

Clayey soil stabilization using alkali-activated cementitious materials

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Received 24 May 2019
Accepted 16 September 2019
Available on line 13 February 2020

ABSTRACT: In this study, a clayey soil classified as A-7-5 according ASTM D3282, was stabilized using alkali-activated cementitious materials (AAC) added to the soil dry in percentages of 20 and 30%. Fly ash (F1, F2) with high unburned carbon content (up to 38.76%), hydrated lime (L) and granulated blast furnace slag were used. Unconfined compressive strength and flexural strength at 28 days of curing and the durability after 12 wetting-drying cycles were evaluated. The results were compared with a soil-cement reference mixture. The soil treated with AAC-F1L showed a volume expansion of 0.51% and volume contraction of -0.57% compared with the 0.59% expansion and -0.68% contraction of the soil-cement reference mixture. Additionally, the mass loss after the wetting and drying cycles is only 3.74% which is slightly lower than the mass loss of the soil stabilized with ordinary Portland cement (OPC) (3.86%) and well below the value specified in Colombian regulations (7%).

KEYWORDS: Soil stabilization; Clayey soil; Alkali-activated cement; Fly ash; Blast furnace slag.

Citation/Citar como: Rivera, J.F.; Orobio, A.; Mejía de Gutiérrez, R.; Cristelo, N. (2020) Clayey soil stabilization using alkali-activated cementitious materials. *Mater. Construcc.* 70 [337], e211 <https://doi.org/10.3989/mc.2020.07519>

RESUMEN: *Estabilización de suelo arcilloso utilizando materiales cementicios activados alcalinamente.* En este estudio, un suelo arcilloso clasificado como A-7-5 según ASTM D3282, se estabilizó utilizando materiales activados alcalinamente (AAC) en porcentajes de 20 y 30%. Se utilizaron cenizas volantes (F1, F2) con alto contenido de inquemados (hasta 38,76%), cal hidratada (L) y escoria granulada de alto horno. Se evaluó la resistencia a la compresión confinada y la resistencia a la flexión a 28 días de curado y la durabilidad después de 12 ciclos de humectación-secado. Los resultados se compararon con una mezcla de referencia suelo-cemento. El suelo tratado con AAC-F1L mostró una expansión y contracción volumétrica del 0,51% y -0,57% respectivamente, en comparación con el 0,59% y -0,68% de la mezcla de referencia suelo-cemento. Además, la pérdida de masa después de los ciclos de humectación y secado es sólo 3,74%, valor ligeramente inferior a la del suelo estabilizado con cemento Portland (3,86%) y muy inferior al valor especificado en la normativa colombiana (7%).

PALABRAS CLAVE: Estabilización de suelos; Suelo arcilloso; Cemento activado alcalinamente; Cenizas volantes; Escorias granuladas de horno alto.

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1. INTRODUCTION

Soil stabilization is primarily used to improve the geotechnical properties of a native soil. Improved properties such as mechanical strength, bearing capacity, permeability and durability facilitate use of the stabilized soil in many engineering applications, as either subgrade or subbase in the construction of roads and railways and in foundations, dams, and embankments. In general, there are several methods to physically or mechanically improve the properties of a native soil; however, “stabilization” is essentially the improvement of soil properties with the incorporation of chemical additives to the soil.

The basic principles of soil stabilization through chemical additives originated in the late 1950s when scientists first used hydrated lime and Portland cement to stabilize expansive clays and even produced lime-fly ash combinations with the same objective (1). Currently, the use of Portland cement and lime to stabilize a wide range of soils for various engineering applications is still a very popular and widespread method. However, these materials have environmental impacts associated with CO₂ emissions, high energy consumption and high cost in certain applications. Therefore, there have been attempts to diversify the stabilizing agents to provide a greater variety of materials for such applications; those attempts include certain industrial by-products (fly ash, slag, cement kiln dust and glass), certain wastes (from demolition, tires, and calcium carbide) and polymer products (polymeric fibres, asphalt products, and bituminous products) (2).

Recently, the alkaline activation process as an option for the stabilization of various types of soils has gained prominence since many of the precursor materials of alkali-activated cements originate from industrial by-products or waste (3). This initiative emerged due to the environmental problems and costs associated with the use of lime and Portland cement (4, 5). However, the alkali-activated cementitious materials may have similar or better performances than traditional cements and similar hardening times for these applications.

Several laboratory studies have been carried out in recent years using the alkaline activation process to stabilize different types of soil with promising results. Wilkinson et al. (2010) (6) carried out a study where they used activated fly ash, slag and hydrated lime to stabilize clayey soils collected across Australia. In that study, soil stabilized with ground granulated blast-furnace slag (GGBS) gained greater strength at early ages compared with soils stabilized with fly ash or hydrated lime in the same proportions. Cristelo et al. (2012) (7) studied the effect of calcium content on marl (also called marlstone) soils stabilized with class C and F fly ash alkali-activated with sodium hydroxide solutions. The results showed that in short times, the mixtures

with class C ash gained more strength compared with the mixtures of soil with class F ash due to the high calcium content of the mixtures with class C ash; however, at older ages, the soils stabilized with class F ashes exhibited higher mechanical strengths. Cristelo et al. (2012) (8) also studied the effect of the type and concentration of the activator on the stabilization of the residual granitic soils with class F fly ash and concluded that the Na₂O:ash ratio has an important role in the development of mechanical strength and that the maximum strength values are achieved when this parameter is optimized.

There were no improvements reported when superplasticizer additives or NaCl were used in mixtures with soil; additionally, the use of Ca(OH)₂ resulted in short-term high mechanical strength. Sargent et al. (2013) (9) conducted a study on the improvement of the mechanical properties and durability of an artificial silty sand soil using alkali-activated industrial wastes such as cementitious materials; among these materials were pulverized fly ash (PFA), GGBS and red gypsum (RG), which were activated with an NaOH and Na₂SiO₃ solution. This study reported that the soil stabilized with GGBS had the best properties in terms of mechanical strength and durability; the authors suggested that soils stabilized with GGBS-PFA and GGBS-RG, from an engineering standpoint, can be used in applications where high stiffness is not required to prevent fracture of the stabilized soil.

Zhang et al. (2013) (10) studied the feasibility of using alkali-activated metakaolin (MK) as an alternative cementitious material to stabilize low-plasticity clayey soil; the results showed that the compressive strength, failure strain, Young's modulus and shrinkage decreased. The ductility of the soil stabilized with MK makes the soil far more effective at mitigating crack formation and in applications where compaction is required.

In stabilized and compacted soil applications, the maximum dry density and optimum moisture content have significant impacts on the final properties of the mixture. The maximum dry density varies with the addition of cementitious material and tends to decrease. This effect is related to the flocculation of the soil particles, since particle flocculation in the structure of compacted soil increases porosity; however, as time passes, the pozzolanic reactions fill these porosities with reaction products that help cement the structure (11).

The conditions of the stabilized soils in the laboratory tests are crucial when soils are stabilized with alkali-activated cementitious materials. Ghadir and Ranjbar (2018) (12) conducted a study of soils stabilized with alkali-activated volcanic ash, in which uniaxial compression tests were performed on specimens with the optimal moisture in the mixture and in dry conditions. The results showed that the alkali-activated ash was more efficient under dry curing

conditions since this sample improved soil resistance by 200% compared with the soil stabilized with Portland cement, whereas under optimal humidity conditions, Portland cement improved resistance by 33% compared with the soil stabilized with volcanic ash. This difference is associated with the effect of water and pH on the kinetics of the alkaline activation reactions of the volcanic ash.

This study evaluated the chemical stabilization of a clayey soil using alkali-activated fly ash-based cementitious materials. Mixtures of fly ash/granulated blast-furnace slag (GBFS) and fly ash/lime activated with NaOH/Na₂SiO₃ solution were used. The results of the laboratory tests, unconfined compressive strength (UCS), flexural strength (FS) and durability were compared with those obtained for the soil stabilized with Portland cement and used as reference system.

2. MATERIALS AND METHODOLOGY

2.1. Materials

The soil used was collected in southern Cali, Valle del Cauca, Colombia, at latitude 3° 21' 45.979"N and longitude 76° 30' 53.277"W. It was initially dried at ambient temperature, and a disc mill was used to de-flocculate the particles. The particle size distribution was determined by sieving, according to ASTM D6913-17 (13), the sieved material showed a very fine texture with 96.75% of the material passed through sieve number 200. The Atterberg limits were determined according ASTM D4318-17 (14). The soil presented liquid limit of 58% and plastic limit of 34%. The Plasticity Index calculated was 24%. These results were used to classify the soil as a A-7-5 according to ASTM D3282-15 (15).

For the preparation of the alkali-activated binding pastes, GBFS and commercial lime were used as sources of calcium, and two classes of fly ash (FA1, FA2) were used as precursors. The FA1, FA2 and GBFS were previously milled for 2 h; after which the

average particle size after the grinding process of the precursors was 37.064 µm, 24.968 µm and 27.729 µm, respectively. The commercial lime had an average particle size of 24.740 µm. A general-use Portland cement (OPC) was also included in the study as reference material. Table 1 shows the chemical composition of the materials used that was determined by X-ray fluorescence (XRF) using a Philips PW-2440 Pro PANalitical MagiX spectrometer, with a maximum power of 4 kW and equipped with a rhodium tube. A NaOH/Na₂SiO₃ combination, in solution form, was used as the alkaline activator.

2.2. Development of the alkali-activated binding pastes

Two alkali-activated binding pastes (F1L and F2G) were designed using response surface models where the SiO₂/Al₂O₃ and Na₂O/SiO₂ molar ratios were considered as the independent variables. The pastes were cured at 30°C. The uniaxial compressive strength (UCS) after 28 days was defined as the dependent variable. The response surface models were optimized to obtain the best combination of independent variables and maximize the response of the dependent variable, producing the contour plots shown in Figure 1.

F1L (Figure 1a) is composed by 80% FA1 and 20% lime, with optimized independent variables SiO₂/Al₂O₃ = 3.0 and Na₂O/SiO₂ = 0.3, yielding an UCS, after 28 days, of 21 MPa. F2G (Figure 1b) is composed by 80% FA2 and 20% GBFS, with optimized independent variables SiO₂/Al₂O₃ = 3.9 and Na₂O/SiO₂ = 0.32, yielding an UCS, after 28 days, of 23 MPa.

2.3. Preparation of the stabilized soil test specimens and testing

Modified Proctor compaction tests were performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of

TABLE 1. Chemical compositions of the materials used as precursors, calcium sources and soil.

Compound (wt.%)	FA 1	FA 2	GBFS	Lime	OPC	Soil
SiO ₂	28.11	28.53	37.74	2.48	21.23	40.64
Al ₂ O ₃	17.47	19.18	15.69	0.91	4.92	20.96
Fe ₂ O ₃	5.27	8.80	1.85	0.39	4.88	21.34
CaO	2.34	6.68	40.30	54.48	64.27	1.49
SO ₃	3.73	2.70	-	0.43	-	-
MgO	0.83	2.24	1.3	0.30	1.61	1.86
TiO ₂	1.03	1.62	0.5	0.05	0.24	1.81
Na ₂ O	1.09	7.94	0.2	0.11	0.26	0.48
LOI	38.76	20.67	-	40.37	-	10.57

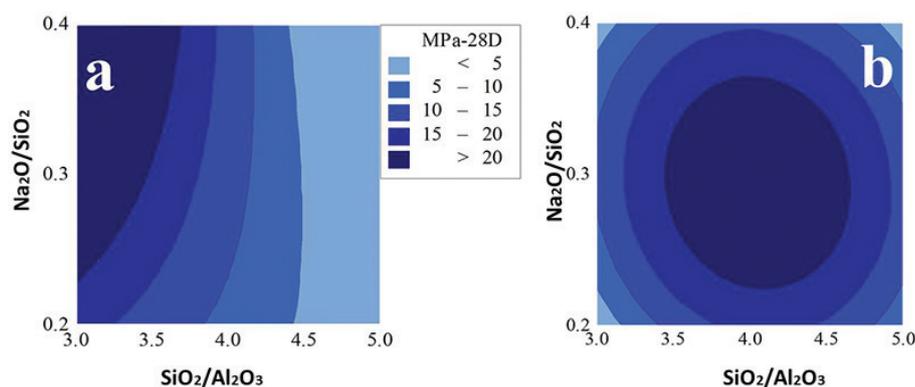


FIGURE 1. Optimization of the synthesis variables of alkali-activated cementitious materials a) F1L and b) F2G.

each mixture, according to ASTM D1557-12e1 (16). The binding paste was added to the dry soil in pre-determined percentages. The soil-cement mixture was prepared with 13 wt.% of OPC, which was the content required for the compaction test according to the classification of the soil (17). The soils stabilized with alkali-activated pastes were mixed with 20% F1L, 30% F1L and 30% F2G.

The soil and the precursor, both in dry state, were manually mixed until a uniform coloration was obtained, for homogenisation. The alkaline activator, calculated as a function of the precursor content, was then slowly, while still mixing. Finally, additional water was added, to guarantee the pre-determined OMC for each mixture.

The specimens were then made by compacting the material into cylindrical moulds, with 52 mm in diameter and 104 mm in height, and prismatic moulds with $50 \times 50 \times 150$ mm, according to ASTM D1632-17 (18). Once compacted, the specimens were cured in a climatic chamber, with a temperature and humidity of 30 °C and 80%, respectively. UCS tests were performed after 7 and 28 days curing, and flexural tests after 28 days, based on ASTM D1633-17 and D1635-12 (19, 20), respectively, in an INSTRON 3300 universal testing machine.

Wetting and drying tests were performed on stabilized soils after 7 days of curing, following the protocol, outlined in ASTM D559-15 (21). Each specimen was subjected to a total of 12 wetting-drying cycles. One full cycle consisted of immersion in potable water for 5 h and then drying for 48 h at 71 °C. This test was done to calculate the changes in the volumes of the stabilized soil specimens and the mass loss during the wetting and drying cycles. The volume change was calculated by measuring (in saturated and dry conditions) the average height and diameter of one of the specimens. To calculate the mass loss, the second specimen in the dry condition was brushed in each cycle with a steel brush applying an average force of 15 N, passing 20 times over

the lateral surface of the body and four times over each face of the specimen.

3. RESULTS AND DISCUSSION

3.1. Compaction

The compaction curves for each stabiliser type and content used are shown in Figure 2, and the MDD / OMC of all tests is presented in Table 2. The MDD of the nonstabilized compacted soil is 1.56 g/cm³, and the OMC of this sample is 24.67%. The addition of OPC as stabilizer increases the MDD to 1.59 g/cm³ with an OMC of 26.15%; this phenomenon is related to the addition of a material of higher specific weight to the mixture, and the increase in the moisture content is attributed to the additional water the OPC requires to begin the hydration processes (22). In contrast, by stabilizing the soil using alkali-activated cements, in general, the MDD decreases, compared to the non-stabilized soil.

The addition of 30F1L and 30F2G produced slightly different results, with 1.47 g/cm³ and 26.92% for the former, and 1.51 g/cm³ and 26.27% for the latter. FA1 is the precursor of the 30F1L system, and the loss-on-ignition (LOI) (unburned carbon) of this sample is 38.76%, while FA2 is the precursor of 30F2G with an LOI of 20.67%. Additionally, the proportions of calcium sources for both cements are the same, 20% by weight, but are of different nature and composition. 30F1L contains lime, and 30F2G contains GBFS, which theoretically makes the specific gravity of cementitious material 30F2G higher than that of 30F1L (23, 24). For the OMC of the soil stabilized with 30F1L, this mixture has a slightly higher OMC than that of 30F2G; according to Osinubi (2006) (25), lime content increases the OMC of clayey soils.

The MDD is also affected by the content of cementitious material used to stabilize the soil. With the addition of 20F1L, the MDD was 1.50 g/cm³,

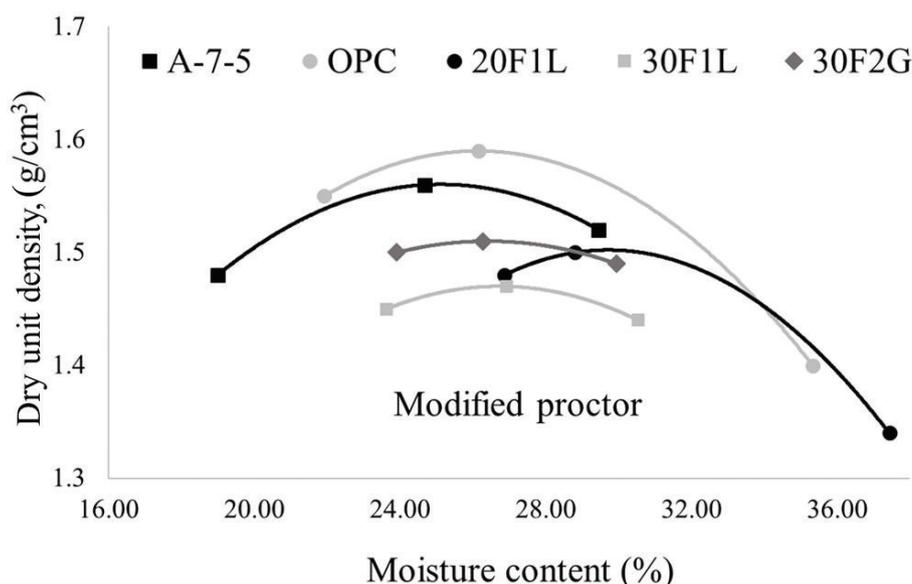


FIGURE 2. Proctor curves.

TABLE 2. MDD and OMC of the original soil and the soil-stabiliser combinations.

Material	Binder content (%)	MDD (g/cm ³)	OMC (%)
A-7-5	-	1.56	24.67
OPC	13	1.59	26.15
20F1L	20	1.50	28.81
30F1L	30	1.47	26.92
30F2G	30	1.51	26.27

which is slightly higher than the 1.47 g/cm³ of the soil stabilized with 30F1L (Table 2), and is consistent with reports from certain authors (11, 22). Regarding the materials used, one of the reasons why the MDD decreases between 20%F1L and 30%F1L, is the amount of unburned material in the precursor (fly ash 1 with 38.76% LOI), which results in a mixture with lower specific gravity.

3.2. Uniaxial compressive strength (UCS)

Figure 3 shows the UCS results of the unsaturated and saturated specimens. For the unsaturated conditions (Figure 3a), the reference mixture (OPC) registered the best performance after 7 days ($UCS_{7D} = 4.79$ MPa), compared with the values obtained using alkali-activated cementitious materials 20F1L, 30F1L and 30F2G, with UCS_{7D} of 3.88, 4.21 and 1.52 MPa, respectively. This trend continues after 28 days, with OPC, 20F1L, 30F1L and 30F2G showing UCS_{28D} values of 6.55, 5.26, 4.45 and 2.43 MPa, respectively. There are two key factors explaining why the performance

of the soil treated with alkali activated cementitious material is worse than that of the reference sample (OPC). One factor is the compositions of the main precursor materials (FA1 and FA2), and the other factor is the chemical composition of the soil. As shown in Table 1, the content of unburned carbon (LOI) is quite high in both ashes (FA1 = 38.76% and FA2 = 20.67%). This carbon content may have a negative impact when the mixture of cementitious material and soil is alkali activated because carbon has a large surface area that absorbs a certain amount of the alkaline activator and removes alkali cations, hindering the kinetics of the dissolution reactions of the precursor, condensation and polymerization of cementitious gels (26–28). The chemical composition of the soil (Table 1) may also have an adverse effect on the strength development of the soil stabilized with alkali-activated pastes due to the laterization degree. This is estimated by calculating the ratio of silicon to sesquioxides ($SiO_2/(Al_2O_3 + Fe_2O_3)$) (22). The soil used in this study has a ratio of 0.96, this means that the chemical weathering process of the soil is quite advanced due to its high amount of iron and aluminium oxides. Certain studies indicate that reactive Fe_2O_3 may precipitate much faster than Al or Si compounds under highly alkaline conditions and generates iron hydroxides or oxyhydroxides that consume the OH^- ions of the alkaline activator, which slows the dissolution of the remaining particles of the precursor material and reduces the number of nucleation sites of the oligomers that form the cementitious aluminosilicate gel. However, other studies suggest that Fe^{+3} acts as nucleation sites since in silicate glasses, Fe^{+3}

is known as a network former due to a charge and ionic radius similar to those of Al^{+3} (29–32).

Regarding the soils stabilized with the same type of alkaline cementitious material but at different proportions, in unsaturated conditions, 20F1L has a higher UCS than 30F1L at 28 days of curing (20F1L $UCS_{28D} = 5.26$ vs. 30F1L $UCS_{28D} = 4.45$ MPa). The reason for this difference is not clear; however, an increase of 20% to 30% in the proportion of cementitious material leads to a slight decrease in the maximum dry density of the compacted mixture (Figure 2). The greater proportion of unburned carbon acts as a “lubricant” between the soil particles and decreases the internal friction between the particles, which affects the resistance to external stresses (33, 34). In contrast, the cementation capability of the 30F2G is lower than that of 30F1L, even though the maximum dry density of the mixture is higher (Table 2). This behaviour is attributed to the effect of the lime on the composition of cementitious material 30F1L. Double charge cations such as Ca^{++} and Mg^{++} can generate nucleation sites quickly without needing the species from the main precursor (FA1) to dissolve, due to the action of the alkaline activator; therefore, the particle agglomeration and cementation of the stabilized soil improves with shorter setting times (35, 36).

Figure 3b shows the results of the UCS tests under water-saturated conditions. The untreated soil completely collapses after a few minutes of immersion in water, and in general, for the different cementitious materials, the compacted specimens maintain their integrity during the saturation period of 4 h before the test, due to the type of bonds that the cementation produces, which are not present in the untreated soil. The untreated soil has a flocculated structure;

this condition creates clay bridges by electrostatic attraction, which provides strength to the material, but the strength is lost when the degree of saturation increases. The structure of the stabilized soils has cementation bonds that make the soil stiffer and stronger. When the soil is saturated, the precipitates can dissolve and gradually break the bonds. The loss of such bonds is slower in stabilized soil than in nonstabilized soil.

In the saturated conditions, the soil stabilized with OPC has the best performance at both 7 and 28 days of curing, $UCS_{7D} = 2.5$ and $UCS_{28D} = 2.7$ MPa, respectively. For the saturated conditions, increasing the proportion of alkaline cementitious material F1L from 20% to 30% impacts the performance of the stabilized soil (20F1L $UCS_{7D} = 1.09$; $UCS_{28D} = 1.26$ MPa vs. 30F1L $UCS_{7D} = 1.36$; $UCS_{28D} = 1.54$ MPa) and improves the soil strength with 30F1L, $UCS_{7D} = 19.85\%$ and $UCS_{28D} = 18.18\%$. As mentioned above, this behaviour can be attributed to the proportion of lime in the alkaline cementitious material 30F1L. Despite the increase in the proportion of unburned carbon in the mixture, the lime immediately reacts with the soil, flocculates, and generates nucleation sites that help cement the soil structure. This effect could change the size and distribution of the pores of the compacted material, thus increasing the tortuosity and decreasing the saturation occurring during the time the sample is immersed in water (37, 38). Regarding the treatment with 30F2G, the soil resists the saturation period much better than the untreated soil, but the strength of this soil is the lowest recorded, either after 7 or 28 days (30F2G $UCS_{7D} = 0.66$; $UCS_{28D} = 0.70$ MPa), and the specimens showed substantial deterioration during the saturation process.

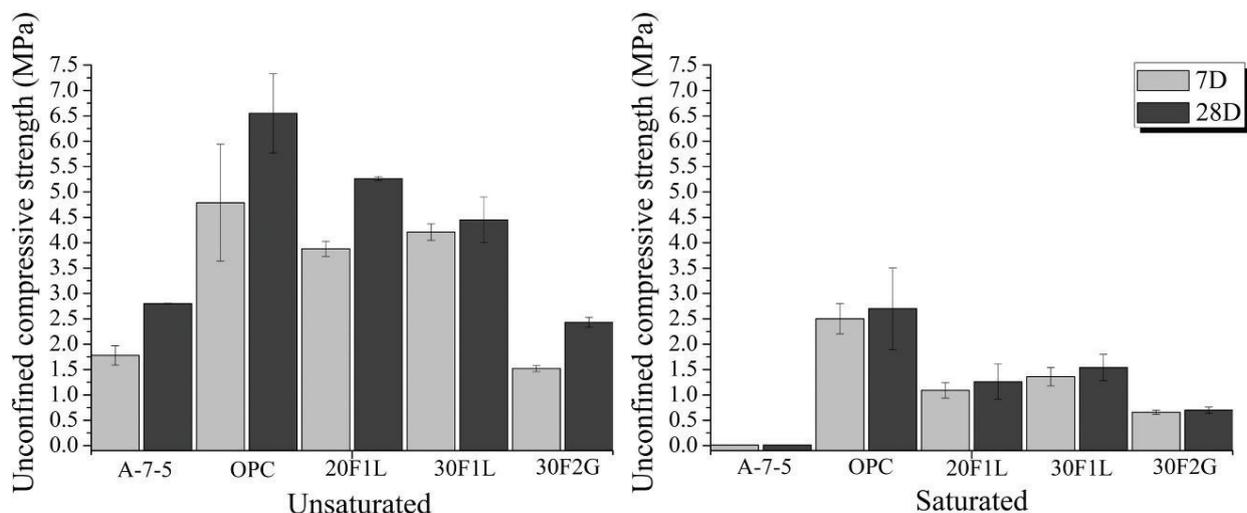


FIGURE 3. UCS of the soil under a) unsaturated and b) saturated conditions.

3.3. Flexural strength (FS)

The FS of the stabilized soil is directly related to the UCS and MDD. The evolution of the FS over the curing period is moderate, compared with that of the UCS. Figure 4 shows the FS for each mixture of stabilized soil. In general, the FS of the different cementitious materials is between 1/3 and 1/5 of the UCS, except that of 20F1L, which is below this range (1/6 at 0.84 MPa).

Studies by Mandal et al. (2018) (39) showed that soils stabilized with different cementitious materials and compacted at low densities had low FS values. However, in these studies, the effect of cementitious materials and the proportion of these materials in the mixture also affected the FS, together with the MDD. When the same alkaline cementitious material is used, although in different proportions, the FS increases (20F1L; FS = 0.84 MPa vs. 30F1L; FS = 0.99 MPa). Such improvement is due to the overall increase in the number of cemented particles. As mentioned above, a higher lime content increases the agglomeration and cementation capability of the soil with cementitious material 30F1L, improving the ability of this soil to dissipate energy in the bending (38). Furthermore, by changing the type of alkaline cementitious material, even if the same content is used, the FS varies (30F1L = 0.99 MPa vs. 30F2G = 0.46 MPa). This is attributed to the agglomeration and hardening effect of the cementitious material. In these types of soils, 30F1L provides better cementation than 30F2G. Therefore, in addition to MDD and UCS, the nature and cementing capability of the cementitious material is essential to improve the FS (40).

3.4. Wetting and drying tests (WDTs)

Figure 5 shows the volumetric variation of the soils stabilized with different cementitious materials

subjected to wetting and drying cycles. The volumetric variation of the soil stabilized with OPC is quite uniform overall. In the first cycle, it expands 0.56% and contracts -1.90%, compared with the initial volume of the specimen after 7 days curing. The rest of the expansion and contraction measurements are made with respect to the last calculated volume, which means that, after 12 cycles, the reference specimen has an average expansion of 0.59% and average contraction of -0.68%.

The soil stabilized with 20F1L has an initial expansion of 0.74% and contraction of -1.99% after the first cycle. Compared with the soil stabilized with OPC, the change in the volume of the soil with 20F1L is greater in both expansion and contraction and, at the end of the 12 cycles, an average expansion / contraction of 0.84% and -0.93% was determined. The volumetric variation of the soil stabilized with 20F1L is far more irregular than the soil-OPC.

The soil stabilized with 30F1L has an expansion of 0.17% and a contraction of -0.97% in the first cycle and, on average, a volume changes slightly lower than that of the OPC and 20F1L, with an expansion of 0.51% and a contraction of -0.57%. The test of the soil stabilized with 30F2G was discarded because the specimen collapsed completely in the second wetting and drying cycle, and it was not possible to determine the corresponding weight and measurements.

The expansion and contraction limits proposed by Nogami & Villibor (41), for paving tropical lateritic soils without stabilization, are used in the present work as a reference (Table 3). This is in accordance with the Rojas et al. (2008) (42) proposal, based on the lack of standard parameters to assess the volumetric variation of stabilized soils. Overall, based on these data, at the end of the WDT cycles, the expansion and contraction

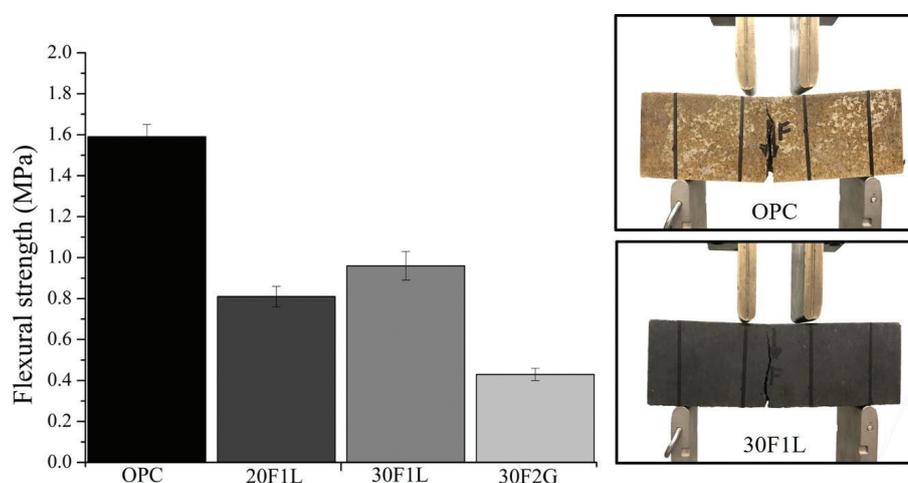


FIGURE 4. Flexural strength.

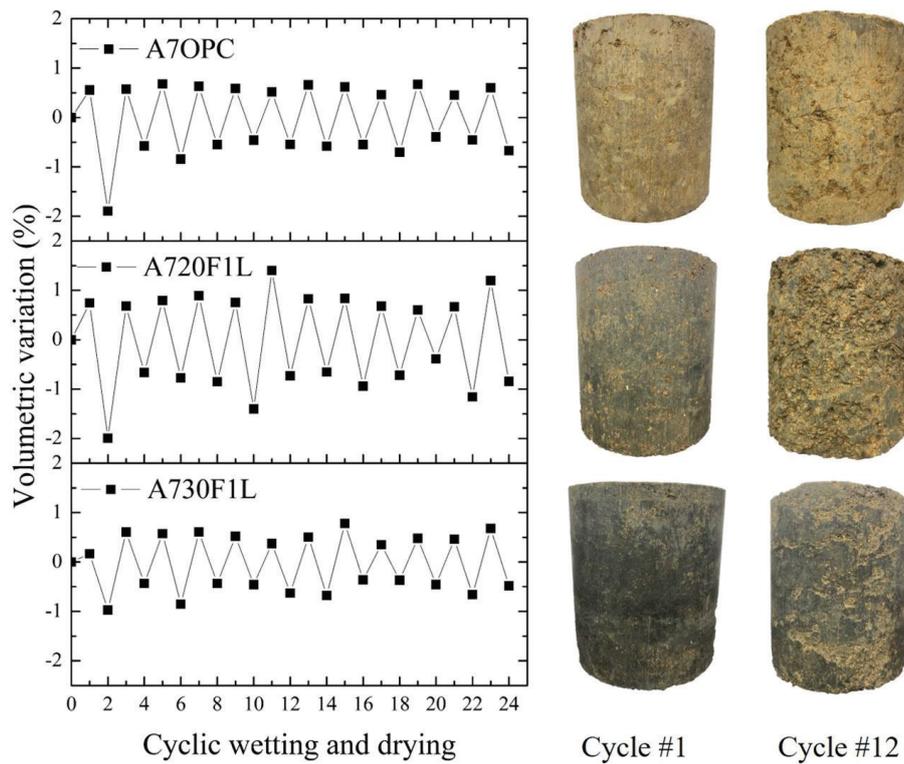


FIGURE 5. Volumetric variation and mass loss for the wetting and drying cycles.

TABLE 3. Volumetric change of untreated lateritic soils. Adapted from Nogami & Villibor (41).

Nivel of Expansion or Contraction	Percentage, %
High	> 3
Average	0.5 to 3
Low	< 0.5

obtained for the different systems can be considered average (0.5 to 3%).

Scanning electron microscope (SEM) images (Figure 6) shows the cementation of soil particles. The soils stabilized with OPC and 30F1L show structures with well-cemented particles that help to obtain a uniform volumetric variation and relatively low expansion and contraction averages, while the soil stabilized with a minor proportion of alkaline cementitious material (20F1L) shows several cracks in the structure. Higher proportions of alkaline cementitious material modified the natural behaviour of the soil, which is naturally very susceptible to significant volume changes under wetting and drying cycles (according to its Unified Classification, ASTM D3282-15). In addition, the cementation observed when stabilizing the soil with 30F2G is poor, which is attributed to the collapse of the sample that prevented the completion of 12 wetting and drying cycles.

The mass loss due to wetting/drying a soil stabilized with different cementitious materials is an important property. Regarding the WDT results of this study, the reference specimen stabilized with OPC at the end of the 12 cycles has a mass loss of 3.86%; the specimen of the soil stabilized with 30F1L has a very similar mass loss of 3.74%, while the soil stabilized with 20F1L loses 10.21% of its mass after 12 cycles (Figure 7). The mass loss calculations were made using the parameters of ASTM standard D 559-15 (21), used for testing soil-cement specimens considering the weight of the water that reacts in the hydration process of OPC.

According to the Colombian standard of the National Roads Institute (43), there are two soil-cement classes depending on the design criteria for the mixture: soil-cement durability (SC-D) and soil-cement durability-resistance (SC-R) (Table 4). Based on the above, clayey soil A-7-5 stabilized with alkaline cementitious material 30F1L could be a viable alternative for pavement design following durability criteria SC-D, since the mass loss of this soil is only 3.74%, lower than the maximum mass loss allowed by the Colombian standards, and the mass loss of this soil is similar to that of the reference soil stabilized with OPC. In addition, the change in volume of this soil under both expansion and contraction is very similar to that of the reference soil stabilized with OPC.

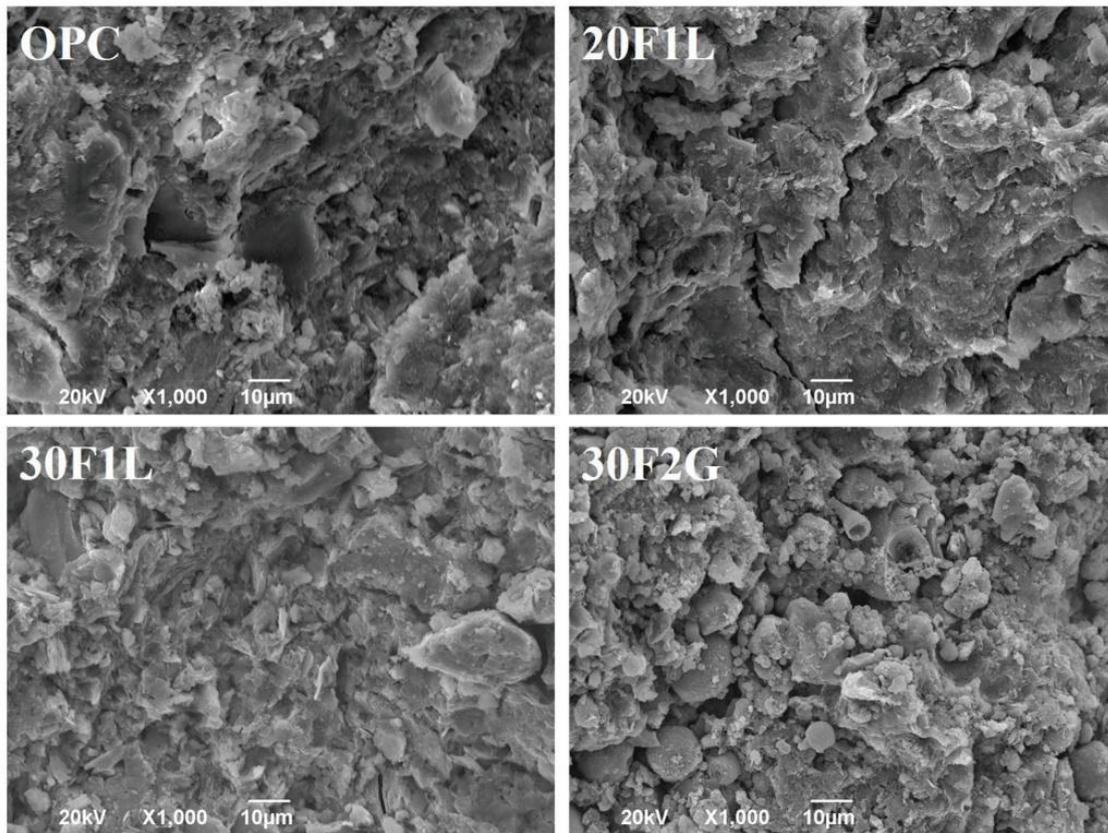


FIGURE 6. Microstructure of the soils treated with different cementitious materials.

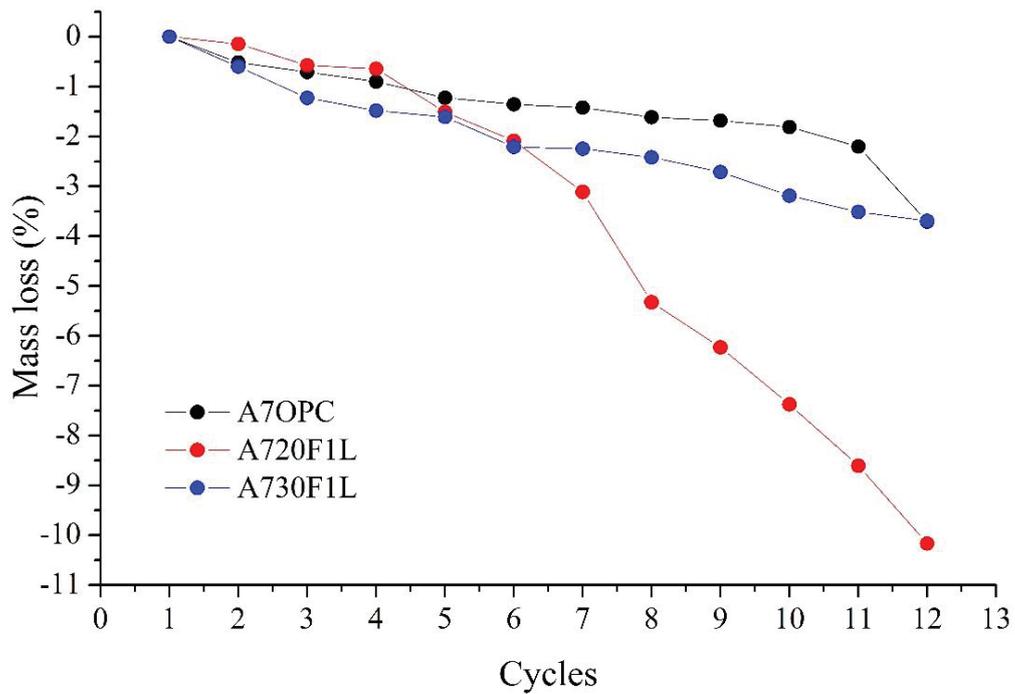


FIGURE 7. Mass loss after wetting and drying cycles.

TABLE 4. Soil-cement design for INVIAS road applications. Adapted from (43).

Test	SC-D	SC-R
Durability		
Maximum mass loss of the compacted mixture in wetting and drying test (%):	14	14
-Soils A-1; A-2-4; A-2-5; A-3	10	10
-Soils A-2-6; A-2-7; A-4; A-5	7	7
-Soils A-6; A-7		
Resistance		
Resistance behaviour with:		
-Increase in OPC content	Increase	Increase
-Increase in age	Increase	Increase
Resistance to UCS at 7 days (MPa):		
-Minimum	(Note 1)	2.1
-Maximum	4.5	4.5 (Note 2)

Soil-cement durability (SC-D) Soil-cement resistance (SC-R).

Note 1: The minimum strength is that obtained from the mixture that meets the durability criterion.

Note 2: In the project, a greater resistance at 7 days can be established.

4. CONCLUSIONS

- The use of alkali-activated cementitious materials to stabilize soils can be a viable alternative to using traditional cementitious materials such as OPC; however, the chemical compositions of the precursor materials of the cementitious material and the soil are of crucial importance when highly alkaline activators are used. This type of soil with high iron oxide content can reduce the cementing problems of certain alkali-activated cementitious materials as long as the alkaline activator is dosed considering the proportion of soil used as a precursor material.
- The types of calcium sources in the alkali-activated cementitious materials used in this study were essential in the stabilization of the soil. The calcium source used in cementitious material 30F1L promoted particle agglomeration and formed nucleation sites, allowing the cementitious material to interact with the soil and stabilize the soil structure.
- The proportion and type of alkali-activated cementitious material used in the soil was crucial to maintaining the structure stabilized when the specimens were subjected to wetting and drying cycles. With a proportion of 30% alkaline cementitious material (30F1L), it was possible to obtain percentages of change in volume and mass loss very similar to those obtained for the reference soil stabilized with OPC. This result indicates that this type of alkali-activated cementitious material can improve several important characteristics of the stabilized soil.

- The soil stabilized with 30% alkaline cementitious material (30F1L) could be an alternative to be explored for designing pavements according to the durability criteria of the road construction regulations of Colombia. This soil meets the durability design criteria for soil-cement mixtures (SC-D). The mass loss for this cementitious material was 3.74%, well below the 7% mass loss allowed by Colombian regulations, and the strength of this stabilized soil after 7 days under saturated conditions was 1.36 MPa.

ACKNOWLEDGEMENTS

The authors thank the Administrative Department of Science, Technology and Innovation (Colciencias) for the support received during the project “Prototype construction of rural housing at scale using innovative materials with low carbon footprint”, contract No. 0696-313-2016, under which this research was conducted. J. F. Rivera thanks “Universidad del Valle” (Cali, Colombia) for the additional support received.

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