RESIDUAL GRANITIC SOIL IMPROVEMENT FOR RAMMED EARTH CONSTRUCTION

MELHORAMENTO DE SOLOS RESIDUAIS GRANÍTICOS A UTILIZAR NA CONSTRUÇÃO EM TAIPA

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ABSTRACT

This paper describes the research developed to evaluate the performance of stabilised residual granitic soil from the north region of Portugal. It is part of a research project designed to investigate the possibility of using this soil for rammed earth construction. Since its reduced plasticity makes the use of lime less effective, and the increasing environmental concerns with cement production can no longer be ignored, the study was focused on binders made from alkaline activation of low calcium fly ash. Therefore, the aim of this work was to determine, through a parametric analysis using laboratory tests, the optimum fly ash – based alkaline activated binder for improving granitic soil, in terms of mechanical strength. Identification of the key parameters allowed the characterisation of the most effective mixtures, which will be later used in the construction of large rammed earth wall panels that will be tested according to proper specifications.

RESUMO

O presente artigo descreve parte do trabalho de investigação realizado com o intuito de avaliar o desempenho de solos residuais graníticos da região Norte, depois de estabilizados. O referido trabalho de investigação insere-se num projeto mais abrangente destinado à aplicação deste tipo de solos em construções em terra, concretamente na construção em taipa. Uma vez que a fraca atividade destes materiais com fração argilosa reduzida e à base de caulinite limita a eficácia da cal no seu melhoramento, e tendo em conta as crescentes preocupações ambientais relacionadas com a produção de cimento, foi utilizado um agente estabilizante obtido através da ativação alcalina de cinzas volantes. O objetivo consistiu assim na determinação da mistura mais vantajosa, em termos de resistência mecânica, sendo que os parâmetros agora determinados serão utilizados na construção e análise de painéis em taipa.

1 - INTRODUCTION

Soil is certainly one of the most ancient building materials. The most common earth construction techniques are rammed-earth and adobe masonry (Houben and Guillaud, 1994). Adobes are bricks prepared with moist earth (to which straw is added sometimes) by simply moulding it in a wooden frame and drying it out in the sun. Then the masonry is prepared by 'gluing' the adobes with earth mortar. A rammed earth wall is made by compacting thin layers of packed earth using a rammer. The development of modern construction materials gradually made the application of earth as a construction material less and less attractive, which had more to do with social than with technical disadvantages. Inclusively, this trend had a significant influence on the lack of production of specific regulation codes. However, the recent growing concern with a meaningful and sustainable development is a serious motivation for seeking environmentally friendly construction materials. Also, a curious change of mentality occurred, since what was until recently a social embarrassment is now seen as a very modern material, capable of producing comfortable and visually impressive buildings. Rammed earth walls are relatively thick (0.5 to 0.9 m), and the dwellings are usually one or two stories high, in order to limit the compression stresses. That is because these walls have a reduced compressive strength when compared with other building materials, which currently causes serious limitations in terms of architectural and structural design.

One of the major techniques used to overcome the problems created by under-performing soils is the mixing with a cementitious binder. Usually these binders are cement and/or lime, which glue the soil particles together through chemical reactions. In the case of cement, the reactions are mainly hydraulic, while with lime they are pozzolanic. This means that cement needs only water to react and increase in strength; while lime needs water and a pozzolanic material, like soil. Both binders share the fact that their reactions with water depend largely on their specific surface. Moreover, although the type of reaction is different for lime and cement, the final product is very much alike, based on calcium and silicium compounds. In terms of mechanical strength, cement-based binders usually deliver significantly better results than lime-based binders.

Traditionally, the soils used for rammed earth construction have a distinctive clayey behaviour, since the cohesion plays an important role in the structural stability of the walls, and it also helps preventing disaggregation of the wall surface. Since the clay fraction is significant, the chemical improvement of these soils is very often made with lime, due to the very effective and permanent reactions between the calcium compound and the pozzolanic fraction. Also, although the compressive strength achieved is lower than with cement, it is usually enough for the purpose of current earth construction designs. However, soils from northern Portugal are mostly granitic, with a clay fraction composed mainly by kaolinite in quantities lower than 10% (Viana da Fonseca and Coutinho, 2008). Therefore, and since a clay fraction of at least 10% is needed for the soil to be stabilised with lime (Department of Transport, 1991; Greaves, 1996; Lindh, 2001), more appropriate binders need to be used. One obvious choice would be cement, however, environmental and durability concerns with cement production and application are increasing rapidly and can no longer be ignored. The environmental issues related with cement production was – together with strength and durability concerns – the main motivation to study the application of a geopolymeric binder (alkaline activation) for the improvement of residual granitic soil to be used in rammed earth construction. This technology – alkaline activation of fly ash – was already tested for soil improvement in geotechnical applications (Cristelo et al, 2012; Cristelo et al, 2011). The geopolymeric binder is usually obtained through alkaline activation of waste materials, and its application is rapidly increasing in the construction industry, not only as a technically sound construction material; but also as an important contribution for the reduction in cement consumption, since it allows its substitution in significant percentages, while at the same time uses an industrial by-product, namely fly ash.

In general terms, alkaline activation is a reaction between alumina-silicate materials and alkali or alkali earth substances, namely: $R\mathrm{OH}$, $R\mathrm{(OH)2}$, $R_2\mathrm{CO_3}$, $\mathrm{R_2S}$, $\mathrm{Na_2SO_4}$, $\mathrm{CaSO_4.2H_2O}$, $R_2\mathrm{.(n)SiO_2}$, in which R represents an alkaline ion like sodium ($\mathrm{Na^+}$) or potassium ($\mathrm{K^+}$), or an alkaline earth ion like calcium ($\mathrm{Ca^{2+}}$). It can be described as a polycondensation process, in which the silica ($\mathrm{SiO_2}$) and alumina ($\mathrm{AlO_4}$) tetrahedra interconnect and share the oxygen ions. The process starts when the high hydroxyl ($\mathrm{OH^-}$) concentration of the alkaline medium favours the breaking of the covalent bonds Si-O-Si, Al-O-Al and Al-O-Si from the vitreous phase of the raw material, transforming the silica and alumina ions in colloids and releasing them into the solution. The extent of dissolution depends upon the quantities and nature of the alumina and silica sources and the pH levels. In general, minerals with a higher extent of dissolution will result in higher compressive strength after the process is complete. At the same time, the alkaline cations $\mathrm{Na^+}$, $\mathrm{K^+}$ or $\mathrm{Ca^{2+}}$ 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. If calcium is present in the mixture in significant amounts the dissolved Al-Si complex will diffuse from the solid surface and produce a dominant C-S-H gel phase. Otherwise there is the poly-condensation of the dissolved gel with the Si and Al ions precipitating around the nuclei points, sharing all oxygen ions and forming a Si-O-Al and Si-O-Si three-dimensional structure (the formation of Al-O-Al is not favoured), more stable than those existing in the original aluminosilicate source. 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.

The aim of this paper is to determine, through a parametric analysis using laboratory tests, the optimum fly ash – based alkaline activated binder for the improvement of soil to be used in rammed earth construction. This evaluation was made in terms of mechanical strength of each mixture after specific curing periods. Different compositions were considered, with the following specific objectives:

- Effect of maximum particle size.
- Influence of hydrated lime, sodium chloride and concrete superplasticisers.
- Effect of binder composition.

2 - METHODOLOGY

2.1 - Materials

Laboratory tests were performed with granitic residual soil recovered near University of Minho, in Guimarães. It can be considered as representative of the typical soils from the north of Portugal. After being submitted to characterisation analysis according to BS 1377 Parts 1, 2 & 4, 1990: particle size distribution, Atterberg limits and compaction parameters using Proctor tests (Table I) – it was classified as '*SM – silty sand*' (ASTM D 2487-83, 1985). Additional characterisation included Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) to determine chemical composition.

Table 1: Soil properties

Plastic Limit (%)	-
Liquid Limit (%)	33.8
Optimum water content (%)	12.2
Maximum dry density (kN/m^3)	19.2
Clay content (%) [$\phi < 0.002$ mm]	5.7
Silt content (%) [$0.002 < \phi < 0.06$ mm]	14.0
Sand content (%) [$0.06 < \phi < 2$ mm]	45.6
Gravel content (%) [$2 < \phi < 20$ mm]	34.8
D_{10} (mm)	0.007
D_{30} (mm)	0.179
D_{60} (mm)	1.482
Cu	201.9
Cc	2.9

The fly ash used had low calcium content (class F) and was obtained from a Portuguese thermo-electric plant. Its characterisation was carried by scanning electron microscopy (SEM) and chemical analysis by energy dispersive spectroscopy (EDS) (Table 2). Its total mass available for dissolution is approximately 74% (Si and Al).

Table 2: Chemical composition of the fly ash (wt. %)

Si	Al	Fe	Ca	K	Ti	Mg	Others	L.O.I.[a]
49.85	23.55	9.09	7.37	3.07	1.91	1.62	3.54	2.59

[a] L.O.I. = Loss on ignition

The sodium silicate was originally in solution form, with a specific gravity of 1.45 g/cm^3, a sodium oxide (Na_2O) content of 13% and a SiO_2 : Na_2O ratio of approximately 2 : 1 by mass. The sodium hydroxide was originally supplied in flake form with a specific gravity of 2.13 g/cm^3 at 20ºC and 95-99 % purity, and was dissolved in water to achieve different concentrations of 10, 12.5 and 15 molal before being mixed with the silicate in a sodium silicate : sodium hydroxide ratio of 2 : 1. This ratio was previously studied by different authors (Villa et al, 2010; Criado et al, 2007; Hardjito and Rangan, 2005), who concluded that a value of 2 favours the strength gain.

The sodium chloride (NaCl) and the calcitic hydrated lime ($Ca(OH)_2$) were both 99% pure. Regarding the water-reducing admixture, Rheobuild 1000 from BASF was used.

2.2 - Sample preparation and testing procedure

The parametric analysis to evaluate the effectiveness of each composition was based on unconfined compressive strength (UCS) tests, performed after a pre-determined curing period under specific conditions. UCS samples were cylindrical, with 38mm in diameter and 76mm height, and one result was the average of three tests.

The soil was oven dried and sieve down before being thoroughly mixed with the fly ash and only then the activator was added and mixed. A kitchen appliance was used for mixing, and every mixture batch was just enough to form the three samples necessary to produce one result, in order to avoid excessive delays between mixture preparation and moulding. This propeller type mixer achieves its purpose due to axial and turbulent flow, and is suitable for suspensions with viscosities up to 20 Pa.s (Larsson, 2004). After mixing for 3 minutes and cast into the moulds in three layers, the samples were vibrated by tapping the mould continuously for 25-30 seconds for each layer, in order to release the trapped air bubbles Terashi and Kitazume, 2011).

Finally, the moulds were covered with a Plexiglas cap and stored in an oven at 60ºC for twelve hours. After this the samples were removed from the moulds and stored back in the oven (again at 60ºC) in a sealed bag up until two hours before trimming and testing. The curing periods considered were 1, 3 and 7 days. Curing at high temperatures allowed a significant reduction in the necessary period for significant reactions between the activator and the fly ash to occur (Villa et al, 2010). The value of 60ºC was chosen since it has been reported (Winnefeld et al, 2010) that curing geopolymers at temperatures higher than 80ºC can be detrimental to its properties. Also, it is inside the interval reported by Bondar et al (2011) as optimum for curing alkali-activated natural pozzolans.

Specific tests to optimise sample preparation showed that a circular saw can easily cut through this material without any damage to its structure, and was therefore used to trim the samples to an approximate length while also creating perfect horizontal plans for the contact with the compression machine plates. A low testing speed (0.30 mm/min) was used to mitigate any influence of this parameter on the test result.

3 - RESULTS AND DISCUSSION

3.1 - Effect of maximum particle size

Full details of all the mixtures tested are shown in Table 3. A set of UCS tests was performed to evaluate the most suited maximum particle size. According to the New Zealand Standards (NZS 4298:1998), the soil used in earth construction needs to be sieved down if a significant amount of large aggregate particles are present in its composition. Therefore, the question of which would be the most effective maximum particle size was raised. Two different sieves were used: 4.75 and 6.30 mm. The soils resulting from the sieving process are shown in Figure 1.

Table 3: Identification and composition of the mixtures tested

Label	Fly ash / soil (%)	Activator / solids ratio	NaOH concent (molal)	Additives (%)
SG4.75	25/75	0.375	12.5	0
SG6.30	25/75	0.375	12.5	0
SGNaCl	23 / 75	0.375	12.5	NaCl (2)
SGCa(OH)$_2$	15 / 75	0.375	12.5	CaO (10)
SGCSP	23.5 / 75	0.350	12.5	CSP (1.5)
SG1A	25 / 75	0.400	12.5	0
SG1B	25 / 75	0.350	12.5	0
SG2A	25 / 75	0.375	10.0	0
SG2B	25 / 75	0.375	15.0	0
SG3A	20 / 80	0.375	12.5	0
SG3B	30 / 70	0.375	12.5	0

Samples with a maximum particle size of 4.75 mm have a more uniform distribution than that with 6.30 mm, meaning that the soil is less graduated, which can usually be related to a lower mechanical strength. However, UCS results from Figure 2 show that it is beneficial, in terms of strength gain, to use a finer soil fraction. This can be concluded after the 4.75 mm mixtures produced better UCS values than the 6.30 mm. It should be noted that these results might be influenced by the size of the sample, meaning that in a bigger volume, like a rammed earth wall, the inclusion of the particles between 4.75 and 6.30 mm, or even bigger, might have a positive effect on compressive strength.

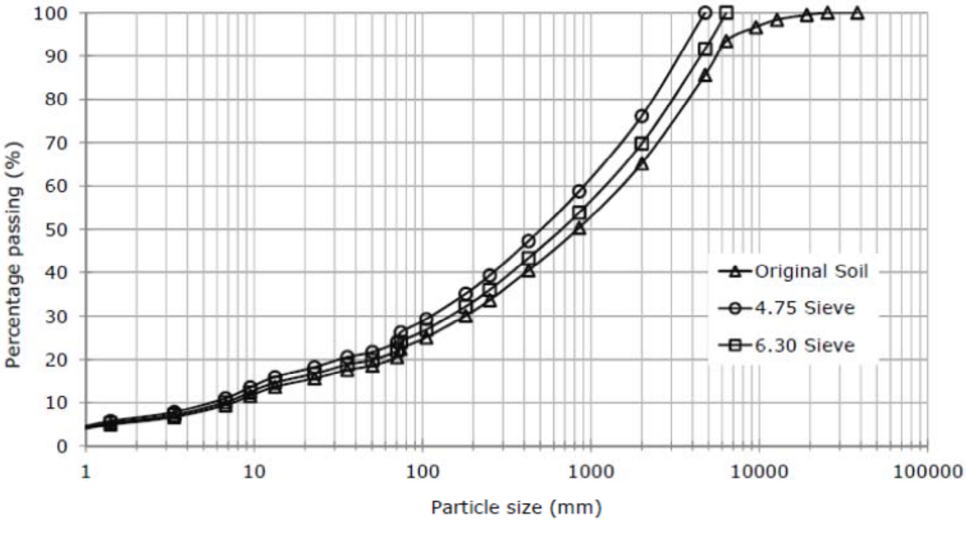

Figure 1: Particle size distribution of samples sieved down to 4.75 and 6.30 mm

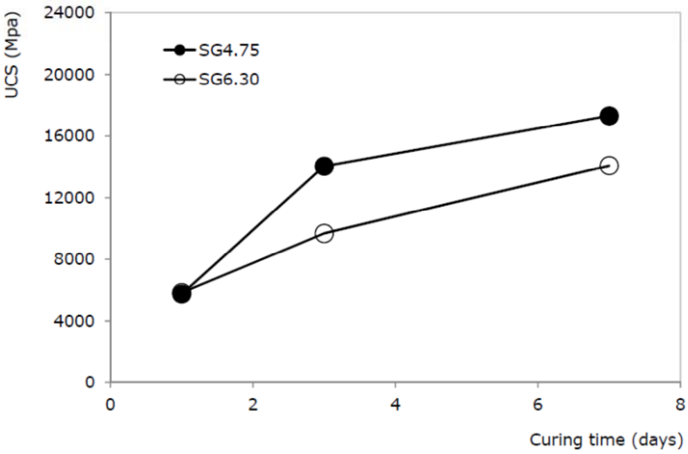

Figure 2: UCS results of alkaline activation mixtures SG4.75 and SG6.30

3.2 - Influence of CaO, NaCl and superplasticiser on strenght gain

After setting the best option in terms of maximum particle size, a second set of tests was carried out with the purpose of evaluating the influence of calcium hydroxide ($Ca(OH)_2$), sodium chloride (NaCl) and a common concrete superplasticiser (CSP).

Calcium silicate hydrate (CSH) is known to be the major component regarding the binding properties of Portland cement, while alkaline activation of low calcium raw materials – like fly ash type F – produces binders resulting from aluminosilicate structures. However, Yip et al (2005) found that it is possible to have geopolymeric and CSH gels forming simultaneously within the same binder. In high concentrations of NaOH (> 7.5 molal), the geopolymeric gel is predominant, with small calcium precipitates scattered across the mixture. The effect of these precipitates – namely an initial strength improvement relatively to the mixture without calcium – is not observed unless a significant source of calcium hydroxide is available at the initial phase. Hu et al (2009) concluded that adding calcium to the activator accelerates the synthesis of the fly ash-based geopolymers. In the present work, and with the objective of evaluating the effect of additional calcium on strength gain rate, samples with a lime content of 40% of the fly ash – or 10% of the total solids content – were prepared. Higher values could favour the formation of a CSH gel based matrix instead of an aluminosilicate network with CSH gel as a secondary reaction product (Alonso and Palomo, 2001).

Several authors (Sing et al, 2011; Davoudi and Kabir, 2011; Cristelo et al, 2009) have previously reported the enhancement of soil – lime stabilisation with sodium chloride (NaCl). Although no information could be found on the effect of such additive on alkaline activation, and the exact chemical reactions that might occur in this case are not fully understood, it was decided to test its effect on the strength gain rate of the mixtures. Specific mixtures were prepared in which 8% of the fly ash mass (2% of the total solids mass) was substituted by NaCl. The optimal NaCl percentage in soil–lime stabilisation is usually between 1 and 2% of the soil mass. Higher values increase the Na^+ ions in the solution which in turn increase the double layer around the soil particles.

Previous research (personal communication) concluded that the reduction in Na2O : ash ratio is beneficial for the strength gain process. Therefore, a superplasticiser was used in some mixtures to try to reduce the liquid phase necessary for mixture homogenisation. The capacity of these additives to lower the water demand might compensate some strength reduction, previously reported by Kong & Sanjayan (2010). Some samples were prepared with the ash partially substituted by a commercial superplasticiser. Hardjito & Rangan (2005) concluded that the use of superplasticiser beyond 2% of the fly ash mass will likely cause deterioration in compressive strengths. Sathonsaowaphak et al (2009) also reported a decrease in strength but only for superplasticiser contents higher than 6% of the fly ash. A value of 6% was therefore used in this study. Based on previous experience, the reduction in the liquid : solids ratio due to the CSP, relatively to the remaining mixtures, was approximately 7%. During sample preparation, and based on the homogenisation level of the mixtures, it was discover that this reduction could have been more pronounced, and therefore optimisation of this ratio will be carefully addressed in a future study.

Results from Figure 3, comparing strength gain of the mixtures with quicklime, salt and superplasticiser, show that mixtures $SGCa(OH)_2$ presented a significant short term improvement, but technically no further improvement could be observed after one day curing. This behaviour is common in calcium-based systems. Winnefield et al (2010), when studying the compressive strength behaviour of high and low calcium fly ash, reported a similar behaviour for both types of ash analysed, i.e. short-term improvement (at two days curing) followed by no improvement over the next 28 days. However, the curing temperature used was 80ºC, which might explain why the UCS of the low calcium fly ash geopolymers – although improving significantly more than the high calcium geopolymers after two days – did not improve beyond that period. The higher curing period probably accelerated the reactions to such an extent that the observed behaviour during the present study also occurred in the research by Winnefield et al (2010), but it all happened in the first two days of curing.

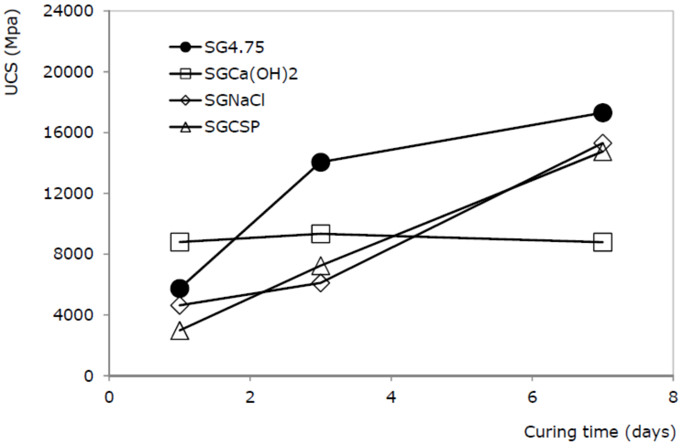

Figure 3: UCS results of alkaline activation mixtures with NaCl, CaO and CSP additives

Using the values obtained with the mixtures SG4.75 as a reference, NaCl and CSP additives had, in general, a negative effect on mechanical strength (Figure 3). The effect of these additives was significantly different from that obtained with the $Ca(OH)_2$, since they showed a lower short term improvement but a very significant strength gain at 7 days curing when compared with the $SGCa(OH)_2$ mixtures. Relatively to the SG4.75 results, the NaCL mixtures showed significantly lower UCS values than SG4.75 at 1 and 3 days curing, and closer values at 7 days. Therefore, the sodium chloride did not perform the role of catalyser that was observed previously in soil stabilisation with lime also using sodium chloride (Sing et al, 2011; Davoudi and Kabir, 2011; Cristelo et al, 2009). The reduction in the liquid : solid ratio – relatively to the SG4.75 mixtures – achieved with the CSP did not correspond to an increase in performance, since UCS for every curing period was higher for the specimens without the CSP. It could be that a potential increase in strength, by decreasing the Na2O : ash ratio when adding the CSP, was eliminated by a reaction between the activator and the CSP that reduced the effectiveness of the Na2O (Kong & Sanjayan, 2010). Further tests are necessary to analyse any potential interaction between the sodium and the superplasticiser.

3.3 - Effect of binder composition

Table 3 shows the composition of the SG1, SG2 and SG3 mixtures, which were prepared to understand the influence on unconfined compressive strength (UCS) of the activator / solids ratio, the activator concentration and the ash percentage, respectively.

Regarding SG1 (Figure 4), results seem to indicate that the optimum value for the activator (liquid) / solids ratio was 0.375 (SG4.75). This result is somehow unexpected, since previous results (personal communication) showed an increase in strength with a decrease of the referred ratio. SG2 results (Figure 5) show that up to 3 days curing there is not a significant difference between the concentrations tested. However, it is clear that 10 molal concentration (SG2A) did not performed as well as the remaining two mixtures after 7 days curing. Similar results between 12.5 and 15 molal indicate that an optimum concentration might be found in this interval. Further tests are being planned to analyse this behaviour more accurately (including lower than 10 molal mixtures), since a concentration higher than necessary implies an increase in activator cost. SG3 mixtures showed a significant improvement in performance with an increase in ash content. Results for the 30% fly ash at 7 days curing are the highest obtained during these tests. It is important to notice that the mentioned increase in fly ash content did not imply an increase in activator, which would have a much more significant impact on final cost. Also, this increase is also responsible for a decrease of the activator / ash ratio, and therefore further tests are being planned to address the influence of this specific ratio on UCS.

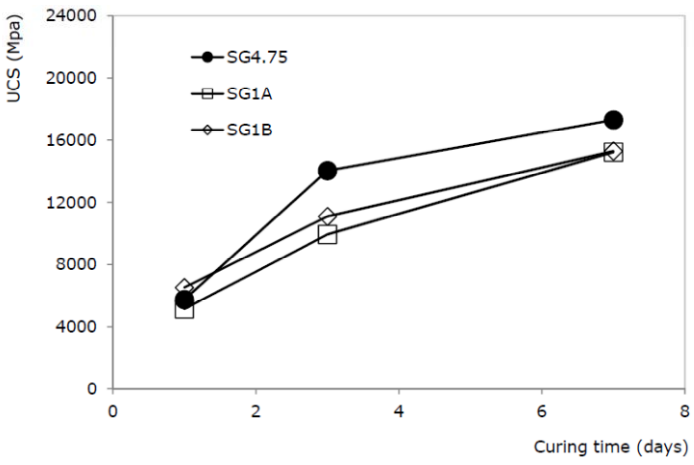

Figure 4: Effect of activator / solids ratio on UCS

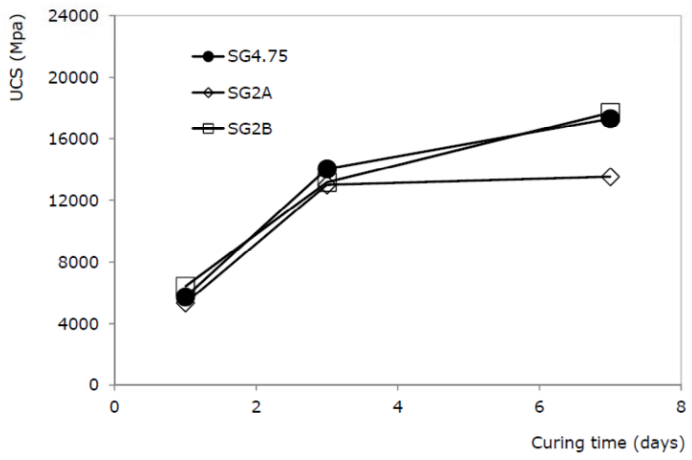

Figure 5: Effect of activator concentration on UCS

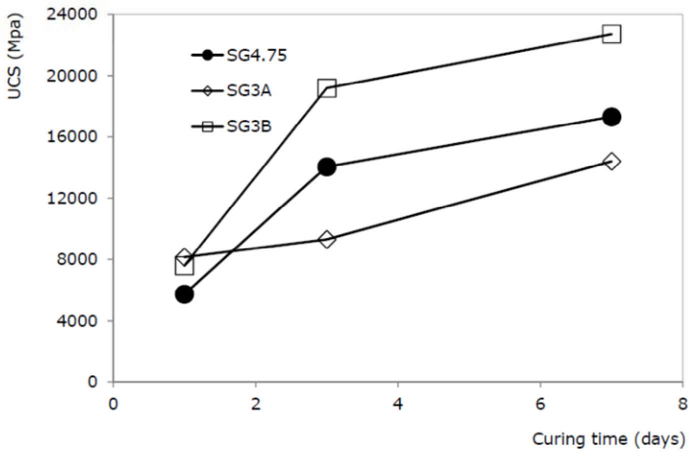

Figure 6: Effect of ash content on UCS

3.4 - SEM / EDS analysis

The different mechanical behaviour evidenced by the mixtures tested is strongly related with the microstructure of the binding agent. Figures 7 and 8 represent a set of SEM images showing the morphology of the most relevant mixtures in terms of composition and reaction evolution. This morphology analysis is useful to understand the reactions that occur during the strength gain process.

SEM images of mixtures SG4.75 at 1, 3 and 7 days curing are shown in Figure 7 (7a through 7d). From this set it is clear the evolution from compact or hollowed spheres of different size – but with regular and smooth surfaces – to a system in which the amorphous aluminosilicate gel (Fernández-Jiménez and Palomo, 2005) is predominant. As this gel develops, it increases the strength of the mixture by not only acting as a bonding agent but also by filling the pore space. Comparing Figures 7a, 7b and 7d it is clear the reduction in pore volume. A similar reduction in void space was also reported in Horpibulsuk et al (2010), when studying the microstructure development of cement-stabilised clay. In all images are visible the spaces previously occupied by round fly ash particles, which were tear when the samples were created. Although unreacted spherical particles are still visible after 7 days curing, they seem to be hollow after being partially dissolved during the reaction process (Point 1 in Figure 7d). The described evolution represents the progressive dissolution of the raw fly ash by the activator. Figure 8c shows deposits of small sodium crystals (Area A) that did not yet react with the SiO_2.

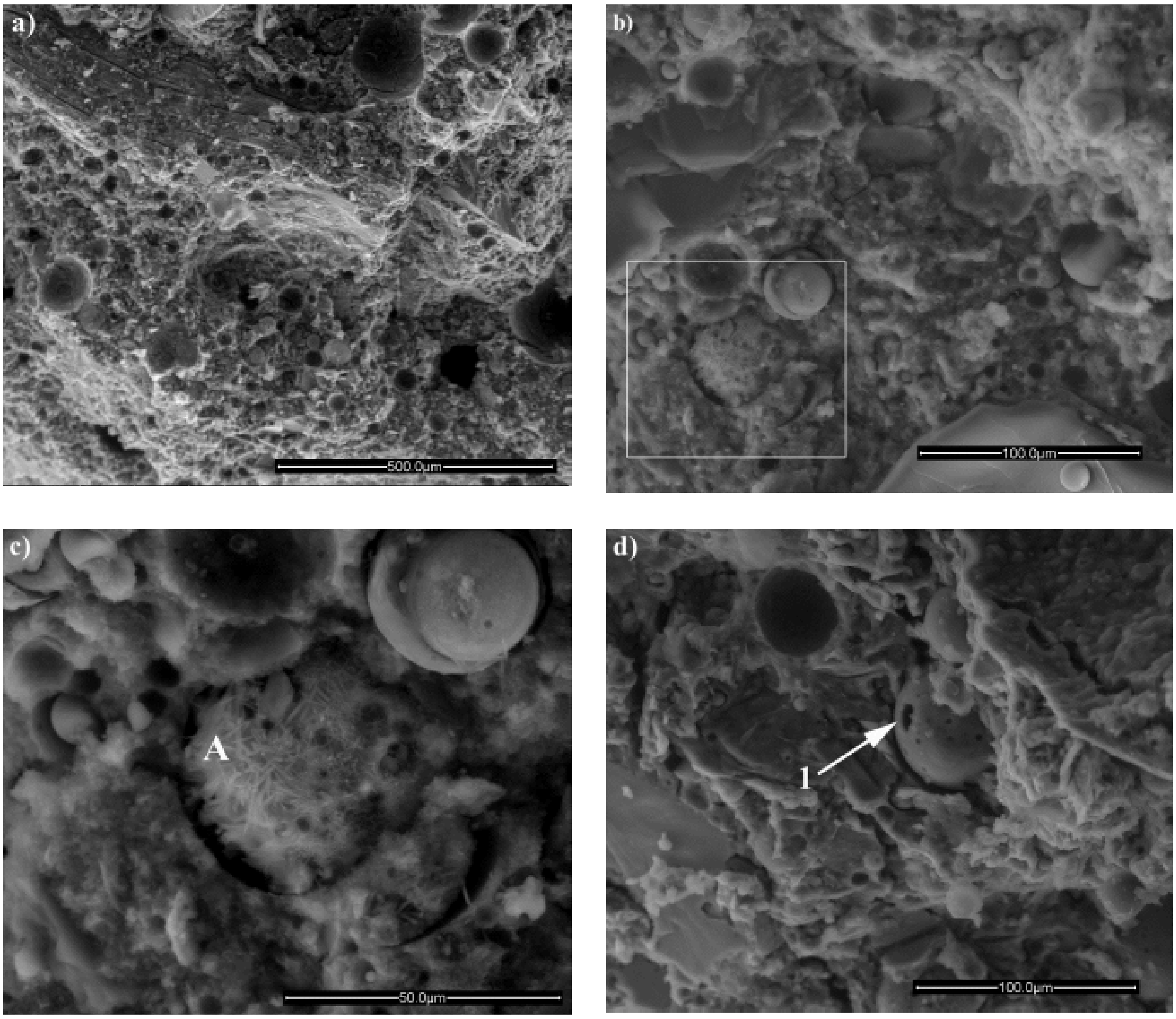

Figure 7: SEM images of mixture SG4.75 after 1 (7a), 3 (7b and 7c) and 7 (7d) days curing

Images in Figure 8 show the microstructure of mixtures SGNaCl (a) and SGCSP (b), after 7 days curing. In both cases aluminosilicate gel can be seen surrounding original soil particles (Area B), but ash spheres with just a few small dissolution surface points indicate that a significant reaction did not occur, which might explain the lower strength levels achieved by these mixtures regarding the reference SG4.75 mixture. These results confirm that the sodium chloride and the superplasticiser did not have the expected effect of accelerating and improving strength gain.

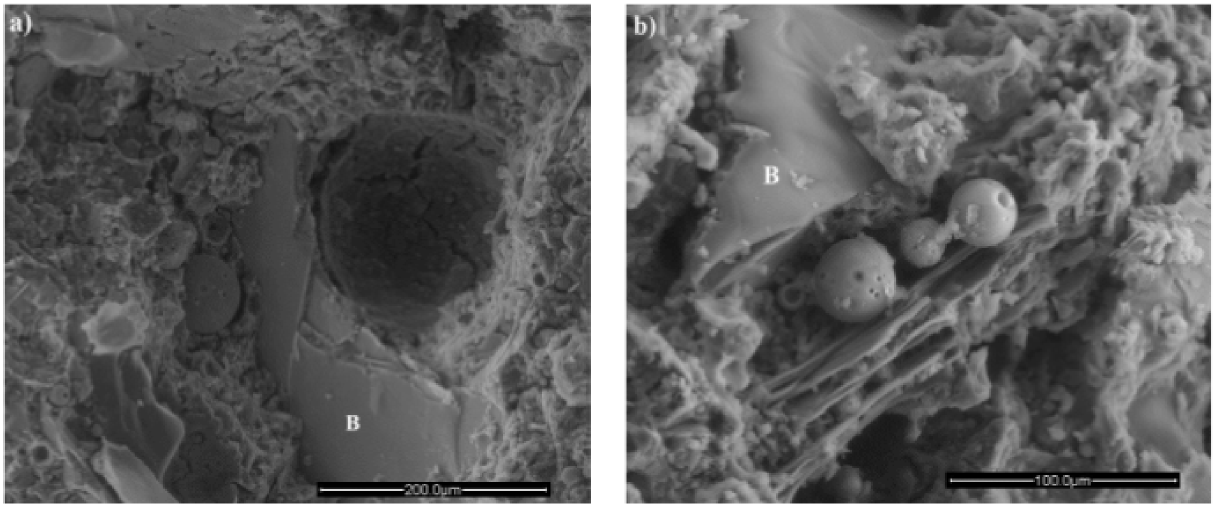

Figure 8: SEM images of mixture SGNaCl (8a) and SGCAP (8b) after 7 days curing

EDS analysis of the mentioned areas is presented in Table 4. The Si : Al ratio, also presented in Table 4, decreased with curing period for the mixture SG4.75. This was expected since the aluminium is continuously released into the aluminosilicate gel matrix with the fly ash dissolution (Winnefeld et al, 2010). The Na : Si ratio also decreased with curing time (SG4.75), reflecting an increase of the alkalis intake in the reaction products. Also significant is the narrow interval for the Na : Al ratio, showing the high dependency between the alkali and the aluminium, which is explained by the role of the Na^+ ions on the alkaline activation reaction, compensating the excess negative charges resulting from the progressive changes in the aluminium : oxygen coordination.

Table 4: EDS analysis of the mixtures from Figures 8 through 10

Label	Curing	Na wt %	Al wt %	Si wt %	K wt %	Ca wt %	Fe wt %	Si:Al	Na : Si	Na:Al
SG4.75	1 d	21.7	24.7	41.5	2.4	1.8	5.3	1.68	0.52	0.88
SG4.75	3 d	18.4	21.5	42.7	3.1	2.6	8.7	1.99	0.43	0.86
SG4.75	7 d	15.6	15.4	55.2	3.8	1.7	5.2	3.58	0.28	1.01
SGNaCl	7 d	19.1	18.7	37.1	3.6	2.0	11.7	1.98	0.51	1.02
SGCSP	7 d	19.4	18.4	48.0	2.3	2.3	5.8	2.61	0.40	1.05
SG1A	7 d	18.3	22.4	42.9	2.8	2.6	7.6	1.92	0.43	0.82
SG3C	7 d	15.4	14.5	57.6	2.9	1.6	5.2	3.97	0.27	1.06

4 - CONCLUSIONS

This study clarified some issues regarding the application of alkaline activation of fly ash to soil stabilisation. This technique, not yet fully understood and developed, poses additional complications when used with soil, since the soil brings another set of intrinsic relations and delicate compromises. However, it is possible, based on the research here presented, to detect some influencing factors. Activator concentration is clearly an important factor to consider, especially since a compromise with the activator:solids ratio needs to be achieved and the necessary workability of the mixture strongly depends on the total water content. The maximum particle size of the soil should be minimised prior to mixing with the ash, although some further analysis is necessary to conclude if that is a general rule for every type of soil and if it has a minimum optimum value. Finally, the additives used did not seem to justify the time, trouble and money, since the strength results obtained were always inferior to those achieved without any additive. However, if time is an issue, the use of hydrated calcium might be a solution, although in that case maximum strength will be compromised.

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