MECHANICAL BEHAVIOUR OF COMPRESSED EARTH BLOCKS STABILISED WITH INDUSTRIAL WASTES

COMPORTAMENTO DE BLOCOS DE TERRA COMPRIMIDA ESTABILIZADOS COM RESÍDUOS INDUSTRIAIS

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RESUMO

A construção em alvenaria de blocos de terra comprimida (BTC) é uma técnica de construção em terra moderna com um atual interesse crescente, mas a sua sustentabilidade ambiental é muitas vezes desvalorizada pelo recurso a técnicas de estabilização química tradicionais (adição de cal e cimento). Este artigo apresenta um programa experimental onde é avaliada a possibilidade de se manufaturarem BTC com solo residual granítico (SRG) do Norte de Portugal. Mostrou-se que os SRG não são adequados e que o seu uso na produção de BTC requer estabilização química. Realizou-se um estudo de composição envolvendo estabilização por adição de cimento e de ligantes geopoliméricos à base da ativação alcalina de cinza volante ou lamas calcinadas. Em seguida, manufaturam-se BTC estabilizados com ativação alcalina de cinzas volantes e testaram-se as suas propriedades mecânicas. Além disto, caraterizou-se o comportamento em compressão da alvenaria construída com estes BTC. Em geral, a estabilização com ativação alcalina de cinzas volantes revelou excelentes resultados no que diz respeito ao melhoramento da resistência.

ABSTRACT

The construction of masonry with compressed earth blocks (CEBs) is a modern earth construction technique with current growing interest, but its environmental sustainability is many times depreciated by the use of traditional chemical stabilisation techniques (lime and cement addition). This paper presents an experimental program where the possibility of manufacturing CEBs using granitic residual soils (GRS) from northern Portugal is addressed. The GRS were shown to be inadequate and their use for manufacturing CEBs requires chemical stabilisation. A composition study involving stabilisation by addition of cement and addition of geopolymeric binders resulting from the alkaline activation of fly ash or of calcinated sludge was carried out. Then, CEBs stabilised with alkaline activation of fly ash were manufactured and their mechanical properties were tested. In addition, the compressive behaviour of masonry built with these CEBs was also characterized. In general, the stabilisation with alkaline activation of fly ash revealed excellent results with respect to the improvement in strength.

1 - INTRODUCTION

Earth has been used as a building material for sheltering since ancient times (Houben and Guillaud, 2008). Building with earth continues to be a popular solution (sometimes the only feasible solution) in developing countries, such as Peru, Angola, Yemen and India. In developed countries, such as Portugal, Spain, France and Germany, the practice of building with earth has fallen into disuse over the past century. Thus, nowadays, the earthen built stock in these countries constitutes a small percentage of the total stock. This was a consequence of their technological and economical development, which led to the extensive use of the so-called modern building materials, such as concrete and steel. Despite the actual contrast between developing and developed countries, it is estimated that about one fourth of the World's population still lives in an earth building (Jaquin, 2013), highlighting the importance of this type of building solution. Figure 1 illustrates the distribution of earth construction around the World, where its presence in all inhabited continents is remarked.

The earth construction concept is frequently associated to vernacular architecture, where available local building materials are used, namely locally available soils. The different properties between soils associated to cultural, economic and climatic factors contribute for the fact that several building techniques can be found around the World (Houben and Guillaud, 2008). Despite that, the most common techniques are adobe masonry, rammed earth (known in Portugal as *"taipa"*) and wattle-and-daub (known in Portugal as *"tabique"*).

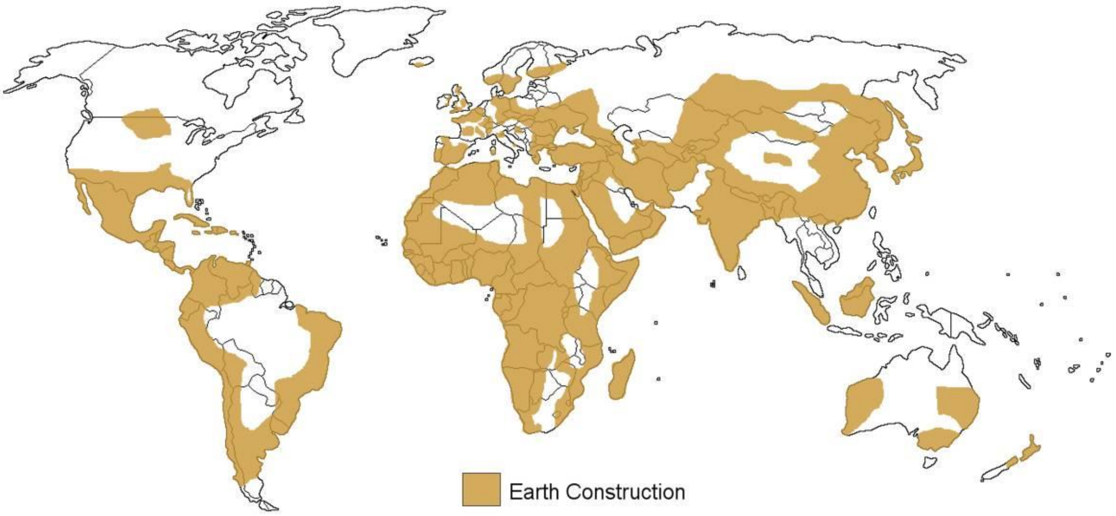


Figure 1 – Distribution of earth construction around the World (adapted from AEI (2012)).

Adobes are sundried bricks or blocks prepared from a pasty mixture of earth and water, which may also include the addition of straw, lime and dung. Typically, the adobes are moulded in timber bottomless moulds, by simply filling them or by throwing lumps of moistened earth (Figure 2a). The top surface is smoothed either by using the hand, a timber tool, a trowel or a wire. Then, the adobes are immediately demoulded and put to dry under the sun (Minke, 2006). The dimensions of the adobes are very variable from region to region. For example, in Spain one can find adobes with dimensions of 150x150x300 mm^3 in several places, whereas in some regions of Portugal the dimensions are 400x150x300 mm^3 (Gomes, 2008). Upon drying, the adobes are ready to be used as masonry units to build walls, arches, vaults or domes. The mortar used in the masonry is in general earth-based, being usually prepared with the same soil used in the production of the adobes. In Portugal, this technique has main presence in the region of Aveiro, namely in the buildings characterized by the *"Art Nouveau"* architectonical style.

Building in rammed earth consists in compacting moist earth by layers inside a removable formwork to build monolithic walls (Figure 2b). The construction of a traditional wall is carried out by courses (like masonry), where the formwork runs horizontally along the perimeter of the construction and then is lifted to build the next course. Nowadays, the trend is to use the same metallic shutters used in concrete technology to constitute a formwork that covers the entire wall. The compaction of a rammed earth wall can be executed resorting to manual rammers (made of timber) or to mechanical apparatus such as pneumatic and vibratory rammers, which allow reducing substantially the labour and time consumed in the construction. In Portugal, the rammed earth built stock is mainly concentrated in the southern region, namely in Alentejo, Algarve and Ribatejo (Rocha, 2005; Correia, 2004).

The wattle-and-daub technique consists of a grid structure of timber elements, which is filled and covered by earth, and it serves to build walls, arches, vaults and domes (Figure 2c). The timber grid is responsible for the bearing capacity and it can be constituted by wooden poles nailed together, by wickerwork or by a plaited straw support (Houben and Guillaud, 2008). The earth infill serves as protection of the bearing structure and has almost no structural function. In general, the earth mix presents high clay content and includes very often the addition of natural fibres (e.g. straw). In Portugal, this technique is frequently found in historical city centres from the northern region, as a technique locally termed as "tabique", which was used to build both external and internal walls (Pinto et al., 2010).


(a) (b) (c)

Figure 2 – Earth construction techniques: (a) adobes being manufactured; (b) construction of a rammed earth Wall; (c) external wall made of "*tabique*" (Pinto et al., 2010).

The earthen materials resulting from the aforementioned techniques are in general considered to be non-standard, since most of the times they are not produced according to an industrialized process with quality control (Bui et al., 2008). The heterogeneity and variability of the soils used to manufacture these earthen materials are also responsible for introducing variability and little reliability on their already low mechanical properties. This makes very difficult the design of earth constructions according to the demands of modern codes. Furthermore, there are few countries with specific codes and standards for earth construction, such as New Zealand (NZS, 1998a; NZS, 1998b and NZS, 1998c), Peru (SENCICO, 2000) and USA (NMAC, 2006). These facts explain the little acceptance for this type of construction by most of the designers and authorities in developed countries. On the other hand, there has been also little acceptance by the potential inhabitants, which is explained by some cultural assumptions that associate this type of construction to poverty (from developing countries) and to a type of construction with poor seismic behaviour and with lacking durability against water.

However, the aforementioned assumptions can be considered not exactly correct, especially when addressed to modern earth construction. In fact, the last few years have registered a growing demand for earth construction in developed countries, explained by the realising of some advantages featured by these constructions. In general, earth constructions are acknowledged by their owners for promoting a comfortable and healthy interior ambient, since they feature a good thermal performance, good noise isolation and are capable of controlling the air moisture to healthy values. Another advantage that has been put forward in the last years is the low environmental impact of this type of construction. In general, building with earth requires low CO_2 emissions and when the constructions lose their use, the materials can be returned to the nature almost without any processing (Pacheco-Torgal and Jalali, 2012).

The need in accepting the earthen materials as standard building materials and in improving the quality of earthen structures led to the introduction of improvements in the manufacture and building processes of the traditional techniques. The masonry built with compressed earth blocks (CEBs) is probably the most popular case, where CEBs can be seen as an upgrade of adobes. The CEBs are manufactured resorting to specific presses, where the moist soil is compressed into a block. This technique was first introduced in the fifties with the development of one of the first manual presses by G. Ramires, which became worldwide known as CINVA-RAM (Barbosa and Mattone, 2002). Nowadays, the compaction of CEBs can also be carried out resorting to hydraulic presses (Doat et al., 1991) that apply a substantially higher pressure than manual ones (Gomes, 2008). This building technique is popular in countries such as India, Brazil, Zimbabwe, Australia, Germany and France, where it has been used as a sustainable and low-cost solution for housing. The use of a press, besides promoting a higher density of the blocks (and thus an improvement in strength) also allows the homogenisation of their shape, flatness and dimensions. This also means that the resulting earthen materials present lower variability.

Chemical stabilisation by addition of lime or Portland cement is frequently used in the manufacturing of CEBs. This process aims at increasing the mechanical properties of CEBs and at improving their susceptibility against water. However, the embodied energy of earthen materials increases substantially with the stabilisation (Houben and Guillaud, 2008; Reddy and Kumar, 2010; Lax, 2010), making this type of solution less competitive with respect to the cost and the environmental impact. In order to mitigate these aspects, materials with lower embodied energy than that of lime and cement should be incorporated instead. The history of earth construction is rich in examples of such materials, which include "peculiar" ones such as cow-dung, cactus juice and blood (Eires et al., 2010). However, the stabilisation effectiveness and reliability of these materials is little when compared with that of lime and cement.

More recently, the stabilisation with alkaline activation of fly ash has been studied as an alternative environmentally friendly technique in geotechnical applications (Cristelo et al., 2011; Cristelo et al., 2012a) and rammed earth construction (Silva et al., 2013). The alkaline activation of fly ash enables the formation of what is called a geopolymeric binder. When this type of binder is mixed with the soil, it hardens and forms a matrix that involves and binds the particles, forming a soil-binder interface that usually delivers strength levels higher than the soil alone. 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, $CaSO_4{\cdot}2H_2O$, $R_2(n)SiO_2$, in which R represents an alkaline ion like sodium (Na^+) or potassium (K^+), or an alkaline earth ion like calcium (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 resulting polymeric structure of Al–O–Si bonds constitutes the main structure of the hardened geopolymer matrix, which is very similar at a molecular level to natural rocks, sharing their stiffness, durability and strength. Among many raw materials rich in silica and alumina, fly ash is probably the most popular one used in alkaline activation, but others can be mentioned such as high-furnace slag and metakaolin (Roy, 1999). The first two are waste materials from the industry, which makes their use in the production of geopolymeric binders as a way to revalorize them in the building industry. Furthermore, the stabilisation of soils with alkaline activation of fly ash have been shown to be capable of delivering similar mechanical performance to that obtained from addition of lime or cement (Cristelo et al., 2012b). Thus the integration of the alkaline activation in the production of CEBs is expected to be a solution to mitigate the environmental impact of the stabilisation, while maintaining the good mechanical performance delivered by the addition of lime or cement.

This paper presents an experimental program where the alkaline activation is tested as solution for stabilisation of CEBs manufactured using a typical granite residual soil (GRS) from northern Portugal. This type of soil was selected as local case study, where the abundance of this material may allow and promote local CEBs production and construction, as well as, the reuse of GRS exceeding from geotechnical works.

Regarding the experimental program, the suitability of the GRS for the production of unstabilised CEBs was first assessed with basis on its geotechnical properties. Then, it was decided to proceed with the chemical stabilisation of the soil, where the alkaline activation of fly ash was the main focus. In addition, some trials were also performed using cement and sludge from a water treatment station, which was subjected to a thermal treatment. The mechanical properties of selected compositions were assessed for several ages by performing compression tests on cylindrical specimens. Then, CEBs were produced and their mechanical properties were characterized, namely through compression and flexural tests in dry and saturated conditions. Finally, the compression behaviour of the masonry performed with the CEBs was also characterized.

2 - SUITABILITY OF GRS FOR UNSTABILISED CEBs PRODUCTION

The soil used in the experimental program was collected from Guimarães (Louredo) and its geotechnical properties were characterized, namely in terms of particle size distribution (PSD), Atterberg limits, maximum dry density and optimum water content (standard Proctor). These properties were then compared with recommendations, which allowed concluding about the suitability of this soil for manufacturing unstabilised CEBs.

The particle size distribution of the soil was performed by means of sieving and sedimentation analysis according to the LNEC E196 (LNEC, 1966) procedure. Figure 3 compares the PSD of the soil against the envelope of GRS from the region of Porto (Portugal) presented by Viana da Fonseca (1996). The fact that the PSD curve of the soil fits within almost all the envelope means that this can be considered a representative GRS from northern Portugal.

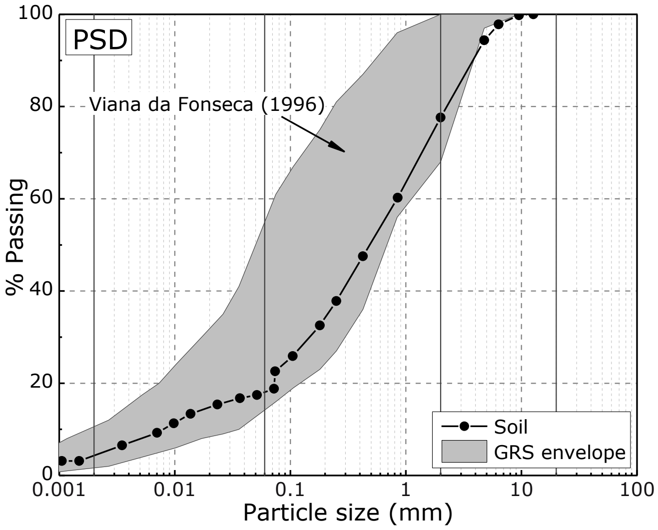


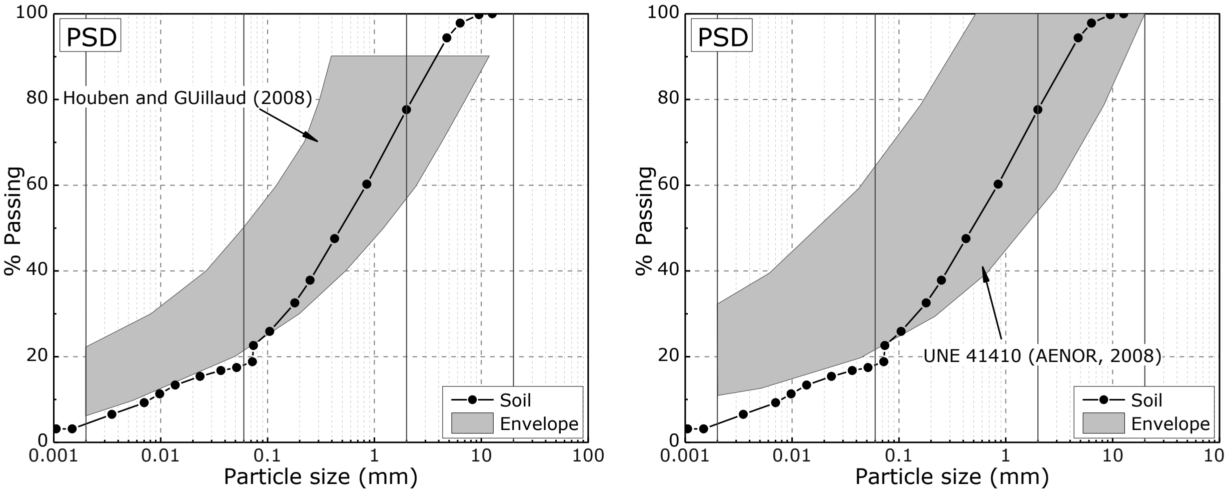
Figure 3 – Comparison between the PSD curves of the soils and the envelope presented by Viana da Fonseca (1996) for GRS from the region of Porto, Portugal.

In Figure 4, the PSD curve is plotted against the envelopes recommended by Houben and Guillaud (2008) and by the Spanish Standard UNE 41410 (AENOR, 2008) for manufacturing CEBs. In both cases is highlighted the fact that the soil is lacking in fines, namely in clay. As depicted in Table 1, the soil clay content is of about 4%, which is clearly inferior to the minimum value recommended by the HB 195 (Standards Australia, 2002) for unstabilised CEBs, namely 10%. The UNE 41410 (AENOR, 2008) requires the same minimum percentage, but a more restrictive criterion is given by discarding the use of any soil with inferior clay percentages. Even in the case of stabilised CEBs, the less restrictive HB 195 (Standards Australia, 2002) recommends a clay percentage higher than 5%. This means that the clay content of the soil may be insufficient to develop adequate strength and resistance against water. Furthermore, such low clay content may have practical implications in the manufacturing of the CEBs in terms of productivity. Under these circumstances, the initial cohesion provided by the clay fraction might be insufficient to allow the immediate handling of the CEBs; the manufacture process consists in compacting the CEB in the press, removing it immediately in order to be put to dry or cure and to continue the manufacturing process. The only positive characteristic of the soil, with respect to its PSD, is the fact that the maximum particle size is inferior to 25 mm and 20 mm, as recommended by HB 195 (Standards Australia, 2002) and UNE 41410 (AENOR, 2008), respectively. This may mean that the use of this soil would not require sieving.

Table 1- PSD of the soil used in the experimental program.

Clay (%)	Silt (%)	Sand (%)	Gravel (%)
4	14	60	22

(clay < 0.002 mm / 0.002 mm ≤ silt < 0.060 mm / 0.060 mm ≤ sand < 2.0 mm / 2.0 mm ≤ gravel < 20 mm)



(a) (b)

Figure 4 – Comparison between the PSD curve of the soil and the envelopes for CEBs recommended by: (a) Houben and Guillaud (2008); (b) UNE 41410 (AENOR, 2008).

The potential lack in strength and in initial cohesion of unstabilised CEBs produced with the soil being analyzed is also evidenced by its Atterberg limits, determined according to NP 143 (LNEC, 1969). The liquid limit (LL) of the soil is of about 28% and the plastic limit (PL) could not be determined, classifying the soil as non-plastic. The lack of plasticity of the soil indicates insufficient clay content and is not recommended in earth construction because of the aforementioned reasons.

The compaction properties of the soil were determined according the standard Proctor test, described in LNEC E197 (LNEC, 1967). The maximum dry density of the soil is of about 1.71 g/cm^3 and the optimum water content (OWC) of about 12%. According to Doat et al. (1991), the low maximum dry density obtained is expected to result in earthen material with fairly poor performance (1.65 g/cm^3<γ_d<1.76 g/cm^3). Therefore, the soil being analysed is not suitable for manufacturing unstabilised CEBs, since its geotechnical properties seem not to be adequate for obtaining an earthen material with adequate strength and durability. This means that using this soil would require chemical stabilisation.

3 - CHEMICAL STABILISATION OF GRS FOR CEBs PRODUCTION

3.1 - Methodology

The alkaline activation was chosen as the main stabilisation technique to be studied in the experimental program presented in the paper. This decision results from previous research where this technique was studied in the stabilisation of rammed earth construction (Cristelo et al., 2012b; Silva et al., 2013), from which good indicators were taken in terms of mechanical performance. The stabilisation by addition of cement was also tested and served as reference. It should be noted that given the characteristics of the soil analysed in the previous section, the obvious stabilisation solution would consist in the addition of cement. Furthermore, some trials were performed with sludge from a water treatment station, which was subjected to a thermal treatment. The sludge was used in the stabilisation by alkaline activation, substituting completely the fly ash. The study of possible alternatives for reusing the sludge is the main reason behind this decision. Before proceeding with the manufacturing of CEBs, the three types of stabilisation solutions aforementioned were first tested in a composition study carried out at the Civil Engineering laboratory of University of Trás-os-Montes e Alto Douro (UTAD). The compositions of the mixtures tested are presented in Table 2, where W/S is the water-solids ratio, A/S is the activator-solids ratio and Silic/Hidrox is the ratio between the silicate and hydroxide solutions. The W/S and the A/S ratios were defined to be slightly higher than the OWC of the soil in order to take into account the addition of fine particles (cement and fly ash). Furthermore, these values were adjusted by trial-and-error to obtain adequate workability of the mixtures for manufacturing CEBs (Soares, 2013). The compression strength was the parameter assessed in the composition study and was tested for the ages of 7, 28, 60, 90 and 180 days, in the case of the mixtures with cement and fly ash. In the case of the mixtures with sludge, it was tested for a single age of 90 days.

Table 2- Composition of the mixtures tested.

Mixture	Soil (wt.%)	Cement (wt.%)	Fly ash (wt.%)	Sludge (wt.%)	W/S (wt.)	A/S (wt.)	Silic/Hidrox (wt.)	Na_2O/Fly ash (wt.)	Na_2O/Sludge (wt.)
SC2.5	97.5	2.5	-	-	0.150	-	-	-	-
SC5.0	95.0	5.0	-	-	0.146	-	-	-	-
SFA10.0	90.0	-	10.0	-	-	0.134	0.5	0.250	-
SFA15.0	85.0	-	15.0	-	-	0.137	0.5	0.170	-
SS10.0	90.0	-	-	10.0	-	0.134	0.5	-	0.250
SS15.0	85.0	-	-	15.0	-	0.137	0.5	-	0.170

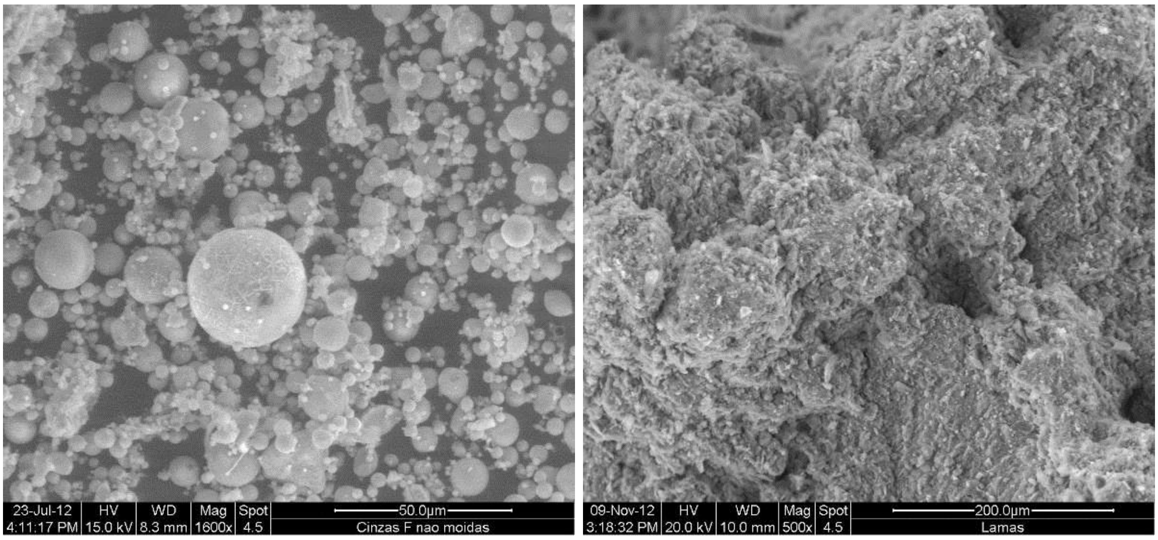
3.2 - Materials

The GRS soil collected from Guimarães was used in the preparation of the tested mixtures without being sieved, but it was dried in advance in oven at 110ºC. The cement used was the CEM II/B-L 32.5N, provided by CIMPOR Portugal. The fly ash was obtained from a Portuguese thermo-electric power plant (PEGOP), and is characterized mainly by its low calcium content (type F classification) and by 74% of mass available for dissolution (Si plus Al) (see Table 3). The sludge was collected from the water treatment station of Sordo (Vila Real, Portugal) with water content of about 528%. The processing of the sludge consisted in drying it in oven at 110ºC and then in its calcination at a temperature of about 950ºC. This process resulted in a high decrease of the volume of the sludge. The resulting calcinated sludge consisted in a very friable material in the form of deformed granules. The chemical analysis (EDS) revealed 43% of mass available for dissolution (see Table 3). The scanning electron microscopy (SEM) images of the fly ash and calcinated sludge are presented in Figure 5. The fly ash particles are characterised by a spherical shape and the surface of the calcinated sludge granules is completely irregular.

Table 3- Chemical composition (wt.) of the fly ash and calcinated sludge (EDS).

Material	Si	Al	O	Na	Mg	P	S	K	Ca	Ti	Mn	Fe
Fly ash	48.8	21.8	-	1.3	1.6	0.6	1.2	4.4	3.9	1.8	-	14.7
Sludge	18.1	24.9	44.1	0.8	0.4	0.3	-	1.9	0.7	0.2	1.2	7.5

The sodium silicate was acquired in solution form, with a density of 1.45 g/cm^3, a sodium oxide (Na_2O) content of 13% and a SiO_2:Na_2O ratio of about 2. The sodium hydroxide was originally acquired in flake form, with a density of 2.13 g/cm^3 at 20ºC, and 95-99% purity, and was dissolved in water to achieve a concentration of 12.5 molal before being mixed with the sodium silicate to compose the activator.



(a) (b)

Figure 5 – SEM images of the: (a) fly ash (1600x); (b) calcinated sludge (500x).

3.3 - Sample preparation and testing procedure

For all mixtures, the soil was dry mixed with the solid phase of the stabilising binder (cement, fly ash or sludge) using a planetary mixer until achieving homogenisation. Then, the liquid phase (water or activator) was added and mixed until the mixture got again completely homogenised. It should be noted that the mixing of the sludge mixtures resulted in the complete breakdown of the sludge granules, promoting a good distribution of this material among the soil. Each mixture was used to produce three cylindrical specimens with 70 mm of diameter and 140 mm of height, using specific metallic moulds. Each specimen was compacted in three layers, whose top surfaces were scrapped each time in order to promote adhesion with the next layer. The density of the specimens was defined such that the solid phase of the mixtures would fulfil the maximum dry density obtained from the proctor test (1.71 g/cm^3). The specimens were demoulded after 24h by extrusion and were stored until testing at room temperature (20ºC±2) and involved in a plastic film. The manufacturing process of the specimens granted that the testing surfaces (contacting with the machine plates) would be perfect horizontal plans. The load was applied under displacement control at a rate of about 0.20 mm/min.

3.4 - Results and discussion

The results of the compression tests are summarized in Table 4, where each value corresponds to the average of three tests. The failure mode of the specimens is illustrated in Figure 6, which seems to be similar for any of the stabilisation binders used. When comparing the results obtained for 90 days of age, the stabilisation by alkaline activation of fly ash presents the best performance, while the cement stabilisation presents the worst. With respect to the alkaline activation of fly ash, it is observed that the higher the fly ash content, the higher is the compressive strength. An increase of 50% in fly ash content resulted in increase in strength of about 26% for 90 days of age. Nevertheless, the increase in strength from 90 days to 180 days of age is very significant, showing that the hardening of the mixtures with fly ash is slower. In the case of the mixture with 10% of fly ash, the increase in strength was of about 111%, while in the case of the mixture with 15%, it was of about 102%.

Table 4- Compressive strength of the mixtures tested (coefficient of variation is given in brackets).

Mixture	Compressive strength (N/mm^2)				
	Age (days)				
	7	28	60	90	180
SC2.5	0.11 (5%)	0.34 (1%)	0.49 (2%)	0.51 (3%)	0.51 (3%)
SC5.0	0.69 (4%)	1.20 (5%)	1.31 (7%)	1.49 (4%)	1.73 (1%)
SFA10.0	0.74 (1%)	1.40 (7%)	1.23 (4%)	1.85 (1%)	3.91 (6%)
SFA15.0	0.83 (9%)	3.08 (10%)	3.35 (3%)	2.33 (10%)	4.71 (8%)
SS10.0	-	-	-	1.87 (3%)	-
SS15.0	-	-	-	1.50 (7%)	-


(a) (b) (c)

Figure 6 – Failure mode of the specimens stabilized with: (a) cement; (b) fly ash geopolymer; (c) sludge geopolymer.

Figure 7 compares the strength evolution of the fly ash mixtures with that of the cement mixtures. As it can be seen, the time evolution is much less significant in the case of the cement mixtures, where at least 80% of the maximum compressive strength (180 days) is established after 60 days. Despite the hardening of the cement mixtures being faster, the fly ash mixtures outperform them even at the earlier ages. It should be pointed out that the mixtures with fly ash present a higher percentage of binder available for stabilisation. However, this does not mean that all fly ash is expected to be dissolved and involved in the formation of the geopolymeric binder. The slow hardening of the mixtures with fly ash should be a factor to be taken into account in an industrial situation where CEBs are produced. This means that enough curing time should be given to the CEBs before being used in the construction or, possibly, thermal curing may be used for accelerating the process (Villa et al., 2010). Figure 7 also shows an important decrease in compressive strength of mixture SFA15.0 at 90 days of age. On the other hand, mixture SFA10.0 presents a not so important decrease in compressive strength at 60 days of age. This unexpected behaviour of both mixtures may be explained by the development of the geopolymeric crystalline network under ambient temperature, whose assessment would require a deeper research involving mineralogical analysis. Nevertheless, these results must be verified with further experimental research.

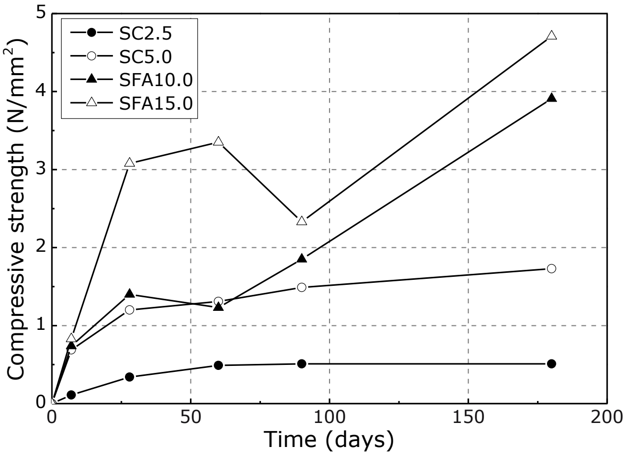


Figure 7 – Evolution of the compressive strength of the mixtures.

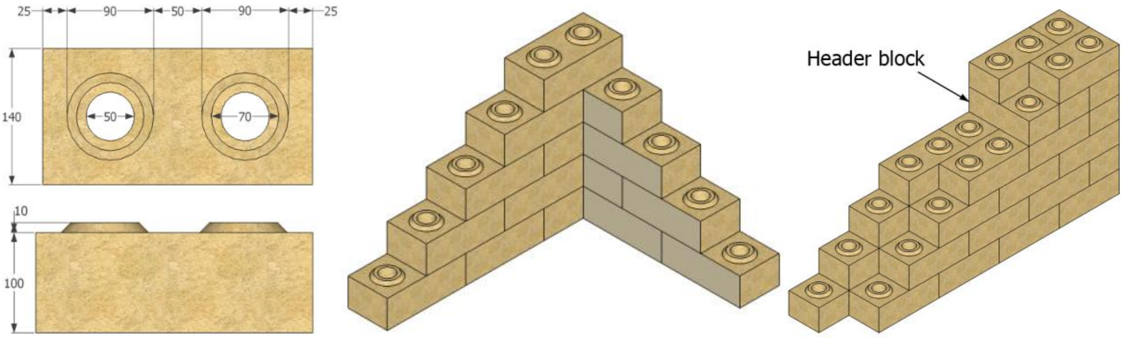
With respect to the minimum required compressive strength for producing CEBs, only the mixtures with fly ash outperform the rule of thumb of a minimum value of about 2 N/mm^2 (Houben and Guillaud, 2008). In the case of the mixture with 10% of fly ash, this situation only occurs for an age of 180 days. It should be noted that this minimum strength is referred to the strength of blocks and not to the type of specimens here analyzed. In general, this last type of specimens is expected to be less strong than the blocks, due to the fact that the lower slenderness of the blocks promotes a higher confinement effect. By taking into account the good performance of the mixtures with fly ash, namely SFA10.0 and SFA15.0, it was decided to proceed with both in the manufacturing of CEBs. Another important factor contributing to this decision is the fact that the addition of fly ash contributes to an increase of the fines content, required for the development of initial cohesion in the CEBs to allow their immediate handling after compaction.

Despite the relative good performance of the compositions incorporating sludge, these were discarded from the experimental program, since the calcination of the sludge requires high energy consumption. This process increases substantially the environmental impact of this stabilisation solution. Nevertheless, some trial CEBs were manufactured using the aforementioned mixtures, as discussed later.

4 - MECHANICAL BEHAVIOUR OF STABILISED CEBs BY ALKALINE ACTIVATION OF FLY ASH

4.1 - Geometry

The geometry adopted for the CEBs resulted from a parallel research project between University of Minho and Mota-Engil SA (project HiLoTec). The aim of the project consisted in the development of a simple and innovative construction technology for the construction of sustainable buildings in seismic developing countries, namely in Malawi (Ramos et al., 2011). The selected geometry consists in a type of hollow block, which allows building masonry walls with single- and double-leaf, as illustrated in Figure 8. This type of block is recommend by Minke (2001) and the Auroville Earth Institute (AIE, 2005) for regions with non-negligible seismic hazard, since the holes allow introducing vertical reinforcements and decreasing the weight of the blocks. The masonry built with these blocks consists in a dry-stack interlocking system, relying on a docking mechanical connection between CEBs, which does not require the use of mortar in the joints. This last feature allows a simpler building process, which promotes shorter building periods and lower building costs. Further information on the constructive system is addressed in Ramos et al. (2011).



(a) (b) (c)

Figure 8 – Dry-stack interlocking CEBs masonry system (Sturm et al., n/p): (a) dimensions of the block (in mm); (b) single-leaf wall; (c) double leaf-wall.

4.2 - Manufacturing and testing procedures

The two compositions incorporating alkaline activation of fly ash (SFA10.0 and SFA15.0) were used for manufacturing the CEBs tested in the experimental program. The blocks were manufactured using a Terstaram manual press (Belgium), which allows applying a pressure higher than $2\ N/mm^2$ (Figure 9a). The mixtures were prepared in a vertical shaft mixer with free spinning trident paddles. The solid phase materials were first dry-mixed until total homogeneisation (~5min). Then, all the activator was added and the mixing continued until the homogeneisation occurred again (~5min). After mixing, the mixtures presented a slightly dry appearance and allowed the formation of a ball with the hands, but the execution of a successful trial of the drop ball test was not possible. Nevertheless, it was possible to manufacture the CEBs, meaning that this test is not adequate for these mixtures when looking for the ideal consistency for starting the compaction. Each mixture was then used to prepare a batch of ten CEBs. In order to control the production, the material required to perform each CEB was weighted in advance, using the same criterion used in the manufacture of the cylindrical specimens (see Section 3.3). A total of 80 CEBs were produced for each composition. After the compaction, it was possible to handle immediately the CEBs, showing that the percentages of fly ash adopted introduced adequate percentages of fines for the CEBs featuring initial cohesion (see Figure 9b). Nevertheless, it should be noted that adopting mixtures with less than 10% would not produce adequate results. This statement is supported by the fact that a few CEBs with 10% of fly ash crumbled when handled. The CEBs were put to harden on the floor for about 3 days (Figure 9c) and then were packed on a pallet until testing. The curing of the CEBs occurred under laboratory conditions at a temperature of about 20±2ºC and exposed to the air. This resulted in the occurrence of some efflorescence at the exposed surfaces of the CEBs, which seemed to have only a slight visual impact on the colour; changing from dark grey to light grey.

With respect to the trial CEBs manufactured with the sludge mixtures (see Figure 9d), it was observed that they failed in three aspects, which support even further the decision in discarding this stabilisation solution. First, the addition of sludge did not introduce adequate percentage of fines required for development of the initial cohesion of the CEBs. Second, the surface of the CEBs, while hardening, started desegregating, which was possibly caused by the occurrence of efflorescences. Third, the packed CEBs at the bottom cracked due to the weight of the top ones. This last aspect shows lack of binding and strength provided by the geopolymeric binder formed from the alkaline activation of the sludge. Possibly, these aspects can be improved by milling the sludge in order to introduce fines and to promote a better dissolution. This hypothesis was also tested by manufacturing some CEBs with sludge milled in a ball-mill (milling time of about 20 min). This process resulted in some improvements, however it was insufficient since the CEBs presented excessive disaggregation and lack of binding, even after 180 days of curing.

The mechanical properties of the CEBs were tested at the Civil Engineering laboratory of University of Minho, after a curing time of about 180 days. Compression and three-point bending tests were carried out in order to assess the compressive and tensile strength of the CEBs, respectively. The CEBs were tested both in dry and saturated states, where this last case served to assess the decrease in strength due to the presence of water. The CEBs where saturated by submerging them in water during at least 24h and until about 30 min before testing.

The compression tests on the CEBs were carried out according to the procedure of EN 772-1 (CEN, 2011), but the load was applied under displacement control at a rate of about 4 μm/s in order to try capturing the post-peak behaviour. Four specimens were tested for each composition and moisture condition (air dry and saturated), in a total of sixteen. The top and bottom platens from the mould of the Terstaram press were used as testing platens in order to ovoid cutting and capping the specimens. These platens have the same shape of the CEBs, meaning that they are able to distribute uniformly the load on the top and bottom surfaces of the specimens (see Figure 10a).

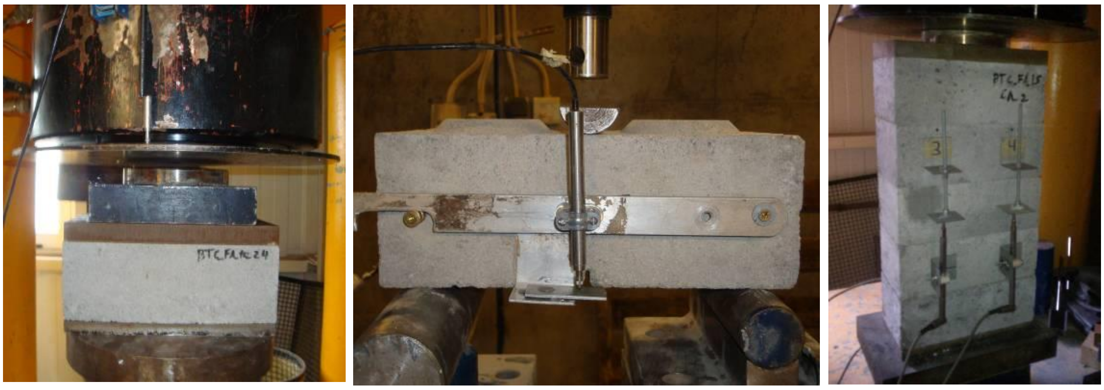
(c)

(a) (b) (d)

Figure 9 – CEBs production: (a) Terstaram press; (b) fly ash CEBs being manufactured; (c) CEBs stabilised with alkaline activation of fly ash left to harden; (d) disintegration of a CEB stabilised with alkaline activation of sludge.

The three-point bending tests were carried out according to the procedure of EN 772-6 (CEN, 2002), but adjustments of the tests setup were carried out by taking into account the HB 195 (Standards Australia, 2002). Previously to the tests, the CEBs were notched resorting to a circular saw, which was operated in dry conditions. The notch depth was of about 10 mm and the width of about 3.5 mm. This procedure aimed at forcing the failure surface at occurring at middle span and at avoiding its occurrence at sections with holes. The specimens were supported by cylindrical metallic rollers, featuring a 220 mm span. The load was applied at middle span, under displacement control at a rate of about 2 μm/s. The deflection at middle span and the crack opening at the notch were measured by means of LVDTs (see Figure 10b). Four specimens were tested for each composition and moisture condition (air dry and saturated), in a total of sixteen specimens.

The behaviour in compression of the masonry built with the two types of CEBs was also assessed, in addition to the mechanical properties of the single units. For this purpose, compression tests were carried out on dry-stack prisms constituted each by five overlapping CEBs. This type of specimens, when compared with wallet-specimens, has the advantages of being simpler and demanding a lower loading capacity. However, it is noted that this type of specimen is not fully representative of the masonry pattern. The tests were carried out according to the procedure of ASTM C1314-03b (ASTM, 2003), but the load was applied under displacement control at a rate of about 5 μm/s. The platens from the mould of the Terstaram press were also used in this test. Four specimens were tested for each composition, in a total of eight specimens. Only the air dry condition was taken into account for this case. The vertical displacements were measured between the second and the fourth block by means of two LVDTs placed on each face of the prism (see Figure 10c).



(a) (b) (c)

Figure 10 – Mechanical tests preformed: (a) compression test on a single CEB; (b) three-point bending test; (c) compression test on a masonry prism.

4.3 - Results and discussion

4.3.1 - Compression tests of CEBs

Table 5 presents the results of the compression tests carried out on the CEBs, where γ_b is the air dry density of the blocks, $f^d_{c,u}$ is the average compressive strength of the specimens tested under air dry condition and $f^s_{c,u}$ is the average compressive strength of the specimens tested under saturated condition. It should be noted that the compressive strength was computed by taking into account the net area of the CEBs. In general, the failure mode of the specimens was characterized by the formation of a pyramidal-trunk, which is explained by the confinement introduced by the loading platens (see Figure 11).

Table 5- Results of the compression tests on a single CEB in terms of average compressive strength (coefficient of variation is given in brackets).

Mixture	γ_b (kg/m^3)	$f^d_{c,u}$ (N/mm^2)	$f^s_{c,u}$ (N/mm^2)	$f^s_{c,u}$ / $f^d_{c,u}$
SFA10.0	1810 (1%)	8.8 (11%)	5.6 (10%)	0.64
SFA15.0	1854 (1%)	12.0 (8%)	8.0 (21%)	0.67

As expected, the mixture SFA15.0 presented average values of the compressive strength higher than those of mixture SFA10.0; $f^d_{c,u}$ and $f^s_{c,u}$ are, respectively, 1.36 and 1.42 times higher. The higher percentage of geolpolymeric binder is the main reason supporting this statement. The higher density of the CEBs manufactured with mixture SFA15.0 also helps to explain this. With respect to the CEBs tested under saturated condition, it should be noted that the water intake of the CEBs was, in average, of about 5.5% and 6.5% for the mixtures SFA10.0 and SFA15.0, respectively. This means that the open porosity of both types of CEBs is similar and is not very high. The reduction of the compressive strength with the presence of water was also similar in both mixtures, namely 0.64 and 0.67 times for mixture SFA10.0 and SFA15.0, respectively. Both cases correspond to an important decrease in strength. Nevertheless, the minimum value obtained for $f^s_{c,u}$ was of about 4.9 N/mm^2 (SFA10.0), which corresponds to a very acceptable value.

(a) (b)

Figure 11 – Failure mode of the CEBs tested under compression: (a) air dry; (b) saturated.

Both mixtures presented a $f^d_{c,u}$ much higher than the thumb rule of a minimum compressive strength of about 2 N/mm^2 for CEBs. With respect to the Spanish standard UNE 41410 (AENOR, 2008), both mixtures resulted in CEBs that can be classified as class BTC 5. This is the highest class provided, where the normalized compressive strength (5% fractile) must be superior to 5 N/mm^2. On the other hand, the lowest class provided is BTC 1, where the normalized compressive strength (5% fractile) must be superior to 1.3 N/mm^2. The normalized compressive strength of each specimen (air dry) is obtained by multiplying the compressive strength by the shape factor (0.92), which results in average values of about 8.1 N/mm^2 and 11.0 N/mm^2 for the mixture SFA10.0 and SFA15.0, respectively. Despite of the number of tests performed being little to allow a reliable statistical analysis to compute the 5% fractile, it should be said that the lowest normalized strength obtained was of about 7.3 N/mm^2 (mixture SFA10.0).

With respect to the New Zealand standard NZS 4298 (NZS, 1998b), the CEBs also respect the minimum compressive strength required, whose value is of about 1.52 N/mm^2 (takes into account the aspect ratio of the CEBs). This means that there is still margin to adjust the quantities of fly ash and activator, in order to reduce the cost and the environmental impact of the stabilisation solution. Nevertheless, it should be highlighted that reducing the fly ash percentage below 10% would require introducing fine particles by other means (see Section 4.2).

The results obtained show that the compressive strength of the CEBs is substantially higher than that of typical CEBs. For example, for CEBs stabilised with 5-10% of cement, Walker and Stace (1997) report compressive strengths varying between 0.30 N/mm^2 and 7.11 N/mm^2. The obtained compressive strengths are very comparable to those of standard masonry units. According to Mohamad (2007), the concrete blocks found in the USA and Brazilian markets present compressive strength higher than 4.5 N/mm^2. This means that the CEBs tested may also compete with these standard units in terms of mechanical performance.

4.3.2 - Three-point bending tests

Table 6 presents the results of the three-point bending tests carried out on the CEBs, where $f^d_{b,u}$ is the average flexural strength of the specimens tested under air dry condition and $f^s_{b,u}$ is the average flexural strength of the specimens tested under saturated condition. The failure of all specimens occurred at the middle span cross-section and the failure crack followed a vertical plane, meaning that the notch served its purpose (see Figure 12). In the case of the CEBs tested under air dry condition, the failure was brittle, since the specimens failed instantly after a very short plastic phase. On the other hand, the saturation of the CEBs resulted in a softer failure, which was more evidenced in the CEBs with lower strength (see Figure 13).

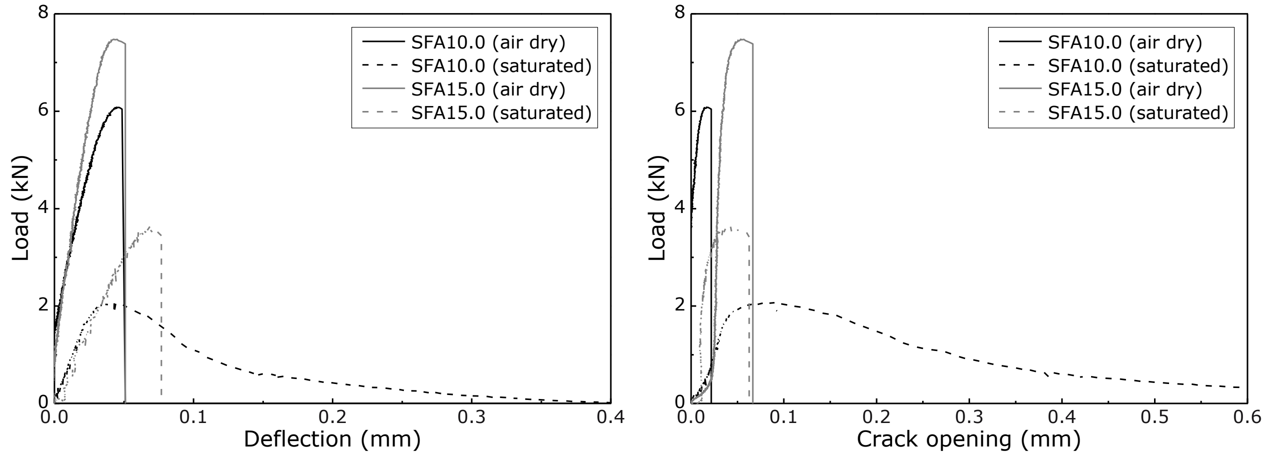
Table 6- Results of the three-point bending tests in terms of average flexural strength (coefficient of variation is given in brackets).

Mixture	γ_b (kg/m^3)	$f^d_{b,u}$ (N/mm^2)	$f^s_{b,u}$ (N/mm^2)	$f^s_{b,u}$ / $f^d_{b,u}$	$f^d_{c,u}$ / $f^d_{b,u}$
SFA10.0	1810 (1%)	1.8 (14%)	0.7 (36%)	0.40	4.89
SFA15.0	1854 (1%)	2.3 (11%)	1.1 (9%)	0.49	5.22

(a) (b)

Figure 12 – Failure mode of the CEBs tested under three-point bending: (a) failure at the middle span of an air dry CEB; (b) crack tip initiation at the middle span of a CEB tested saturated.

The flexural strengths obtained for CEBs manufactured with mixture SFA15.0 are higher than those obtained for the CEBs manufactured with mixture SFA10.0. The same reasons pointed out for the compressive strength can be mentioned for this case as well, namely the higher geopolymeric binder content and density of the CEBs manufactured with mixture SFA15.0. The standard NZS 4298 (NZS, 1998b) addresses a minimum flexural strength as a mechanical requirement for CEBs. In this case, the flexural strength must be superior to 0.25 N/mm^2, which corresponds to the case of both mixtures by a large margin. According to the standard NZS 4297 (NZS, 1998a), the compressive strength of the CEBs can be estimated as 3.5 times the flexural strength. This relation provides an underestimation of the compressive strength of the CEBs tested, but the aforementioned standard assumes this relation to be on the safe side. The flexural strength also suffered an important decrease due to the presence of water, which was of about 0.40 and 0.49 times in the case of mixture SFA10.0 and SFA15.0, respectively. It should be noted that the water intake of the CEBs manufactured with mixture SFA10.0 was of about 5.5%, while that of mixture SFA15.0 was of about 6.1%.



(a) (b)

Figure 13 – Examples of curves obtained from the three-point bending tests: (a) load-deflection; (b) load-crack opening.

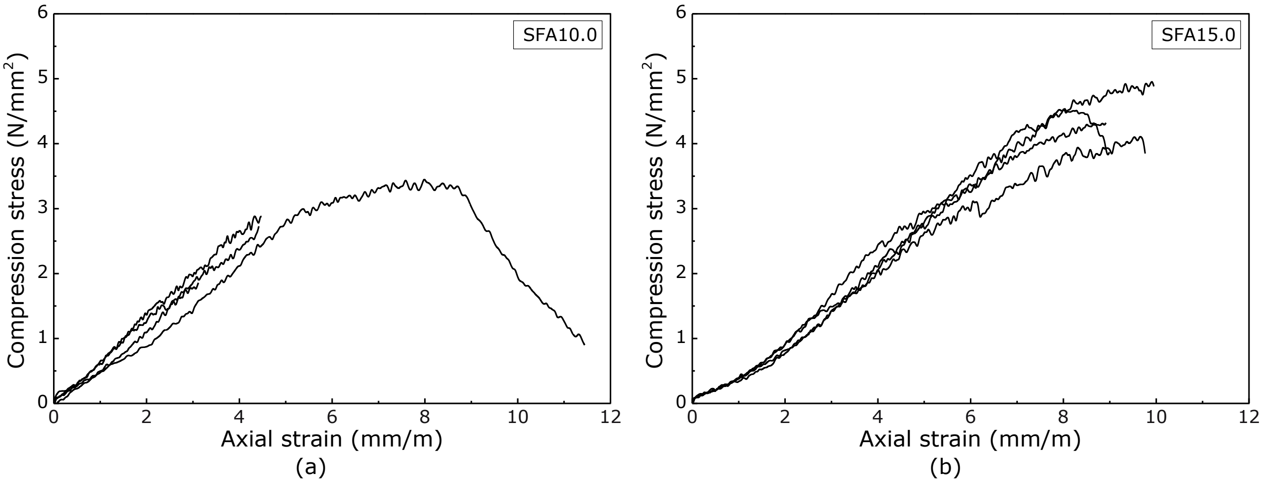
4.3.3 - Compression tests of prisms

The results of the compression tests carried out on the masonry prisms are summarized in Table 7, in terms of average compressive strength ($f_{c,p}$) and average Young's modulus ($E_{0,p}$). The first parameter was computed by taking into account the net area. The second parameter was computed between 5% and 30% of the compressive strength by linear fitting of the respective compression stress-axial strain curves, which are presented in Figure 14. These curves are characterized by an initial adjustment phase, which is related with the adjustment of the contact between CEBs at the dry joints. It should be noted that some curves are incomplete due to early detachments of the LVDTs from the specimens caused by occurrence of damage.

Table 7- Results of the compression tests carried out on masonry prisms (coefficient of variation is given in brackets).

Mixture	$f_{c,p}$ (N/mm^2)	$E_{0,p}$ (N/mm^2)	$f_{c,p}$ / $f^{d}_{c,u}$	$f_{c,p}$ / E_0
SFA10.0	3.3 (15%)	551 (16%)	0.38	167
SFA15.0	4.6 (9%)	463 (8%)	0.39	100

The compressive strength of the masonry prisms is found to be 0.38 and 0.39 times the compressive strength of the individual CEBs, respectively for the mixtures SFA10.0 and SFA15.0. This relation is very similar in both mixtures, which may mean that the compressive strength of the individual CEBs may provide a good estimation of the compressive strength of the masonry built with these CEBs. On the other hand, according to the standard NZS 4297 (NZS, 1998a), the compressive strength of the masonry is assumed to be half of the compressive strength of the CEBs. Therefore, this standard would lead to an overestimation of the compressive strength of the masonry for design purposes in this case. The lower relation value obtained from the tests is possibly related with the type of masonry and respective failure mode. The inexistence of bed mortar in the joints may introduce tensile stress concentrations in the CEBs, which are responsible for weakening the masonry during loading. With respect to E_0, both mixtures promoted similar values for the respective masonry. However, E_0 was unexpectedly higher for mixture SFA10.0, which is probably explained by the fact that the deformation of the specimens is mostly controlled by the dry stack joints, namely with respect to the adjustment of possible imperfections of the contact surfaces between CEBs (such as loose particles and protuberances at the contact surfaces). It should also be noted that the standard NZS 4297 (NZS, 1998a) provides and overestimation of the Young's modulus as a function of the compressive strength of the CEBs, where the first is assumed to be 300 times the second.



(a) (b)

Figure 14 – Compression stress – axial strain curves of the masonry prisms tested under compression: (a) mixture SFA10.0; (b) mixture SFA15.0.

Figure 15 illustrates the failure mode of a masonry prism constituted by CEBs manufactured with mixture SFA15.0. This failure mode was common to all specimens and was characterized by distributed cracking in the three middle CEBs of the prism. The cracks seemed to develop continuously from one block towards the next ones, showing transmission of tensile and shear stresses at the dry joints. The CEBs in contact with the testing platens presented little cracking, probably due to the confinement promoted by them. Nevertheless, spalling was a common damage in these CEBs. Furthermore, some localized damage was also observed, namely in the form of spalling of the corners of some CEBs and crushing at the horizontal joints. These types of damage were probably a consequence of stress concentrations caused by imperfections of the CEBs at the surfaces in contact.

Figure 15 – Failure mode of a masonry prism constituted by CEBs manufactured with mixture SFA15.0.

5 - CONCLUSIONS

This paper presents an experimental program addressing a modern earth construction technique, namely the masonry construction with CEBs. This technique is studied as an alternative building solution for northern Portugal, where GRS are common. The aim was to promote and contribute for the development of this building solution, namely with respect to use of stabilisation techniques with enhanced sustainability. The experimental program followed a mechanical approach, where the mechanical performance of CEBs manufactured with GRS and alkaline activation of fly ash was the main focus.

The experimental program was initiated with the assessment of the suitability of a typical GRS from northern Portugal for manufacturing unstabilised CEBs. The geotechnical characterization performed allowed to conclude that the soil studied is unsuitable on its natural state. The lack in clay content was the main reason pointed out, since it compromises the strength of the CEBs and the manufacturing process. This led to the conclusion that manufacturing CEBs with GRS seems to be feasible if chemical stabilisation is introduced in the process.

Three stabilisation techniques were studied in an initial composition study, namely the addition of cement and addition of geopolymeric binders resulting from the alkaline activation of fly ash or of calcinated sludge. The compositions incorporating the geopolymeric binders were those presenting better mechanical performance (compressive strength), especially those with fly ash. The composition study also showed that the hardening process of the mixtures with fly ash is significantly slower than the hardening of the mixtures with cement. The mixtures with fly ash showed an important increase in compressive strength even at 180 days of age, while that of the mixtures with cement was almost stable at 60 days of age. This is an aspect that must be taken into account in the production of CEBs with alkaline activation of fly ash, namely with respect to the required curing period.

The alkaline activation of calcinated sludge was shown to be inadequate for the production of CEBs, since the trial CEBs manufactured showed low cohesion upon the compaction, as well as disaggregation problems. On the other hand, the alkaline activation of fly ash allowed introducing adequate percentage of fines to promote the initial cohesion required by the manufacturing process. Nevertheless, it was observed that a percentage of fly ash inferior to 10% is not recommended for the soil used in the experimental program.

The mechanical tests performed on the CEBs stabilised with fly ash showed that the greater is the percentage of geopolymeric binder incorporated, the greater is the expected strength. Furthermore, the levels of strength delivered by this stabilisation technique were shown to be much superior to the requirements of reference standards on masonry construction with CEBs. The presence of water in the CEBs was shown to lead to an important decrease in strength. Nevertheless, the levels of strength delivered by the alkaline activation of fly ash were adequate even in the saturated condition. The compression tests carried out on the masonry prisms showed a strong decrease in compressive strength relative to that of single CEBs. A relationship between the strength of the masonry and the strength of the CEBs could be established in order to estimate the strength of the masonry as a function of the strength of the units.

In general, the stabilisation with alkaline activation of fly ash revealed excellent results with respect to the improvement in strength in the manufacturing of CEBs with GRS. This means that there is a large margin for optimization of the mixtures in order to reduce the percentage of geopolymeric binder, and thus reduce the cost and environmental impact of the stabilisation solution. Only after this process, the sustainability of this alternative stabilisation solution can be further assessed. The durability of these materials is another topic that also needs to be addressed in future research.

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