Procedia Engineering
Volume 143, 2016, Pages 187–195
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Silty Sand Stabilized with Different Binders

Sara Rios[1*], António Viana da Fonseca[1], Srikanth Sagar Bangaru[1]
[1] *CONSTRUCT-GEO, Faculty of Engineering (FEUP), University of Porto, Porto, Portugal*
sara.rios@fe.up.pt; viana@fe.up.p; srikanthsagar.bangaru@okstate.edu

Abstract
The paper presents results of unconfined compression strength and seismic wave measurements during curing on a silty sand stabilized with three type of binders: geopolymers, lime and a mixture of lime and fly ash. Unconfined compression tests and indirect tensile tests were performed after 63 days of curing, and seismic wave measurements with ultrasonic transducers were measured during the curing period. The tests results show that specimens stabilized with geopolymer give much higher strength and stiffness results than the other binders. The specimens prepared with soil-lime-fly ash mixtures show a just slight increase in strength comparing to soil-lime specimens, conversely to what has been reported by other authors.

Keywords: Geopolymer; fly ash; lime; seismic wave velocities; unconfined compression strength

1 Introduction

Artificially cemented soils have been used as very convenient materials for transportation infrastructures, such as subgrades in roads or railways (Viana da Fonseca A. , Rios, Amaral, & Panico, 2013) (Viana da Fonseca, Amaral, Panico, & Rios, 2014). One of the major advantages is that in situ soils can be used, avoiding economic and environmental costs related with collection, transport and disposal. In general, ordinary Portland cement is used although its production is responsible for releasing a significant amount of carbon dioxide to the atmosphere. The total CO_2 production derived from the cement industry is estimated to represent between 5 to 8% of the global carbon dioxide emissions (Scrivener & Kirkpatrick, 2008). This has led to the development of new binders such as geopolymers made by the alkaline activation of fly ash. On the other hand, some authors (Narendra, Sivapullaiah, & Ramesh, 2003) (Consoli, Dalla-Rosa, & Saldanha, Variables Governing Strength of Compacted Soil-Fly Ash-Lime Mixtures, 2011) (Consoli, Dalla-Rosa, & Saldanha, 2011) have shown that adding a mixture of low calcium fly ash and lime to the soil provides much high strength improvement than using

[*] Corresponding author. Tel.: +351 22 508 1728; fax: +351 22 508 1891.
E-mail address: sara.rios@fe.up.pt

Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.024

lime alone. This is very interesting because the production of lime also generates carbon emissions and therefore, the possibility to reduce the lime content while increasing strength is much more sustainable.

2 Background

Geopolymers as described by (Davidovits, 1991) result from the reaction between aluminosilicate materials (like fly ash) and alkaline solutions such as sodium or potassium silicates and hydroxides. To improve the conditions for the alkaline activation, the original raw material source of the aluminosilicate material should be subjected to a preliminary thermal treatment that transforms its structure from crystalline to amorphous creating an environment where chemical combinations are easier. For that reason, raw materials with a natural or artificial thermal history, such as fly ash, blast-furnace slag, Portland cement residues, pozzolanic wastes, or metakaolin, are more suitable for alkaline activation than noncalcined materials (e.g., clay or feldspars). The conceptual model used to describe the reaction mechanism can be summarized in the following sequence: dissolution, precipitation/gelation, and crystallization/hardening (Duxson, et al., 2007). In the precipitation/gelation stage, also named as polymerization, the smaller molecules agglutinate to form larger molecules that precipitate in the form of short-range ordered aluminosilicate gel, a three-dimensional structure where Si occurs in a variety of environments. This three-dimensional network continues to grow and the gel evolves from an Al structure to a Si structure while the mechanical strength notably increases. The application of geopolymers for soil improvement start from the same hypothesis used for Portland cement, that is, the soil does not participate in the chemical reaction, but the created binder bonds the soil particles.

These geopolymeric reactions made by low calcium fly ash are quite different from the pozolanic reactions that support the hardening of soil-lime mixtures. In lime mixtures the soil takes part in those reactions and therefore the type of soil has a major influence on the treatment success. Clayey soils are often treated with lime, since cation exchange and flocculation reduces their water content and plasticity index. Clay is also better for the pozzolannic reaction because it provides silica and alumina ions for the formation of calcium hydrate aluminosilicates similar to the products generated by the curing process of Portland cement.

3 Experimental Program

3.1 Materials

The soil involved in this research program is classified as silty sand according to the Unified Classification System (ASTM, D 2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), 2000). It results from the weathering of Porto granite, a rather abundant rock in the north and central regions of Portugal. The particle size distribution plotted in Figure 1 shows evidence of a very well graded soil containing about 30% fines from which only 8% is clay (mainly kaolinite). The Atterberg limits gave values of w_L =34% and w_P =31% thus IP=3, which makes this soil non plastic. The specific gravity of the solids was determined as 2.72. The effective diameter, D_{50}, is 0.25 mm, with uniformity and curvature coefficients of 113 and 2.7 respectively (Viana da Fonseca, Rios, & Amaral, Structural Anisotropy by static compaction, 2013).

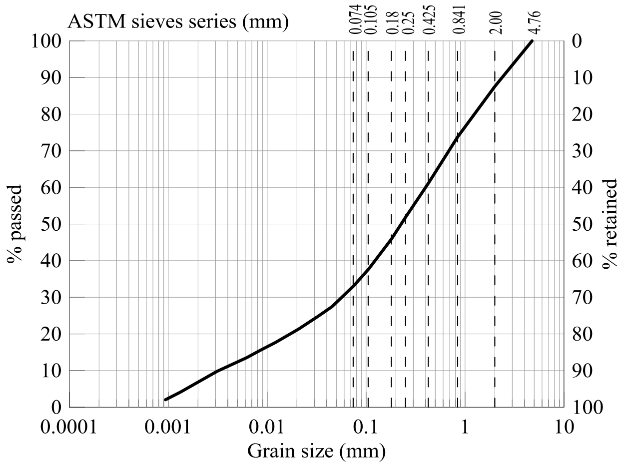

Figure 1 Grain size distribution of the soil known as Porto silty sand

Type F fly ash (FA) according to (ASTM, C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, 2012)was obtained from a coal thermoelectric power plant in central Portugal. A chemical analysis has shown that FA is mainly 54.84% SiO_2; 19.46% Al_2O_3; 10.73% Fe_2O_3; 4.68% CaO; 4.26% K_2O; 1.40% TiO_2; 1.79% MgO and 1.65% Na_2O. The loss on ignition value was not specifically determined for the present fly ash, but it should be around 2.59, according to (Cristelo, Glendinning, Miranda, Oliveira, & Silva, 2012), that has worked with a fly ash from the same thermoelectric power plant. A percentage of 10% of fly ash calculated from the amount of dry soil was considered.

Dry hydrated lime [$Ca(OH)_2$] was also used, for which the specific gravity of lime grains was assumed 2.49 (Consoli, Dalla-Rosa, & Saldanha, Variables Governing Strength of Compacted Soil-Fly Ash-Lime Mixtures, 2011) (Consoli, Dalla-Rosa, & Saldanha, 2011). Considering the results of the ICL method (Rogers, Glendinning, & Roff, 1997) obtained by (Consoli, Dalla-Rosa, & Saldanha, 2011) (Consoli, Dalla-Rosa, & Saldanha, 2011) with similar soil and FA percentages, a percentage of 3% of lime calculated from the amount of soil and fly ah was considered.

The alkaline solution for geopolymers comprises sodium hydroxide and sodium silicate. Sodium hydroxide in flake form with a specific gravity of 2.13 at 20ºC and 95-99% purity was dissolved in water up to the desired concentration of 7.5 molal. The sodium silicate was already in solution form with a specific gravity of 1.5 and SiO_2/Na_2O ratio of 2 by mass. Equal parts of sodium hydroxide and sodium silicate are used (SS/SH=1).

Five different mixtures were prepared as expressed in Table 1. For each mixture, three specimens were moulded in order to have representative results.

Mixture name	Soil (%)	FA (% of dry soil)	Lime (% of dry soil+FA)	Alkaline solution (Yes or No)
Soil	100	0	0	No
AA_FA10	90	10	0	Yes
L3	97	0	3	No
L3_FA10	87	10	3	No
L3_FA20	77	20	3	No

Table 1 Mixture properties

3.2 Specimen Preparation and Procedures

The specimens were moulded on the optimum point of the Modified Proctor test performed on this soil with 10% of fly ash (Figure 2). The procedure for the preparation of test specimens started by mixing the dry soil and fly ash (and/or lime) until complete homogenization using an automatic mixer for 5 min (speed 3) joining afterwards the alkaline activator (or water) with additional 5 min mixing at speed 3 according to (ASTM, D 3551 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, 2008). The mixture is statically compacted in three layers in a lubricated mould of 70 mm of diameter and 140 mm of height according to (ASTM, D 1632 Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory, 2007). After being extracted from the mould the specimen was placed in a temperature controlled room (20ºC) for curing. For the specimens with geopolymers (AA_FA10), the preparation of the alkaline activator needs to be done by steps. The mixture of solid sodium hydroxide with water was prepared in the previous day (or at least 3 hours before) to allow sufficient time to cool. During this period the solution was left inside a closet to avoid air currents. After this period, this solution was mixed with the sodium silicate solution immediately before the moulding stage.

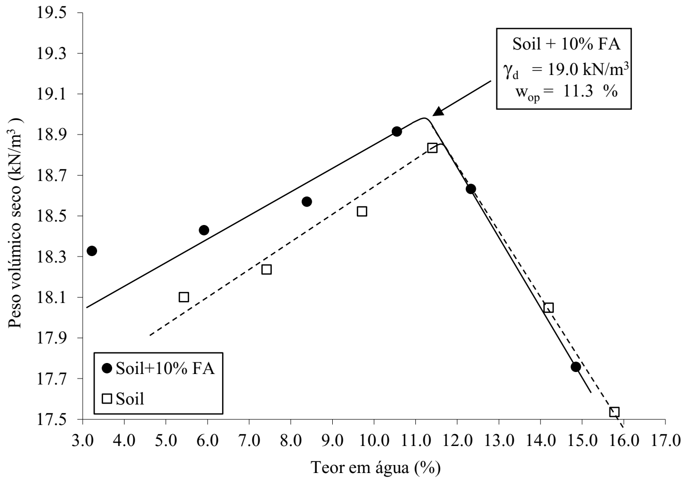

Figure 2 Modified Proctor test of the soil and soil-ash mixture

The experimental program comprises unconfined compression tests (based on EN 13286-41 – (CEN, EN 13286-41 Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures, 2003) and indirect tensile tests (based on EN 13286-42 – (CEN, EN 13286-42 Unbound and hydraulically bound mixtures - Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures, 2003) after 63 days of curing and seismic wave measurements with ultrasonic transducers during the curing period (7, 14, 21, 28, 35, 42, 49, 56 and 63 days). UCS and indirect tensile tests were performed in a loading machine equipped with a load cell of 25 kN of capacity at 0.1 mm/min. Compression and shear waves were measured by means of P and S wave ultrasonic transducers as described by (Amaral, Viana da Fonseca, & Rios, 2013). These transducers were linked to a signal generation and data acquisition Pundit lab unit from Proceq connected to a laptop computer for display and data storage. To improve coupling between the transducer and the specimen, contact gel for ultrasound testing was used which highly improves the signal quality without damaging the specimen. In fact, one of the main advantages of these transducers is the easiness of application avoiding holes in the specimen which could prevent the subsequent wave analysis or the unconfined compression tests performed at the end of curing periods.

Several fixed frequencies were used ranging from 24 to 500 kHz. Depending on the specimen stiffness, some frequencies led to clearer signals than others, but the propagation time was not sensitive to frequency, i.e, it was mostly constant with it.

4 Results and Discussion

4.1 Compression and Tensile Strength

Figure 3 presents the unconfined compression strength (UCS) of the soil and its mixtures with lime. As reported by several authors (Little, 1995) (Bell, 1996) (Consoli, et al., 2012), the addition of a small lime percentage (3%) was enough to increase six times the soil strength, even a coarser soil like this silty sand. Moreover, the introduction of fly ash to the soil-ash mixture contributed to a higher increase in strength than the obtained in the mixture of soil with lime only. This was more significant when the fly ash percentage was increased from 10% to 20%. However, in the results obtained by (Consoli, Dalla-Rosa, & Saldanha, Variables Governing Strength of Compacted Soil-Fly Ash-Lime Mixtures, 2011) (Consoli, Dalla-Rosa, & Saldanha, 2011) the improvement was much more significant since strength increased 12 times when 12.5% of fly ash was added to a mixture of soil and 3% of lime, and increased 25 times when 25% of fly ash were added. The soil used in the work reported by (Consoli, Dalla-Rosa, & Saldanha, Variables Governing Strength of Compacted Soil-Fly Ash-Lime Mixtures, 2011) (Consoli, Dalla-Rosa, & Saldanha, 2011) was also a silty sand, but the specimens were placed in water before the tests to minimize suction conversely to the work reported in this paper where the specimens were tested at their moulding water content.

The tensile strength obtained in L3 and L3_FA10 mixtures was found to be 6% of their corresponding unconfined compression strength.

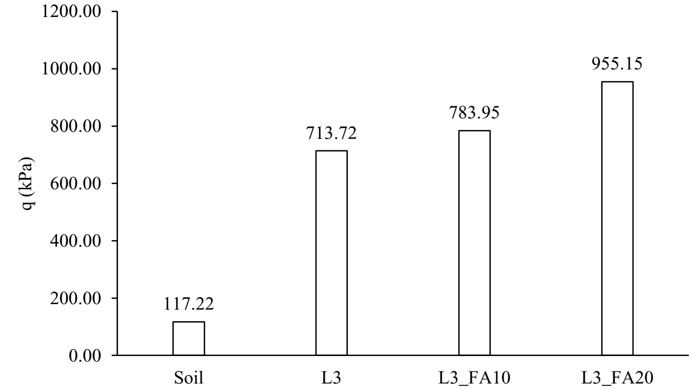

Figure 3 Unconfined compression strength of the soil, and its mixtures with lime (L3), and lime-fly ash (L3_FA10 and L3_FA20)

These results were compared to the unconfined compression strength obtained in the soil improved with the geopolymer (AA_FA10). This specimen prepared as described before and tested in the same conditions of the others obtained 7783 kPa, which represents an increase of 66 times the soil strength, 11 times the L3 strength, 10 times the L3_FA_10 strength, and 8 times the L3_FA20 strength. For this reason it was not included in Figure 3 to avoid the use of different scales. According to (Bignozzi, Manzi, Natali, Rickard, & van Riessen, 2014) who has reported strength values for mixtures of sand and geopolymers (although for a different application such as mortars), the strength of the soil improved with geopolymer could be even greater if for example, higher fly ash percentages and/or higher NaOH concentrations were used.

The results of the indirect tensile strength (ITS) for this mixture (AA_FA10) represented 9% of the unconfined compression strength obtained.

Since three specimens were moulded for each test condition (5 types of specimens in UCS or ITS) the results presented here are the average of the three equal tests.

4.2 Dynamic Stiffness Evolution with Curing

The purpose of having seismic wave measurements during the curing period of the specimens was to obtain the evolution of the elastic Young modulus with time. The interpretation of the wave signals was performed by a time domain analysis as expressed by (Viana da Fonseca, Ferreira, & Fahey, A Framework Interpreting Bender Element Tests,combining time-domain and frequency domain methods, 2009), in order to obtain the propagation time of S and P waves, t_S and t_P respectively. From these, the S and P wave velocities (V_S and V_P) were calculated dividing the travel distance, which corresponds to the height of the specimen, by the corresponding time. From the theory of elasticity, is it well known that compression (V_P) and shear (V_S) wave velocities are related to the confined (M_0) and shear (G_0) moduli, respectively, according to Equations (1) and (2),

$$\boldsymbol{M_0 = \rho V_P^2} \quad (1)$$

$$\boldsymbol{G_0 = \rho V_S^2} \quad (2)$$

Where ρ is the bulk density of the material.
Equation (3) provides the Poisson's ratio value (ν), from which the dynamic Young's modulus (E_0) can be derived, using Equation (4).

$$\boldsymbol{\nu = \frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{2\left(\frac{V_P}{V_S}\right)^2 - 2}} \quad (3)$$

$$\boldsymbol{E_0 = 2G_0\,(1 + \nu)} \quad (4)$$

The results of the Young modulus values express the same differences presented before for strength with high stiffness modulus in AA_FA10 mixture and much smaller values on the others lime, and lime-fly ash mixtures.

Figure 4 shows the results obtained in the soil treated with geopolymer, representing the six specimens moulded for this mixture (3 for ITS and 3 for UCS). The results are very consistent, since only one specimen showed smaller values during some time of the curing period but then recovering back to the trend. A value of 1000 MPa of E_0 was obtained at 7 days of curing which doubled after 42 days, indicating that the stiffness increase with time follows a power law. Moreover, it is clear that the stiffness does not give signs of stabilisation for the considered period up to 63 days. It is possible that the same could be happening in strength, which constitutes a major difference between this mixture and the soil-cement mixtures that stabilise at 28 days.

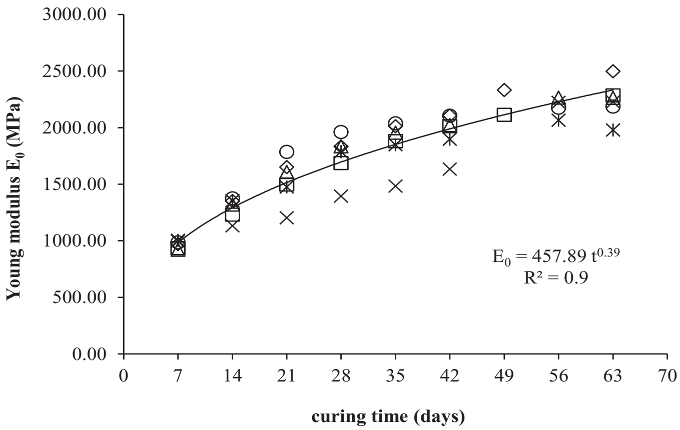

Figure 4 Young modulus evolution with curing time of the soil treated with geopolymers (AA_FA10)

Figure 5 presents the results of the elastic stiffness evolution with time for a representative specimen of each of the other mixtures (soil with lime, and soil-lime-fly ash). It is clear from the figure that none of them seems to evolve much during curing at least in terms of the elastic stiffness. It is possible that these mixtures may take longer to cure but still it was expected that some evolution could be observed during 63 days.

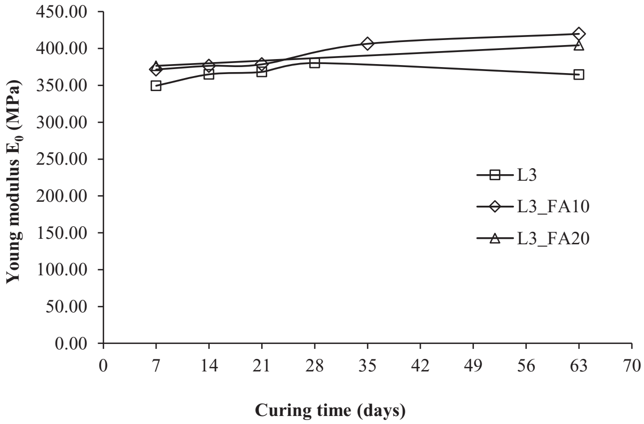

Figure 5 Young modulus evolution with curing time of the soil treated with lime and lime-fly ash mixtures

5 Conclusions

The paper presents a comparison between three types of binders: geopolymer, lime, and lime mixed with low calcium fly ash, to explore the distinct possibilities of using a waste by product like fly ash in the soil improvement solution. The use of fly ash also aims to reduce the consumption of lime and cement whose production releases great quantities of carbon dioxide to the atmosphere.

The results show that the treatment with geopolymer provides much higher strength and stiffness than the others, as well as a substantial increase with time. In any case, the addition of 3% of lime was able to increase in 6 six times the soil strength, and the mixtures of lime and fly ash increased in 7 and 8 times the soil strength depending of the fly ash content of 10% and 20% respectively. The indirect tensile strength was found to be around 6% the unconfined compression strength for the soil-lime and soil-lime-fly ash mixtures, and 9% for the geopolymeric mixture.

The evolution of the elastic Young modulus with time in the mixture with geopolymers follows a power law for the studied period (up to 63 days) which does not seem to stabilize, conversely to what typically happens in soil-cement mixtures.

It could be interesting to repeat this study in fine grained soils with significant clay content where lime, and fly ash may be more effective.

Acknowledgements

The authors would like to acknowledge the company Pegop – Energia Eléctrica SA which runs the thermoelectric power plant of Pego, for the supply of fly ash. The financial support of the Portuguese Science and Technology Foundation through SFRH/BPD/85863/2012 scholarship is also acknowledged which is co-funded by the Portuguese Ministry of Science and Technology (MCTES) and by European Social Fund (FSE) through POCH program.

References

Amaral, M., Viana da Fonseca, A., & Rios, S. (2013). Numerical Methodology to Minimize Resolution and Sensitivity Effects in P-Wave Measurements. Geotechnical Testing Journal, 36(2), 1-10.

ASTM. (2000). D 2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). United States.

ASTM. (2007). D 1632 Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory. United States.

ASTM. (2008). D 3551 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. United States.

ASTM. (2012). C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. United States.

Bell, F. (1996). Lime stabilization of clay minerals and soils. Engineering , 42(4), 223-237.

Bignozzi, M., Manzi, S., Natali, M., Rickard, W., & van Riessen, A. (2014). Room temperature alkali activation of fly ash: The effect of Na2O/SiO2. Construction and Building Materials, 69, 262-270.

CEN. (2003). EN 13286-41 Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures. Brussels, Belgium.

CEN. (2003). EN 13286-42 Unbound and hydraulically bound mixtures - Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures. Brussels, Belgium.

Consoli, N., Dalla Rosa, J., Gauer, E., Santos, V., Moretto, R., & Corte, M. (2012). Key parameters for tensile and compressive strength of silt-lime mixtures. Geotechnique Letters, 2, 81-85.

Consoli, N., Dalla-Rosa, A., & Saldanha, R. (2011). Parameters controlling strength of industrial waste-lime amended soil. Soils and Foundations, 51(2), 265-276.

Consoli, N., Dalla-Rosa, A., & Saldanha, R. (2011). Variables Governing Strength of Compacted Soil-Fly Ash-Lime Mixtures. Journal of Materials in Civil Engineering, 23(4), 432-440.

Cristelo, N., Glendinning, S., Miranda, T., Oliveira, D., & Silva, R. (2012). Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction. Construction and Building Materials, 36, 727-735.

Davidovits, J. (1991). Geopolymers - Inorganic polymeric new materials. Journal of Thermal Analysis , 37(8), 1633-1656.

Duxson, P., Fernandes-Jimenez, A., Provis, J., Luckey, G., Palomo, A., & van Deventer, J. (2007). Geopolymer technology: the current state of the art. Journal of Materials Science , 42(9), 2917-2933.

Little, D. (1995). Stabilization of Pavement subgrades and base courses with lime. Texas, United States: Lime Association of Texas.

Narendra, B., Sivapullaiah, P., & Ramesh, H. (2003). Optimum lime content of fly ash with salt. Proceedings of the Institution of Civil Engineers - Ground Improvement , 7(4), 187-191.

Rogers, C., Glendinning, S., & Roff, T. (1997). Lime modificationof clay soils for construction expediency. Proc., Inst. Civ. Eng., 125(3), 242-249.

Scrivener, K. L., & Kirkpatrick, R. J. (2008). Innovation in use and research on cementitious material. Cement and concrete research, 128-136, 38.

Viana da Fonseca, A., Amaral, M., Panico, F., & Rios, S. (2014). Indexation of Dynamic and Static Geomechanical Properties of a Cemented Aggregate for Transportation Engineering. Transportation Geotechnics, 1(1), 36-44.

Viana da Fonseca, A., Ferreira, C., & Fahey, M. (2009). A Framework Interpreting Bender Element Tests,combining time-domain and frequency domain methods. Geotechnical Testing Journal, 32(2), 1-17.

Viana da Fonseca, A., Rios, S., & Amaral, M. (2013). Structural Anisotropy by static compaction. Engineering Geology, 154, 89-97.

Viana da Fonseca, A., Rios, S., Amaral, M., & Panico, F. (2013). Fatigue cyclic tests on artificially cemented soil. Geotechnical Testing Journal, 36(2), 1-10.