compare with and to decide how suitable is the soil. The texture and plasticity are the main properties to be compared. Regarding the texture, there are several recommendations on the content that the soil should present for each fraction (Maniatidis and Walker, 2003). For example, Houben and Guillaud (2008) give an envelope for the particle size distribution, which is compared with the obtained curves in Figure 19.

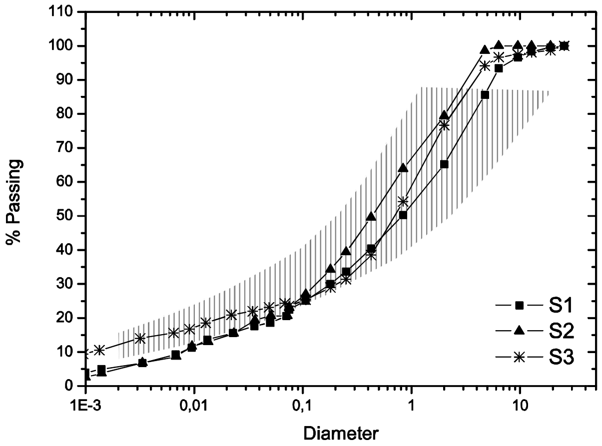


Figure 19 – Comparison between the particle size distribution of the soils and the envelope recommended by Houben and Guillaud (2008).

As it can be seen, all soils are almost within the envelope, but the clay content of S1 and S2 is shown to be fairly low. This is a confirmation of the results obtained from the expeditious tests. Regarding the plasticity of the soils, Houben and Guillaud (2008) recommend that the liquid limit should be between 25% and 50% and the plastic limit between 10% and 25%. This is not the case for soils S1 and S2, whose plastic limits could not be tested due to their low clay content. These authors also present an envelope for the plasticity properties that is given in Figure 20, where soil S3 is represented. The lower clay content of S1 and S3 was also reflected on the erodability index of the rammed earth specimens, where soil S3 seems to have better durability. However, the adequate employment of these soils depends on local climate conditions, which accounts for factors such as the annual rainfall and wind speed to determine the limiting erodibility index (SNZ 4298).

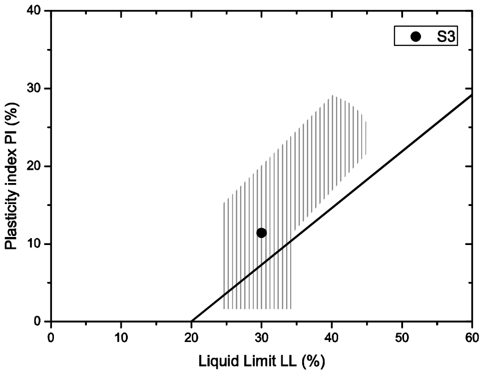


Figure 20 – Plasticity properties envelope by Houben and Guillaud (2008).

The compressive strength values obtained are in general low, and even the maximum value of this parameter for each soil (see Table 13) is by far lower than the minimum strength recommended by some of the documents concerning rammed earth construction (see Table 14). It should be noted that these values are not directly comparable as each document defines different methods (specimens and procedures). The obtained values are, however, within reported values of traditional unstabilized rammed earth, which ranges between 0.25 and 0.6 N/mm^2 (Jaquin, 2008). The compressive strength of these soils seems to be a limiting factor for building unstabilized rammed earth in the north of Portugal. However, corrective measures, such as chemical stabilization, can be introduced to improve this property.

Table 13 – Maximum compressive strength obtained from the compression tests of each set of specimens.

Soil	Maximum compressive strength (N/mm^2)
S1	0.41
S2	0.25
S3	0.41

Table 14 – Required compression strength according to documents regulating rammed earth construction.

Document	Required compressive strength (N/mm^2)
Walker and Standards Australia (2002)	≥2[a]
CYTED (1995)	≥1.2 in 80% of the specimens[b]
NMAC (2006)	>2.1[c]
SNZ 4298 (1998)	>1.3[d]

Notes:

[a] dry unconfined characteristic strength obtained from earth blocks or cylindrical earth specimens. Aspect ratio correction factor must be applied.

[b] characteristic compressive strength on 0.1 m sided cubic specimens.

[c] on cured rammed earth specimens. No info is provided on the specimens

[d] lowest of 5 specimens (cured rammed earth specimens).

4 - SOIL STABILIZATION

Chemical stabilization of rammed earth by addition of current binders, such as cement, lime and bitumen, is a generalized solution to improve its properties, namely its strength and durability. In the case of typical residual granite soils from northern Portugal, cement is the most performing binder, as the clay fraction is composed mainly by kaolinite in quantities lower than 10% (Viana da Fonseca and Coutinho, 2008), which makes the use of lime as the stabilizing agent less efficient. However, the use of cement significantly increases the production cost and somehow decreases the overall attractiveness of rammed earth as a sustainable solution. An alternative stabilization solution proposed by the authors consists in employing a geopolimeric binder, based on the alkaline activation of fly-ash (a waste material), using a sodium – based activator. In general terms, alkaline activation consists in a reaction between alumina-silicate materials and alkali or alkali earth substances, namely: ROH, $R(OH)_2$, R_2CO_3, R_2S, Na_2SO_4, $CaSO_4.2H_2O$, $R_2.(n)SiO_2$, in which R represents an alkaline ion like sodium (Na^+) or potassium (K^+), or an alkaline earth ion like Ca^{2+}. It can be described as a polycondensation process, in which the silica (SiO_2) and alumina (AlO_4) tetrahedra interconnect and share the oxygen ions. The process starts when the high hydroxyl (OH^-) concentration of the alkaline medium favours the breaking of the silica and alumina from the raw material, releasing them into the solution. At the same time, the alkaline cations Na^+, K^+ or Ca^{2+} act like building blocks of the structure, compensating the excess negative charges associated with the modification of the aluminium coordination during the dissolution phase. The resulting products accumulate for a period of time, forming a ion "soup" of high mobility. The resulting polymeric structure of Al-O-Si bonds is the main structure of the new material. Materials formed using reactions between silica and alumina and alkali cations like sodium or potassium are very similar, at a molecular level, with natural rocks, sharing their stiffness, durability and strength.

This stabilization technique is currently being tested by the authors on soil S1, and preliminary tests have been showing promising results regarding strength gain of the material. Different mixtures were tested, focusing on the impact of fly ash content, sodium concentration and activator / solids ratio on unconfined strength (UCS). Figure 21 shows some of those results, which indicate, based on the strength level usually necessary for the soil used in earth construction, that a less intrusive intervention (especially in terms of fly ash percentage) can also be effective. This is desirable not only in terms of financial cost (lower quantities of fly ash imply also lower quantities of activator), but also in terms of the mixture visual result. This is because the binder quantities used produced some significant changes in soil texture, which might not so be desirable from an aesthetical approach, and therefore mixtures with significant less ash are already being prepared.

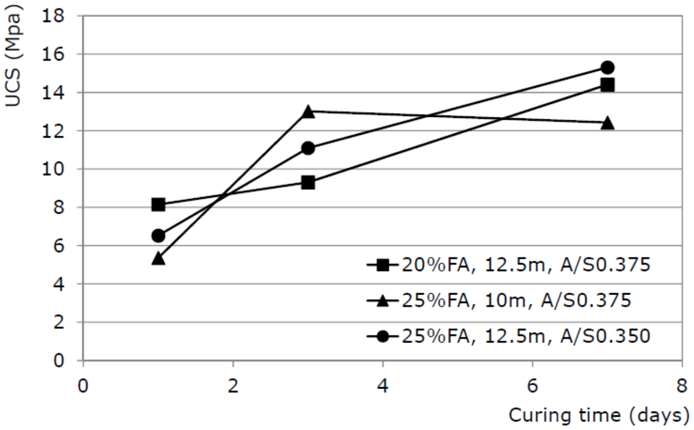


Figure 21 – Preliminary results obtained using alkaline activation of fly ash as a stabilising technique.

5 - CONCLUSIONS

Three typical residual granite soils were tested in order to assess their suitability for unstabilized rammed earth construction. The experimental program included expeditious tests traditionally used in earth construction and more thorough laboratory tests that included geotechnical characterization of the soils and evaluation of rammed earth properties.

The expeditious tests focused mainly on the texture of the soils, whereas it was evidenced that the clay content of the soils S1 and S2 was very low. This deficiency reflected in their plasticity; making it difficult to shape the ball for the dropping ball test and making impossible to shape the soil in the ribbon test. The low clay content also resulted in lower dry strength when comparing with soil S3. In fact, the particle size distribution curves of S1 and S2 confirmed the low clay content evidenced by the expeditious tests, which demonstrates the importance of these types of tests in a preliminary evaluation. The particle size distribution of each soil was also compared with the envelope given by Houben and Guillaud (2008). Soil S3 was well fitted within the envelope, while the soils S1 and S2, as expected, have low fines content.

Regarding the durability of rammed earth prepared with the assessed soils, S3 is the most performing, but all soils can be employed in situations that require a limiting erodibility index equal or higher to that of the material. However, the strength of these soils is far from fulfilling the minimum requirements established in international documents regulating rammed earth construction. Therefore, stabilization seems to be required in order to improve some properties, thus allowing rammed earth construction in the north of Portugal using local soils.

Finally, the authors propose the use of a geopolimeric binder, based on fly ash and a sodium solution, as a stabilizing agent. The results obtained so far seem very promising in improving the properties of this type of soil for rammed earth construction, but further testing is necessary to optimize the strength / visual ratio of the final mixture.

REFERENCES

Aedo, W. and Olmos, A. (2003). Wattle & daub: Anti-seismic construction handbook. CRATerre, France.

ASTM D2487 (2000). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials, West Conshohocken, PA.

ASTM D2488 (2000). Standard Practice for Description and Identification of Soils (Visual-Manual Procedure). American Society for Testing and Materials, West Conshohocken, PA.

ASTM D4943 (1995). Standard Test Method for Shrinkage Factors of Soils by the Wax Method. American Society for Testing and Materials, West Conshohocken, PA.

Cointeraux, F. (1791). Traite dês Constructions Rurales et e Leur Disposition. Paris, França.

Correia, M. (2004). Fortificações islâmicas em taipa militar, *Pedra & Cal*, 24, 16.

Correia, M. and Merten, J. (2005). A Taipa Alentejana – Sistemas Tradicionais de Protecção, IV Seminário Ibero-Americano de Construção com Terra e III Seminário Arquitectura de Terra em Portugal, Monsaraz

Delgado, M. and Guerrero, I. (2007) The selection of soils for unstabilised earth building: A normative review, *Construction and building materials*, 21(2), 237-351.

De Sensi, B. (2003) Terracruda, La Diffusione Dell'architettura Di Terra - Soil, Dissemination of Earth Architecture.

Escobar, M.C. (2011). Rammed earth: feasibility of a global concept applied locally. Msc. Thesis, Advanced Master in Structural Analysis of Monuments and Historical Constructions, Guimarães, Portugal.

Fernandes, M. (2008). A Taipa no Mundo. Seminário de Construção e Recuperação de Edifícios em Taipa, Almodôvar, Portugal.

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

Jaquin, P.A. (2008). Analysis of Historic Rammed Earth Construction. *PhD Thesis*, Dept. of Civil Engineering, Durham University – School of Engineering, Durham, UK.

Jaquin, P.A., Augarde, C.E. and Gerrard, C.M. (2008). A chronological description of the spatial development of rammed earth techniques. *International Journal of Architectural Heritage*, 2, pp. 377-400.

Jest, C., Chayet, A. and Sanday, J. (1990). Earth used for building in the Himalayas, the Karakoram and Central Asia - Recent Research and Future trends. 6th International Conference on the Conservation of Earthen Architecture, Las Cruces, New Mexico, Getty Conservation Institute. Los Angeles.

Lehmbau Regeln (1999). Begriffe; Baustoffe; Bauteile. Braunschweig/Wiesbaden, Germany: Friedr. Vieweg & Sohn Verlagsgesellscahaft mbH.

LNEC E196 (1966). Análise granulométrica. Especifificação do LNEC, Lisbon, Portugal.

LNEC E197 (1967). Ensaio de compactação. Especifificação do LNEC, Lisbon, Portugal.

Maniatidis, V.and Walker, P. (2003). A review of rammed earth construction. Bath, UK: University of Bath.

Minke, G. (2006). Building with earth: Design and technology of a sustainable architecture. Birkhäuse-Publishers for Architecture, Basel-Berlin-Boston.

MOPT (1992). Bases Para el Diseño y Construcción con Tapial. Madrid, Spain: Centro de Publicaciones, Secretaría General Técnica, Ministerio de Obras Públicas y Transportes, Spain.

NMAC (2006). NMAC 14.7.4: Housing and Construction: Building Codes General: New Mexico Earthen Building Materials Code, New Mexico Regulation and Licensing Department, Santa Fe, New Mexico.

NP83 (1965). Determinaçao de densidade das partículas. Norma Portuguesa.

NZS (1998). New Zealand Standard 4297:1998, Engineering design of earth buildings. Wellington: Standards New Zealand, Wellington.

NZS (1998). New Zealand Standard 4298: 1998, Materials and workmanship for earth buildings: Standards New Zealand, Wellington.

NZS (1998). New Zealand Standard 4299:1998. Earth buildings not requiring specific design. Wellington: Standards New Zealand, Wellington.

Oliveira, D.V., Silva, R.A., Lourenço, P.B. and Schueremans, L. (2010). A Construção em taipa e os sismos. Congresso Nacional de Sismologia e Engenharia. SISMÍCA 2010, 20-23 October, University of Aveiro, Portugal.

Rocha, M. (2005). Rammed earth in traditional architecture: construction techniques. In A. C. Terra, Earth architecture in Portugal, Argumentum, Lisbon, Portugal, pp. 22-26.

SAZS (2001). Standards Association Zimbabwe Standard 724:2001: Standard Code of Practice for Rammed Earth Structures. Harare: Standards Association of Zimbawbe.

Standards Australia and Walker, P. (2002) HB 195: The Australian earth building handbook. Sydney (Australia): Standards Australia.

Tellado, M. (1998). Construcciones de tapia en la tierra de Lemos, Proceedings of Segundo Congreso Nacional de Historia de la construcción, Coruña, 22-24 October, pp. 181-188

Viana da Fonseca, A. (1996). Geomecânica dos solos residuais do granito do Porto. Critérios para dimensionamento de fundações directas. *PhD Thesis*, Dept. of Civil Engineering, University of Porto, Portugal.

Viana da Fonseca A., Coutinho R. (2008). Characterization of residual soils, in: "Geotechnical and Geophysical Site Characterization". Ed. Huang, A-B & Mayne, P. Keynote Lecture ISC'3, Balkema, Taylor & Francis Group, pp. 195-248.

Wolfskill, L.S., Dunlop, W.A. and Callaway, B.M. (1970). Handbook for building homes of earth. Department of housing and urban development, Office of International Affairs (OIA), Washington, DC 20410.