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ENGLISH VERSION……..........

Brick dust and fly ash as subgrade stabilizer for Low Traffic Volume Roads: laboratory and test track evaluation

Polvo de ladrillo y cenizas volantes como estabilizador de subrasante para caminos de bajo volumen de tráfico: evaluación en laboratorio y pista de prueba

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Abstract

Currently, there are materials from industry that, under certain physical conditions, can contribute to the improvement of soils mechanical properties. Materials such as brick dust (BD) and fly ash (FA) have high SiO2 and Al2O3 contents, which denote pozzolanic activity. In addition, it has been shown that these materials can be activated when combined with lime. This generates internal cementation processes when the particle size is 0.075 mm. Rural roads in Colombia have one of the highest percentages of the entire road infrastructure, and only about 7% are in good condition. Difficult access conditions, soil susceptibility, the financial impossibility of intervening in this entire network and the need to implement circular economy processes, make these materials attractive in terms of stabilization to improve traffic conditions. BD and FA were applied in dosages of 0%, 3%, 6%, 9%, 12% and 24% in finogranular soils (silt and clay) and sandy soils, compaction was evaluated, and a factorial experimental design was carried out to evaluate the influence of the material on the variable unconfined compressive strength (UCS), through an ANOVA analysis. To evaluate the performance of BD and FA, a test track was made on a low traffic volume road in northern Colombia, which had a sandy soil. BD and FA were added at 12% and activated with lime, in 30 m long cells. To establish a comparative pattern, other cells were made in the same geometric conditions with materials that are usually used in this type of application, such as cement. These cells were evaluated over a period of 16 months. Characteristics such as resilient modulus, international roughness index (IRI) and slip resistance coefficient were measured during this period. The results indicate that when these materials are added to finogranular soils (silts and clays), the UCS increases by 150% with respect to the unstabilized soil, while for sandy soils the strength increases from 70% to 125%. During the evaluation period, the BD and the FA were able to increases of over 50% in the resilient modulus with respect to the unstabilized soil. However, the FA showed comparable results with respect to the cement-stabilized cell. In addition, although the sections deteriorated over time, they maintained their roughness index within the admissible ranges indicative of a good serviceability index.

Keywords: *Soil Stabilization; brick dust; geopolymers; low traffic volume roads; performance.*

Resumen

En la actualidad, existen materiales provenientes de la industria, que bajo ciertas condiciones físicas pueden aportar al mejoramiento de las propiedades de mecánicas de un suelo. Materiales como el polvo de ladrillo (BD) y las cenizas de carbón (FA) tienen contenidos altos de SiO2 y Al3O2, que denotan actividad puzolánica. Además, se ha comprobado que dichos materiales pueden activarse al combinarse con cal. Esto genera procesos internos de cementación cuando el tamaño de grano es de 75 micras. Las vías rurales en Colombia presentan uno de los porcentajes más altos de toda la red vial y solo un 7% aproximadamente se encuentra en buen estado. Las difíciles condiciones de acceso, la susceptibilidad de los suelos, la imposibilidad financiera de intervenir toda esta red y la necesidad de implementar procesos de economía circular hace que estos materiales sean atractivos en temas de estabilización para mejorar las condiciones de tránsito. El BD y FA fueron aplicadas en dosificaciones del 0%, 3%, 6%, 9%, 12% y 24% en suelos finogranulares (limo y arcilla) y suelos arenosos, se evaluó la compactación y se realizó un diseño experimental factorial para evaluar la influencia del material en la variable resistencia a la compresión inconfinada, por medio de un análisis ANOVA. Para evaluar el desempeño del BD y las FA, se realizó una pista de prueba sobre una vía de bajo volumen de tráfico en el norte de Colombia, la cual tenía un suelo arenoso. BD y FA fueron adicionados al 12% y activados con cal, en celdas de 30 m de longitud. Para establecer un patrón comparativo se hicieron otras celdas en las mismas condiciones geométricas con materiales que usualmente se usan en este tipo de aplicaciones como el cemento. Estas celdas fueron evaluadas en periodo de 16 meses. Características como el módulo resiliente, El índice de internacional de rugosidad IRI y el coeficiente de resistencia al deslizamiento fueron medidos en ese período. Los resultados indican que cuando se adicionan estos materiales en suelos finogranulares (limos y arcillas), la resistencia a la compresión inconfinada aumenta un 150% respecto al suelo sin estabilizar, mientras que para suelos arenosos la resistencia aumenta desde un 70% hasta un 125%. Durante el período de evaluación, el BD y las FA lograron presentar aumentos por encima del 50% en el módulo resiliente respecto al suelo sin estabilizar. Sin embargo, las FA presentaron resultados comparables respecto al tramo estabilizado con cemento. Adicionalmente, sin bien, los tramos se fueron deteriorando en el tiempo, mantuvieron su indicen de rugosidad dentro de los rangos admisibles indicativos de buen índice de serviciabilidad.

Palabras clave: Estabilización del suelo; Polvo de ladrillo; Geopolímeros; Caminos de bajo volumen de tráfico; Rendimiento.

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1. Introduction

Due to their binder capacity, some industrial wastes represent an alternative for the improvement of roads with low traffic volume. In the case of construction and demolition waste (CDW), due to its nature and volume, recycling becomes complex; therefore, its use in road construction is considered an efficient way to reuse it and avoid its disposal in landfills (Xuan et al., 2014). In some countries such as the Netherlands, approximately 80% of road base materials are generated from CDW recycling. (Xuan et al., 2014).

Among these materials, brick dust (BD), obtained by grinding construction debris, and bottom fly ash (FA), obtained in the process of burning coal in industrial boilers, stand out. There are different experiences in which the potential of these materials to be used as stabilizers has been evaluated. (Poon and Chan, 2005), (Arulrajah et al., 2014). BD has been used in the concrete industry, looking for the improvement of some properties such as resistance, permeability, durability and thermal stability, using different percentages of addition, working simply as an aggregate or complementing it with alkaline activation processes, to replace a percentage by weight of the sand in the mixes or of the weight of the cement, depending on the case. (Bektas et al., 2009), (Aliabdo et al., 2014), (Bektas, 2014), (Zong et al., 2014). Fly ash (FA), a product of coal combustion in industrial boilers, represents another important source of waste; it has been studied as a cementitious material due to its reactivity and its use in the production of alkaline cements with a low carbon footprint, also known as geopolymers. (Velázquez, 2016), (Zhuang et al., 2016), (Balaguera et al., 2017) (Yip et al., 2005), (Duxson et al., 2007), [13] (Van Deventer, 2012), (Zhang et al., 2014), (Zhuang et al., 2016) and in soil stabilization, has shown potential for addressing microstructural, mechanical and durability variations in stabilized soils (Hossain and Mol, 2011) (McCarthy et al., 2012), (Ozdemir, 2016), (Mahvash et al, 2017).

In countries where bricks are an essential part of the building materials, waste generation is important. An alternative for its final disposal is the trimilling to generate dust (BD) that can be used as a cementitious material. The potential use of BD is based on the fact that it can be a precursor of "raw material" for the activation and obtaining of a geopolymer, since BD is made up of clay with high silica and alumina contents, which during the firing process of the ceramic piece "brick" generates a microstructural modification in the clay, allowing a greater activation when mixed with alkaline hydroxides to obtain geopolymers.

Material fineness has been identified as an important factor in the behavior of geopolymers. A first approach indicates that the particle size of the BD should be less than 75 µm and that to obtain better cementitious properties the size should be less than 35 µm (Teutonico et al., 1993). Blaine fineness (expressed as the total surface area in square centimeters per gram) has also been used to measure the potential for use of these materials, with the optimum for blast furnace slags considered to range from 4,000 cm2/g to 5,500 cm2/g and values above 5,500 cm2/g having little effect on the mechanical strength of the materials. (Kong and Sanjayan, 2008). However, other studies show that higher fineness in materials also requires additional hydration, leading to increased porosity and lower mechanical strength (Pacheco-Torgal, 2008).

In the case of ashes, the most used are the so-called fly ashes (FA), followed by bottom ashes. According to the ASTM standard, FA are those trapped in boiler filters and have diameters smaller than 75 µm (passing mesh No. 200), which generate reactions in crystalline and amorphous microstructures from the synthesis of alkaline aluminosilicates. (Huseien et al., 2017); which means that pozzolanic properties similar to those of Portland cement can be obtained. Bottom ash corresponds to the residues found at the bottom of the boilers, with particle diameters greater than 75 µm (retained mesh N°200), characteristic of unburned coal; this residue is commonly used as filler material since it does not have high pozzolanic potential. Therefore, they are not considered in soil stabilization.

Obtaining materials with the degree of fineness proposed in the literature for geopolymers represents a disadvantage for the use of construction and demolition waste (CDW) with high brick and boiler ash contents from various industries, due to the costs associated with grinding and screening processes. Therefore, the *possibility of using these materials with coarser particle sizes would broaden the prospects for their utilization. A potential use for these materials would be in the construction of road pavement structures with low traffic volume and erosion control. This work evaluates the behavior of soil mixtures with BD and FA with various grain size ranges, by means of laboratory tests and in a full-scale test track for soil stabilization.*

2. Materials and methods

For the evaluation of the effect of BD and FA as a stabilizer, a laboratory test campaign was initially carried out and subsequently the performance of the same materials was evaluated by means of field tests carried out in a full-scale test section.

2.1. Laboratory Tests

To identify the cementing effect of BD and FA, the effect of grain size and clay mineral content on the stabilization process, mixtures of three soils of different textures were analyzed: sandy (S1), clayey (S2) and silty (S3), alkaline activated with lime residue (RC), evaluating the influence of variables such as moisture and curing temperature, stabilizer dosage and curing age. The effect was evaluated by unconfined compressive strength (UCS).

The BD used was obtained from two sources: residue from the brick manufacturing process and from the sweeping of kilns and grinding of waste fragments from brick kilns. FA comes from the coal combustion processes of a thermoelectric power plant; the unburned coal present in FA normally has a larger particle size than the mineral material.

For the alkaline activation of BD and AF, lime was used using the dosages obtained by (Huffman and Bolvin, 2013).

The materials used were characterized chemically and physically by means of X-ray diffraction - XRD and X-ray Fluorescence - XRF tests, for each type of soil, the BD and FA independently. Additionally, for BD and FA, their internal morphology was obtained by scanning electron microscopy (SEM). All materials were tested for grain size (ASTMD422, D1140) and Atterberg limits (ASTMD4318).

To evaluate the effect of the stabilizer, the UCS of the stabilized material compared to the unstabilized materials was defined as a control variable. For this process, the following were determined as influential factors: the amount of stabilizer, where different dosage levels were estimated to verify the behavior of these materials on the soil structure, the curing time and thus determine the evolution over time of the strength of the stabilized soil with the materials used. Additionally, other factors were considered, such as the type of alkaline activator, curing temperature and curing humidity, which presented values already defined as shown by (Huffman and Bolvin, 2013). These parameters are displayed in (Table 1), and with them a factorial experimental design for the following soil types was proposed: sandy soil (S1), clayey soil (S2) and silty soil (S3).

Table 1. *Variables considered in the replicated evaluation in each soil type (S1, S2 and S3).*

Variable	Description
Stabilizer type	BD, FA
Amount of stabilizer	3%, 6%, 9%, 12%, 24%
Alkaline activator	Lime
Curing Temperature	45°
Curing Humidity	95%
Curing Time	7, 28 y 56 days

The experimental design included a total of 30 combinations, with five replicates for each combination, to increase the level of confidence due to the randomness of the results of each replicate. The replicates were replicated for the three soil types under study. The type of alkaline activator, curing temperature and curing humidity were chosen as recommended by (Huffman and Bolvin, 2013).

With these combinations, cylindrical specimens of 50 mm in diameter and 100 mm in height were made, trying to maintain the typical ratio of 1:2 used in the manufacture of laboratory specimens according to ASTM D2166. The specimens were statically compacted at optimum moisture content to achieve the maximum dry density of the modified Proctor test according to ASTM D1557.

2.2. Field Tests

To evaluate the performance of the stabilized material, a full-scale test track of 150 m in length was constructed using in situ soil as subgrade. This track consisted of a series of 30 m long segments, in which BD and FA were used, and Portland cement and in-situ soil without any stabilizing agent were used as controls. The final thickness of the stabilized subgrade for all the segments was 0.15 m. It should be clarified that these structures were not built with a bearing surface for their protection.

Climate and vehicular loads are stresses that contribute to pavement degradation. In the case of the tropics, water is the one that most deteriorates dirt roads. In the short term, because of short duration and high intensity events, degradation of the pavement texture surface occurs, causing undulations of varying severity and loss of skid resistance by detachment of the fine granular surface material, triggering increases in the value of the IRI. In the long term it can lead to loss of resistance and inadequate structural performance.

During track operation, the track was monitored for 8 months, during which time surface resilient modulus was measured using a Low Weight Deflectometer (LWD) following ASTM E2583 to monitor the variation in structural capacity in terms of Resilient Modulus (RM). International Roughness Index (IRI) using MERLIN equipment (Machine for Evaluating Roughness using low-cost Instrumentation MERLIN), to evaluate variations in megatexture. Sliding resistance through the British Pendulum and macrotexture with the sand stain test, and visual inspection of each of the segments was also carried out. Finally, the expected traffic on the road was quantified in terms of equivalent axles.

Precipitation, rainfall intensity, air temperature and relative humidity were monitored by means of a weather station near the test track during the same inspection period, to establish relationships between the weather and the deterioration of each stabilized cell. Daily and monthly records of precipitation and maximum rainfall intensity were extracted in 30 min durations. The daily precipitation records were verified and completed with remote sensing data from the GPM (Global Precipitation Measurement) mission, from the TRMM (Tropical Rainfall Measuring Mission) version 7 (TMPA 3B42) (TRMM Multi-Satellite Precipitation Analysis).

3. Results

3.1. Chemical characterization

The graph in (Figure 1a) corresponds to XRD to soil S1, (Figure 1b) to soil S2, and (Figure 1c) to soil S3. The XRF tests were performed only on the soils and their quantitative results are presented in (Table 2).

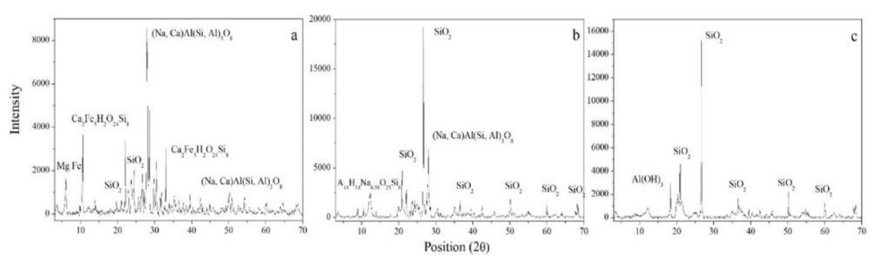

Figure 1. *X-ray diffraction tests for S1, S2 and S3*

The graph in (Figure 2a) corresponds to XRD and scanning electron microscopy (SEM) to BD, (Figure 2b) to FA.

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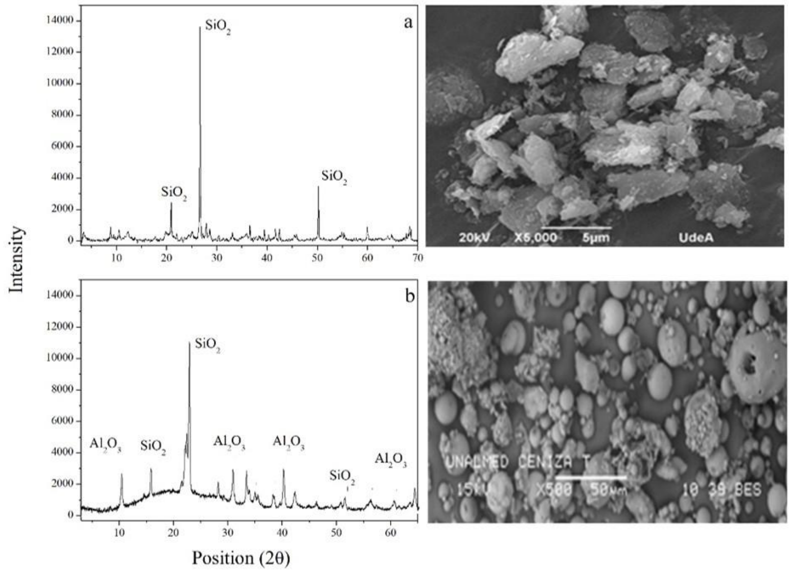

Figure 2. *X-ray diffraction tests for S1, S2 and S3 scanning electron microscopy (SEM)*

Table 2. *XRF to S1, S2, S3 BD and FA*

OXIDE	Composition %p/p				
	Soil S3	Soil S2	Soil 1	BD	FA
SiO_2	41.53	57.42	52.11	48.33	46.2
Al_2O_3	35.45	26.12	19.26	28.6	31.4
Fe_2O_3	20.47	9.54	10.18	11.0	4.75
TiO_2	1.51	0.873	1.27	1.4	-----
K2O	0.656	2.31	0.862	0.6	-----
ZrO_2	0.0549	0.0565	0.0435	-----	0.01
CaO	0.0478	1.73	8.04	2.00	4.46
Cr_2O_3	0.0234	0.0177	0.032	0.1	0.046
CuO	0.0207	-----	0.012	-----	-----

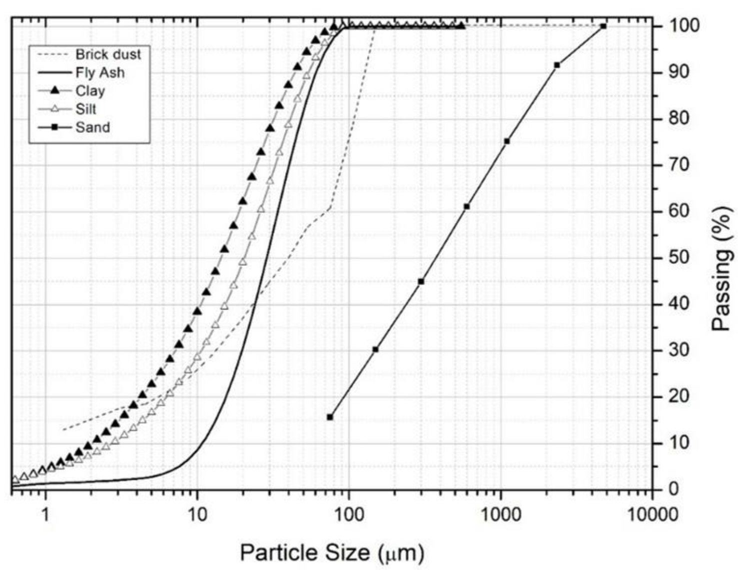

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Figure 3. *Grain-size curve for soils, BD and FA under study.*

Table 3. *Soils data for classification*

	S1 (Sand)	S2 (Clay)	S3 (Silt)
	84	-	-
US sieve N°40-opening: 425 µm (% finer)	50	-	-
US sieve N°200-opening: 75 µm (% finer)	21.84	91.21	86.28
Specific gravity	2.77	2.70	2.70
Liquid Limit (%)	-	57	66
Plastic index (%)	-	32	17
USCS classification (ASTM D2487)		CH	MH
AASHTO classification	A-1b	A-7-6	A-7-5
	S1	S2	S3
2 mm N°10	84	-	-
425 µm N°40	50	-	-
75 µm N°200	21.84	91.21	86.28
Specific Gravity	2.77	2.70	2.70
LL (%) (ASTM D4318)	-	57	66
IP (%) (ASTM D4318)	-	32	17
CUS Classification		CH	MH
AASHTO Classification	A-1b	A-7-6	A-7-5

Modified Proctor compaction tests were performed according to ASTM D1557, obtaining the results shown in (Figure 4) and (Figure 5) for the three types of soil added with BD and FA.

For the three types of soil added with BD and FA, the data are shown as a consolidated curve of maximum dry density and as an optimum moisture curve for each dosage level used, showing the variation trend of these two variables when the addition of BD or FA increases.

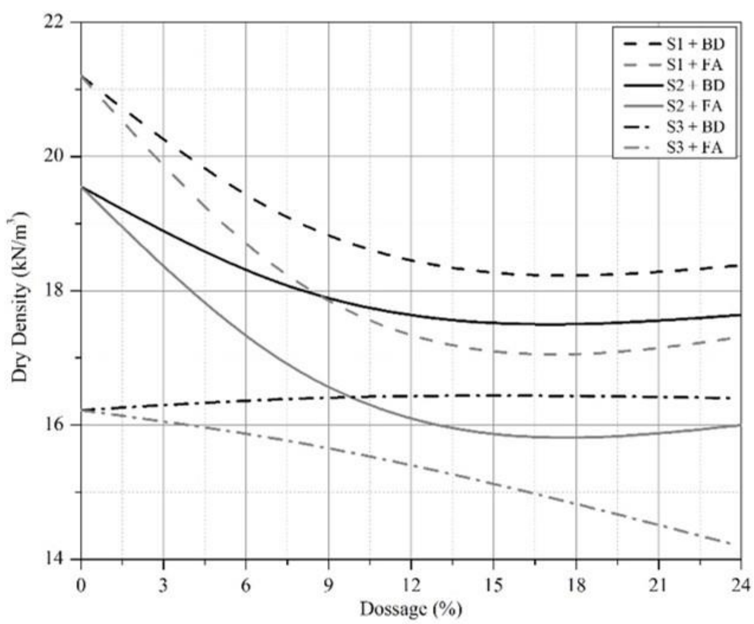

Figure 4. *Consolidated maximum dry density data for the soils under study added with BD and FA in the proposed dosages, obtained from compaction tests.*

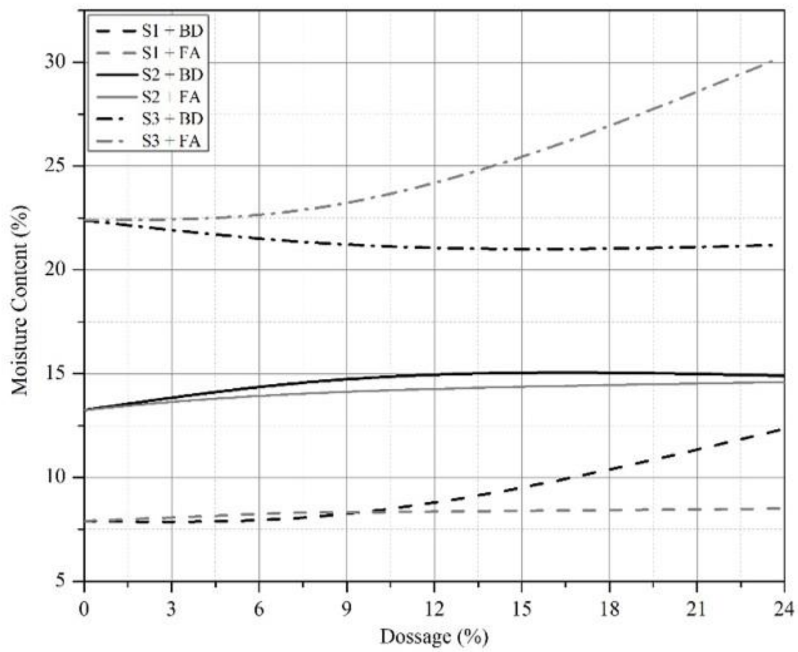

Figure 5. *Consolidated optimum moisture data for the soils under study with BD and FA in the proposed dosages, obtained from the compaction test.*

3.2 Strength test

After making the specimens according to the experimental design shown in (Table 1) and verifying that they had reached their curing age, the unconfined compression test was performed. (Figure 6) shows the results obtained according to the type of soil, the stabilizer used, the stabilizer dosage and the curing age.

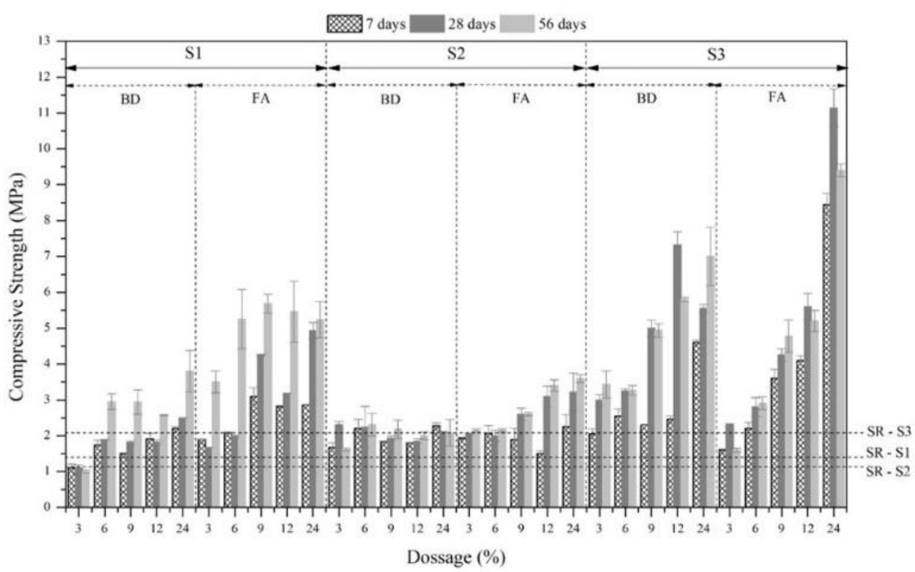

Figure 6. *USC results for each soil type according to dosage, type of stabilizer applied and age of cure.*

As a comparison standard, the UCS of specimens prepared with compacted soils without the addition of BD or FA were *determined; these are shown in (Figure 6) as dotted lines as SR, which represents the reference soil without stabilization.*

(Table 4) shows the results of the ANOVA analysis proposed to analyze the experimental design according to the factors presented in (Table 1), for which all the assumptions of independence and normality were verified, and the p-values were defined. For this analysis, a null hypothesis was proposed, which is that the factors Type of stabilizer, Dosage of stabilizer and age of curing, do not have a significant effect on the variable USC. Then, for a significance $\alpha = 0.05$, i.e. an associated confidence of $\beta = 95\%$, it can be said that if the p-value is less than α, the null hypothesis is rejected. This approach was used according to the type of soil used, in this case, for S1, S2 and S3.

Table 4. *p-values obtained from the ANOVA analysis performed to analyze the effect on the UCS*

Factor in the regression	UCS (Mpa) p - value S1	UCS (Mpa) p - value S2	UCS (Mpa) p - value S3
Lineal			
Stabilizer	0,001	0,013	0,180
Dossage	0,001	0,118	0,001
Curind age	0,001	0,038	0,006
Double interactions			
Stabilizer * Dossage	0,256	0,154	0,005
Stabilizer * Curing Age	0,022	0,099	0,341
Dossage * Curing Age	0,339	0,634	0,505

3.3 Field Tests

The test track used for the actual evaluation of the material's performance (strength and durability) was built on an operating road considered to have a low traffic volume (ESALS > 0.5E6), located in northern Colombia. The construction process followed the general Colombian construction specifications and the Manual for stabilization of low traffic volume roads with alternative materials, by National Road Institute of Colombia – INVIAS. The stabilized in-situ soil corresponded to a sand, which matched very well with the S1 type soil evaluated in the laboratory. The first segment of the test track was constructed with in-situ soil stabilized with 12% lime-activated BD, the second with 12% lime-activated FA, taking into account a compaction with this dosage, compacting the soil according to the maximum dry density obtained in (Figure 4) at an optimum compactation humidity according to (Figure 5). Dossage of 12% in both stabilizers was used because it complied with an increase in resistance to the application of a load and good performance in the compaction processes in the face of the demand for lower densities, which corresponds to (Hidalgo et al., 2018). The third segment was built with 5% cement addition, and the fourth was constructed without any stabilizer addition. The last two segments were used as a comparison standard with respect to the other segments stabilized with BD and FA.

On each segment, periodic evaluations of the surface Resilient Modulus were carried out, which consisted of taking punctual measurements in 6 zones of each cell, specifically on the footprint used for the passage of the tires of vehicular traffic. In this way, readings were taken on the left and right footprint at 10, 15 and 20 m from the beginning of the cell. No readings were taken at the beginning and end to avoid the edge condition generated by the transition zone between stabilized cells. Additionally, the International Roughness Index (IRI), skid resistance and macrotexture were measured. A total of 8 monitoring campaigns were carried out on the test track, obtaining the results shown below.

(Figure 7), (Figure 8), (Figure 9) and (Figure 10) present the results of resilient modulus, International Roughness Index (IRI), coefficient of resistance to sliding (CRD), and surface macrostructure through equivalent height (MTD).

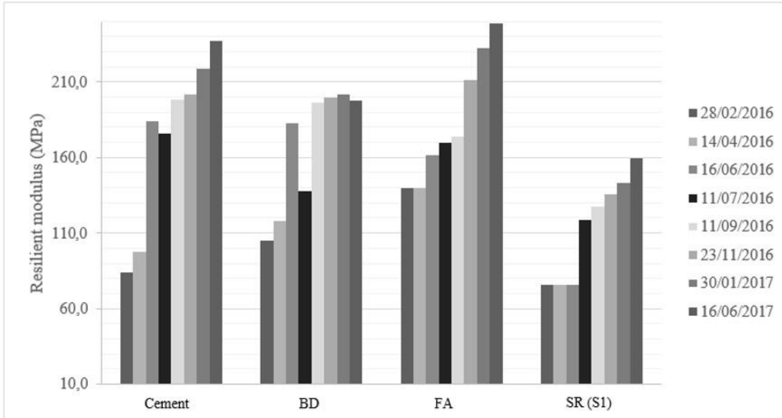

Figure 7. *Resilient modulus results*

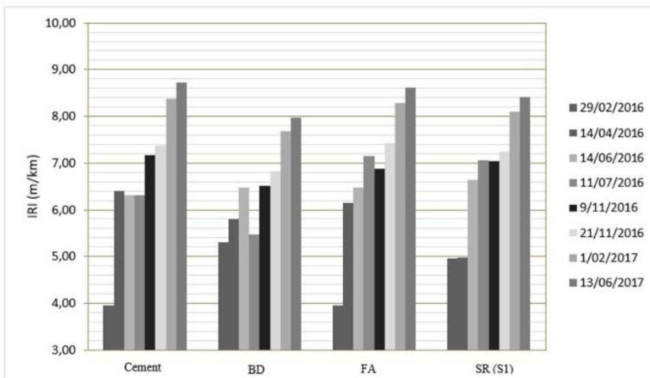

Figure 8. *IRI Results*

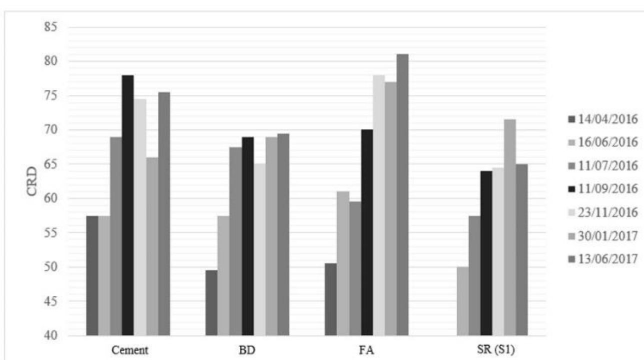

Figure 9. *CRD Results*

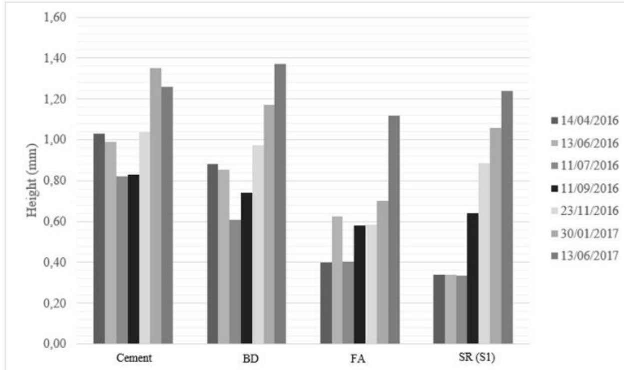

Figure 10. *CRD Results*

4. Discussion

According to the results of the XRD tests show that the S1 grit (Figure 1c) presented very defined peaks indicating that the materials that compose it are of high crystallinity, which provides high physicochemical and mechanical stability to the mineralogical components. Table 2 indicates large amounts of silicon oxide, which constitutes more than 50% by weight. Other oxides such as aluminum, iron and sodium are also present associated with the albite.

For the S2 clay, XRD (Figure 1 b) and XRF (Table 2) tests show that the predominant oxides are those of silicon, aluminum and iron, characteristic of montmorillonite clays. Montmorillonite is a type of phyllosilicate with swelling capacity when in contact with water. Both silica and albite present in this type of soil are associated with silicon and aluminum oxides with a crystalline microstructure that does not present plasticity properties, being these of great abundance in the earth's crust, they are generally mineralogical components that are associated with sands.

For the S3 silty soil, XRD tests show the presence of gibbsite, which is more common in lateritic soils, and is associated with a weathering of the soil enriched in alumina (see (Table 2)), where the final products are usually of high concentration of aluminum hydroxides. (Figure 1) a shows the presence of kaolinite type clays and although the diffractogram shows a characteristic peak of gibbsite, this is not representative since there are other peaks associated with silicon oxide as the main crystalline component. (Table 2) shows that there is a high concentration of aluminum oxide that may be associated with the presence of gibbsite.

(Figure 2a) and (Figure 2b) shows the quartz phases in the BD and FA respectively. The large peaks are indicative of mineralogical phases with high stability, which indicates that thermodynamically they are not very reactive to external chemical agents. Although these phases are present, no mullite crystals are found, which is the most stable phase of the materials composed of silica and alumina. The halo between 16 and 37 in (2θ), identifies the amorphous phase in the BD and FA, this is the one of greater interest mainly because from it the new cementitious phases can be formed when the BD reacts with lime. Also, the SEM show irregular grains high concentrations of silicon oxide and aluminum oxide, indicating that cementitious phases can be easily formed from this product by reacting with the lime.

According to (Figure 1), the BD showed irregular grains with high concentrations of silicon oxide and aluminum oxide, indicating that cementitious phases can be easily formed from this product when reacting with lime.

In (Figure 3) and (Figure 4), it is observed that the addition of BD and FA activated with lime generate changes in the compaction process of the three soils. In the case of soil S1, a decrease in maximum dry density and an increase in optimum moisture can be seen, which is due to the increase in fine particles. For soil S2, an opposite process is observed, in which the maximum dry density increases and the optimum moisture content decreases, which can be explained by the increase in the amount of coarser particles and in the pozzolanic reactions that are generated. For soil S3, a process like that of soil S1 is presented in terms of the decrease of the maximum dry density and the increase of the optimum humidity, which is difficult to explain since, due to its fines content, it should be the opposite process; however, this material presents a lower amount of SiO2, so the pozzolanic reaction is lower.

According to the ANOVA performed and shown in (Table 4) and (Figure 5), the stabilizer material was statistically significant in the variation of the UCS for soil S1 and S2, where -p values of 0.001 and 0.013 were presented, respectively. This means that there were large differences in the average values of UCS, for this case, using BD as an additive, there were average *values of 2.05 MPa in soil S1 and S2. In the case of the addition of FA, average values of 3.6 MPa were presented for S1 and 2.4 MPa for S2, presenting increases of up to 50% with respect to the strength obtained with BD. For the case of soil S3, there was no significant effect with respect to the use of the stabilizer, represented in a -p value of 0.18, where, for the case of BD addition, average values of 4.3 MPa were presented, and for the case of FA addition there were average values of 4.8 MPa.*

For the case of the dosage level, both for BD and FA, -p values of 0.001 are identified for S1 and S3 soils that indicate statistically significant influence on the variation of the UCS of the stabilized soil when the dosage level increases. It was found that when soil S1 is added with BD or FA, UCS increases from average values of 1.6 MPa with 3% additions to average values of 3.7 MPa for 24% additions. Additionally, since the S1 soil without additions presents a UCS value of 1.4 MPa, regardless of the type of dosage level, an increase in strength values of up to 164% is achieved. In the case of soil S3, variations in the UCS ranged from average values of 2.3 MPa to 7.8 MPa, achieving improvements in the soil between 10% and 271% according to the dosage level.

For soil S2, although a -p-value of 0.118 was presented, it is also shown in (Figure 5) that for both FA and BD, the novel dosages used did not have a significant influence on the UCS result, varying between average values of 1.9 MPa to 2.5 MPa. In spite of this, the unstabilized S2 soil presents a value of 1.1 MPa, where improvements between 75% and 125% are achieved, which means that lower or intermediate dosages can be used to achieve improvements in strength when the soil presents these characteristics.

For soils S1, S2 and S3, with -p values of 0.001, 0.038 and 0.006 respectively, as well as for the described ages of 7 days, 28 days, and 56 days, indicate that there is a significant influence of this variable on the strength when BD or FA is added. For soil S1, average values of 2.2 MPa for 7 days, 2.4 MPa at 28 days and 3.7 MPa at 56 days were found, generating an increase in strength up to approximately 70% average over time, with greater intensity when FA is added. For soil S2, average values of 1.92 MPa for 7 days, 2.32 MPa at 28 days and 2.46 MPa at 56 days were found, generating an increase in strength up to approximately 30% average over time, with greater intensity when FA is added at 12% or 24%, as shown in (Figure 5). For soil S3, although there is an important variation, an interesting trend was found when the curing age is 56 days when the soil is added with BD or FA. Average values of 3.2 MPa at 7 days, 4.8 MPa at 28 days and 4.67 MPa at 56 days were found. In this sense, for this type of soil, there was a tendency to decrease the UCS value by 3% on average, where the maximum UCS at 28 days of curing could be found.

These values are consistent with results obtained on soil blocks added with a mixture of lime and BD reported by (Teutonico et al., 1993) which obtained strengths on the order of 1 to 2 MPa and greater durability than other systems based on lime, cement and sand. An important difference in this work is that BD particles are mostly retained on the 75 µm sieve (Figure 2b), whereas (Teutonico et al., 1993) state that the particle size of the BD should be less than 75 µm and preferably less than 35 µm. The results of the present work are more consistent with the results of the study by Pacheco-Torgal et al. (Pacheco-Torgal et al., 2008) who indicate that having a higher fineness in the materials also requires additional hydration, which leads to an increase in porosity and lower mechanical strength. By means of an ANOVA analysis (Hidalgo et al., 2018) verified that for the materials evaluated there is a significant effect on the strength of the material.

In general, the addition of BD and FA generated an increase in the strength of the soils compared to the unstabilized soil, which demonstrates the stabilizing capacity of these materials. This can also be explained by the higher contents of $SiO2$ *57.4% in S2, 52.1% in S1 and 41.5% in S3 and lower contents of aluminum oxides* $Al2O3$ *which are respectively 19.26%, 26.1%, 35.5%. As for the FA, substantial increases in strength were obtained from 3% addition and with greater intensity at 28 days of curing.*

(Figure 6) shows the evolution of the Resilient Modulus of the road surface evaluated from the implementation of the Light Weight Deflectometer (LWD), it is observed in the sector treated with brick dust the consistent and maintained increase of resistance over time compared to other additives used for stabilization, such behavior favors the commissioning of the corridor in a short time after being stabilized, compared to the other proposals studied. The resistance achieved by the road surface is comparable to a CBR 55%, which could represent a granular base.

In relation to the value of the International Roughness Index (IRI – (Figure 7)), during the observation and monitoring period, it is identified that brick dust presents the lowest severity, guaranteeing among the alternatives analyzed the best performance in terms of safety and comfort, which results in lower vehicle operating costs.

As for the coefficient of resistance to sliding (CRD) measured with British pendulum (Figure 8), it is observed that the maximum value reached during the evaluation time reaches 70 quickly for the section treated with brick dust and remains relatively constant until the end of the monitoring period, while the other cementitious products increase until reaching values of 80 in terms of the surface macrostructure, measured through the equivalent height (MTD), from the sand stain technique, for the section stabilized with brick dust intermediate values are observed, which justifies the behavior measured from the

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coefficient of resistance to sliding (CRD).

4.1 Failure mechanism test track BD

The section stabilized with BD generally showed losses of fine material throughout its area (see (Figure 10)). This process was constant throughout the study period, with some superficial losses. The presence of loose aggregates was also identified, concentrated at the ends of the section. Thus, it is the result of the deconfinement caused in some areas of the section due to the combined action of the weather and vehicle traffic, generating a greater volume of particulate material as traffic passes.

Figure 11. *Deterioration evolution in the BD track.*

4.2 Failure mechanism FA test track

The section stabilized with AF presented some tire marks that later became erosion ruts, and throughout the evaluation period other ruts were formed concentrated in the axis, presenting high severity due to the large percentage of affected area they covered (See (Figure 10)). Crocodile skin was also identified at the ends of the road and a pothole in the first 5m of the section, as a result of the deconfinement of the stabilized layer in that area, which later became a loss of the layer by approximately 5 cm. In spite of the erosive processes identified in this section, it was one of the most resistant due to the hardness produced by the stabilization process in the layer. Compared to the other cells, it showed less loss of fine material, which makes it a good dust suppressor.

Figure 12. *Evolution of stabilized section with FA*

5. Conclusion

The addition of BD and FA activated with lime generated favorable changes in the compaction process of the materials. An increase in the maximum dry density and a decrease in the optimum moisture content were observed, which can be explained by the increase in the amount of coarser particles and in the pozzolanic reactions generated.

Likewise, fine granular soils (silts and clays) added with BD and FA show increasing UCS results that can reach values up to 150% of the strength of the soil without addition. For sandy soils such as soil S2, the UCS results are improved between 75% and 125%.

The sector treated with BD type stabilizer showed a consistent and maintained increase of the Resilient Modulus MR over time, compared to other additives used for stabilization in the field. The strength achieved by the soil is comparable to a CBR 55%, which could represent a granular base.

The increase in the strength of soil treated with FA and BD activated is attributed to the potential of these stabilizers to form more robust internal structures through their reaction with lime and water. This phenomenon is evidenced by the silica and alumina contents identified via XRD and XRF, which together account for more than 75% of the composition of both stabilizers. Furthermore, the internal structure morphology observed through SEM confirms the formation of a more cohesive and durable matrix, thereby significantly enhancing the strength of the stabilized soil.

The sector stabilized with BD presented in the field lower severity of the International Roughness Index among the alternatives analyzed, even with unstabilized surfaces, which translates into higher safety and comfort indexes and lower vehicle operating costs.

In terms of skid resistance and macrotexture, it is concluded that in surfaces stabilized with BD there is a rapid increase in the CRD Index, explained by the erosive process of the wheel-surface interaction. This is constantly maintained by the erosive process of the wheel-surface interaction.

6. Author Contributions

Cesar Hidalgo: conceptualization, formal analysis, and writing—review and editing; Fredy Muñoz: investigation, data curation, formal analysis, writing—original draft preparation, writing—review and editing; Gloria I. Carvajal: project administration, funding acquisition and visualization, formal analysis, writing—review and editing; Mario Rodriguez: methodology, supervision and reviewing. All authors have read and agreed to the published version of the manuscript.

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