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Analysis of the physical, hydraulic, and mechanical properties of sugar bagasse ash-clay geomaterial

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ABSTRACT

Sugar cane bagasse ash (SA) is the result of the incineration of residues in the production of sugar which has as its final disposal the sanitary landfills generating environmental impacts. The practice of the circular economy for using SA ash as a stabilizer of clay soils in highway bases and sub-bases requires the study of the potential of ash as an alternative cement. Soil stabilization is commonly done with the addition of cement or lime; however, the production of these materials releases CO2 into the atmosphere. This research estimates the potential use of SA ash as a cementing agent considering the physical, hydraulic, and mechanical properties of clay soil mixed with percentages of 6, 8, and 10% of Uncalcined Sugarcane Bagasse Ash (USA) and Calcined Sugarcane Bagasse Ash (CSA). X-ray fluorescence spectrometry (FRX), methylene blue value test, specific gravity, dry unit weight, granulometric analysis, and Atterberg limits tests were carried out to evaluate the physical properties of the mixtures. One-dimensional consolidation tests, soil water characteristic curves (SWCC), standard Proctor compaction, unconfined compression, and direct shear were carried out to estimate the mechanical and hydraulic properties of the mixtures. An improvement in the physical, hydraulic, and mechanical properties was found with the addition of USA and CSA. Finally, based on the analysis of the physical, hydraulic, and mechanical properties of the Soil-USA and soil-CSA samples, it was determined that the best option as an alternative cementitious agent is found in the 8% Soil-CSA mixture due to the improvement in the plasticity index, gravity density, angle of friction, cohesion, and unconfined compressive in comparison with the other samples and the original soil. However, it is essential to mention that this cementitious addition can prejudice the hydraulic properties and consolidation process. It is vital to consider those parameters when realizing any geotechnical design with this mixture.

Keywords: Soil stabilization; Sugar cane bagasse ash; Physical-mechanical properties of soils and cementitious materials.

1. INTRODUCTION

Currently, waste is necessary to reduce the environmental impact by implementing sustainable development and circular economy objectives. Some waste is disposed of in landfills generating environmental pollution without considering its properties and the potential for reuse in fields such as construction. An example of the above is the case of sugar cane bagasse ashes which are subjected to a combustion process generating potential pozzolanic properties. This material can be used as a substitute for cement for road applications where performance is low – medium [1]. The process for obtaining sugarcane by-products (e.g., sugar and alcohol) generates a residue known as sugarcane bagasse ash (SA).

It should be noted that a vast amount of carbon dioxide (CO_2) is released during the burning of sugarcane bagasse. However, the balance in gas emissions is statistically insignificant for the general process because, during the cycle and culture of the primary material, the generation of CO_2 is compensated [2]. Colombia is the seventh-largest cane producer in the world. Its residue is called bagasse and is used as fuel in sugar production;

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the resulting ashes are called SA [3]. For every ton of sugarcane processed, 270–290 kg of bagasse are generated, and each ton of bagasse produces 23.8 kg of SA. The ash's cementitious properties and chemical compounds depend on the combustion temperature, the bagasse's purity, the collection place, and the boiler equipment [4].

The regulations and specifications of Colombia Standard INV E, establish cemented materials' resistance requirements. To improve their mechanical properties, soils that do not meet these requirements are stabilized using binders such as cement or lime. The addition of cementing agents to soils aims to increase resistance, bearing capacity, and durability in humid conditions, for soil mixtures with cement, lime, bituminous products, silicates, and natural or synthetic materials. Cement production generates 5% of total CO2 emissions annually, making them unsustainable materials that less harmful options must replace. Calcinated SA has amorphous silica contents more significant than 60% regarding the chemical composition and degree of reactivity. This characteristic can allow the use of this residue as a pozzolanic material and, therefore, reduce the expenses and the environmental impact related to its disposal in the environment. In addition, the incorporation of ash can add economic value to the agro-industrial residue and provide technical and environmental advantages with the partial replacement of Portland cement to reach of requirements for INVIAS.

Several authors have proven the viability of calcinated SA as a stabilizing agent for different soil types [5–9]. In general, the authors showed that stabilization with calcinated SA improves strength and facilitates the processes inherent to environmental procedures by reducing residues from the sugar and alcohol industry. In addition, several studies demonstrate that ash is a viable by-product for incorporation as a pozzolanic material in the construction industry, generally forming contents more significant than 60% of amorphous silica [4, 8]. Therefore, using SA as a precursor in alkali-activated systems presents a high potential as a pozzolan, in addition to presenting a new possibility of disposal and reduction of costs inherent to the treatment and disposal process. Thus, this article studies the effect of adding SA (calcinated and non-calcinated) to clay soils in Colombia. The mechanical properties, unsaturated properties (studying the SWCC), and physical-chemical properties of the compacted soil-SA compacted blends are investigated.

2. MATERIALS AND METHODS

2.1. Materials

The materials that were handled in this study for the elaboration of soil samples with ash are high plasticity clay (CH) as the primary matrix, USA (uncalcined sugar cane bagasse) ash, and calcined sugar cane bagasse ash (CSA) as cementitious materials. The soil used for the investigation is from the municipality of Santana Boyacá (Colombia). Three samples were taken by piping at a depth between 3 to 10 cm on the road that connects the urban area of the municipality with the Las Palmas village, as shown in Figure 1.

The distribution of grain sizes of the soil, the CSA, and USA ash is shown in Figure 2. These were obtained based on the INV E standard determination of coarse particle sizes and granulometric analysis employing the hydrometer method to complete the gradation curve. The soil contains 13.12% gravel, 21.28% sand, and 65.6% fine. The hydrometer test determined that 65.6% of the fines, 35.6% correspond to clay, and 30% to silt. The ash size ranges from 0.1 mm to 0.001 mm. 40% of the particles of the CSA ash have a size between 0.1 to 0.01 mm while the USA ash has similar proportions in all particle sizes. The Atterberg limits were based on the Colombian standard INV E. For the natural soil, a liquid limit of 77.81%, a plastic limit of 30.61%, and a plasticity index of 47.2% were obtained, with which the soil was classified as clay with high plasticity (CH) in concordance with the USCS–Unified Soil Classification System. Due to the high percentage of clay, a methylene blue test was carrier, where the presence of clay in the natural soil sample was confirmed. The gravity and specific weight of the soil were 2.8 and 1.65 g/cm^3, respectively.

The chemical characterization of calcined and uncalcined sugarcane bagasse ashes is represented in Table 1, which was carried out using the X-ray fluorescence spectrometry technique (FRX). The test revealed that the soil contains mainly iron (Fe) at 86%, as the second element is titanium (Ti) with 6% and, around 2% is Au, Pd, Cd, Ag, Co, and Zn. The main chemical element of the USA is Nickel (Ni) with 71.53%, followed by Silicon (Si) at 11.04%, Titanium (Ti) at 8.4%, and approximately 9.0% of Al, Pd, Ag, Cd, and Cu. SETAYESH et al. [10] observed the presence of silicon in addition to Al, Fe, Mn, and Ti in the ashes, confirming the properties of ash pozzolanic. The anterior statement confirmed the ce-mentitious properties of USA ashes as they contained aluminum and silicon.

2.2. Samples Preparation

In the preparation of all the specimens, the required amounts of calcined and uncalcined cane bagasse ash were measured as a percentage of the dry soil weight, in total six samples were made: 1) SUSA 6: Uncalcined Cane

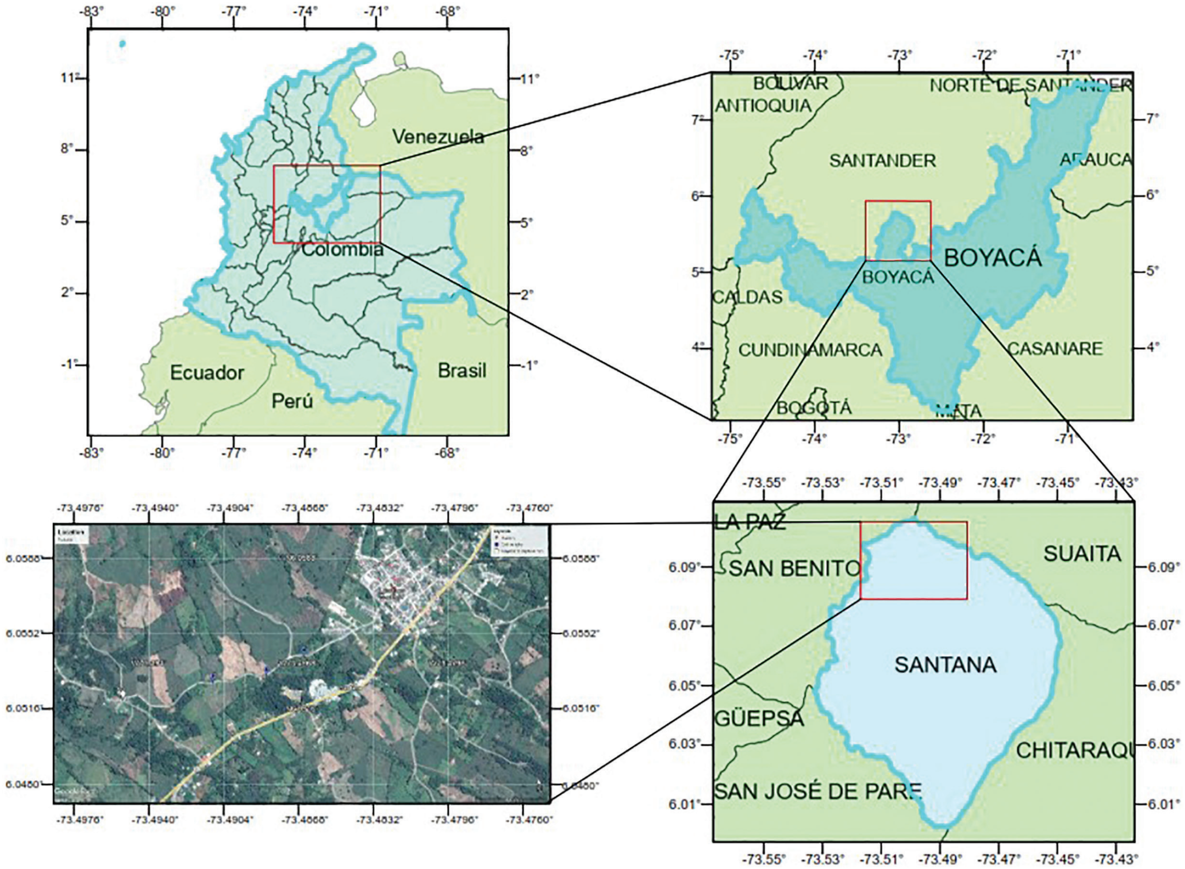


Figure 1: Location in the municipality of Santana, Boyacá, Colombia. Site of soil extraction.

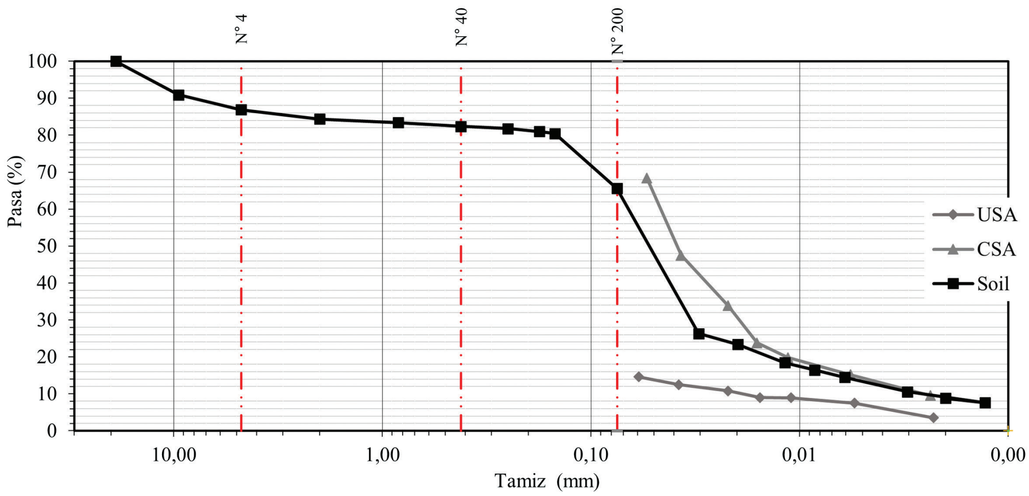


Figure 2: Granulometric curve of the soil, USA, and CSA.

Table 1: SA and USA soil chemical properties.

CHEMICAL COMPOST	CONCENTRATION BY WEIGHT (%)									
	NiO	SiO_2	FeO	TiO_2	Al_2O_3	PdO	CdO	Ag_2O	CuO	MnO_2
Sugar Ash (SA)	0.5	2.4	85	5	1.3	2.1	1.5	1.2	1	0
Uncalcined Sugar Ash (USA)	71.53	11.04	8.4	0	0.8	0.9	1	0.7	0.8	4.83

Figure 3: Soil samples with calcined and uncalcined sugarcane bagasse ash.

Bagasse Ash at 6%, 2) SUSA 8%: Soil – Uncalcined Cane Bagasse Ash at 8%, 3) SUSA 10%: Soil – Uncalcined Cane Bagasse Ash at 10%, 4) SCSA 6%: Soil – Calcined Cane Bagasse Ash at 6%, 5) SCSA 8%: Soil – Calcined Cane Bagasse Ash at 8% and 6) SCSA 10%: Soil – Calcined Cane Bagasse Ash at 10%.

The soil was mixed with the dry ash manually and then added the percentage of water corresponding to the optimum humidity established in the Proctor test, as seen in Figure 3. The mixture of soil and sugarcane bagasse ash was compacted in a 10.1 cm deep mold of diameter by 11.16 cm in height, the samples were removed, and the tests were carried out.

As a reference, the investigation "Analysis of the fatigue properties of macadam stabilized with lime compacted with fly ash and vertical vibration" was taken, where the fatigue properties of soil with 17%, 19%, and 21% lime – ash [11] and the article "Durability of enzymatically stabilized expansive soil in road pavements subjected to degradation by humidity" where the properties of soil with 1% soil subjected to changes in humidity were evaluated [12].

3. RESULTS AND DISCUSSIONS

3.1. Effect of USA and CSA ashes on physical properties of clay

Figure 4 shows the results obtained from the specific gravity test. The specific gravity result of the test clay was 2.73, located in the range of 2.6 to 2.8, which corresponds to the theoretical values of the soil related by some authors [4, 7]. The specific gravity of the USA and CSA is around 1.5, which is lower than that found in investigations to stabilize lateritic soils [6, 8, 9] and fly ash in India with values of 1.8 y 1.9 [13]. The SUSA samples had a specific gravity between 2.5 to 2.67, while the specific gravity of SCSA was between 2.2 to 2.7, which indicated a reduction because the specific gravity of the ashes was lower than the specific gravity of the virgin soil. A lower variation of specific gravity is observed in the SUSA samples compared to the SCSA samples, which indicates a lower density of the material with the water absorption capacity.

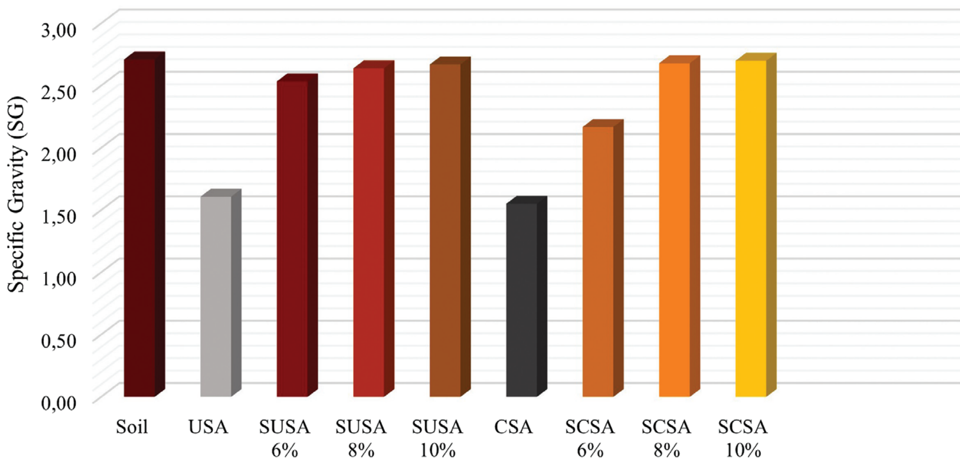


Figure 4: The specific gravity of tested soil, ashes, SUSA, and SCSA.

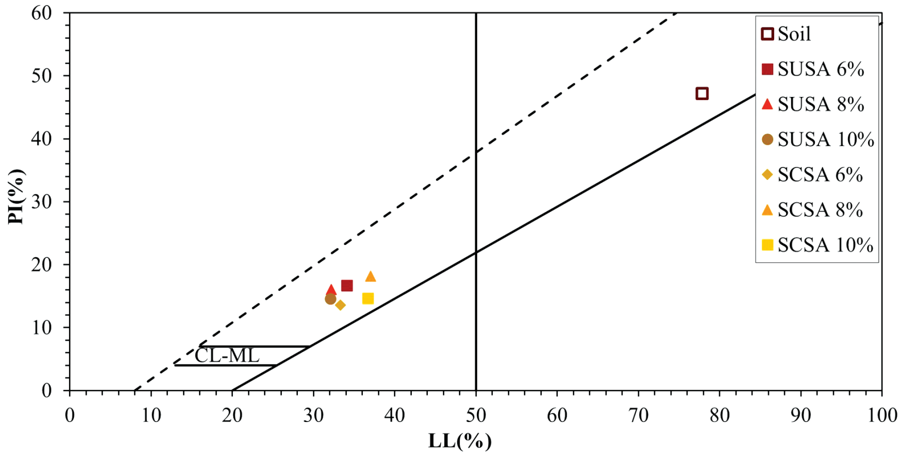


Figure 5: USCS plasticity chart for soil samples, SUSA and SCSA.

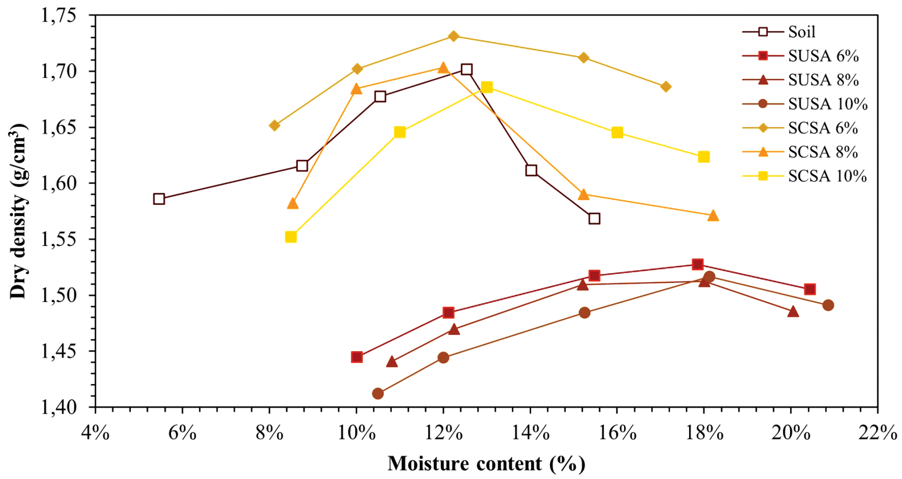


Figure 6: Results of soil compaction tests, SUSA, and SCA.

The high plasticity index is related to soil expansion and instability. On the other hand, the Atterberg limits are directly related to water adsorption and clays' specific surface. In general, it can be said that fly ash improves the properties of clay soils by reducing volumetric changes [13].

Therefore, the Atterberg limits were evaluated in the different mixtures of ash soil, as shown in Figure 5. The LL of the soil was 77.81% and the IP was 47.20%, indicating a high capacity for water adsorption and possible expansion. The LL of the SUSA ash is 32.8% and the IP 16%, while the LL of the SCSA samples is 35.6% and IP 15%, which evidenced a substantial decrease in the plasticity index, the water adsorption capacity and possible reduction in soil expansion.

As can be seen in Figure 6, the moisture relationship test – dry unit weight in soils (Standard compaction test) to compare the different samples and determine which specimen had better compaction and more excellent resistance. The results showed that the soil samples with CSA keep similar values of maximum dry density and lower optimum moisture compared with virgin soil, however, the 6% SCSA sample obtained the best results with a maximum dry density of 1.73 g/cm^{3,} and optimum water content of 12.2% represented a little increase compared with clay specimen. On the other hand, the soil samples with USA decreased proportionately to the clay samples' maximum dry density, and the optimum water content rose, showing the worst behavior mixture of all samples [14, 15].

3.2. Effect of USA and CSA ash on hydraulic properties of clay

A unidimensional consolidation test was carried out to determine the coefficient of permeability and the coefficient of consolidation (Cv) for soil samples, SUSA, and SCSA using the methodologies of Taylor. As seen in Figure 7, Cv decreased in most specimens compared with the clay soil; however, the SUSA samples increased their permeability generated by bigger ash particles. Moreover, in the SCSA specimen, both the consolidation coefficient and permeability showed a decrease that can be explained due to the smaller particle size of the CSA compared with the other specimens. The effect of ash percentages on Cv increase when the uniaxial load is higher. The higher the Cv coefficient, the faster the consolidation will occur, which will improve the geotechnical properties of the soil [16, 17].

Due to the reduction of the permeability of the SCSA mixtures in the consolidation test, the suction tests were carried out on these using the WP4C dew point hygrometer, a device that allows quick measure the suction of soil for a given moisture value. The samples were prepared and left at saturation for 24 hours. The W4PC was turned on and left for 30 minutes to stabilize. Once the suction reading was taken, the sample was weighed (wet weight) and placed in the oven at 110ºC for 24 hours to determine the moisture [18]. The characteristic curve (SWCC), called suction and saturation retention curves, defines the relationship between suction and soil moisture directly related to permeability [19, 20].

On the other hand, suction is essential to the shear strength of unsaturated soils due to apparent cohesion; therefore, the maximum shear stress occurs at larger suction values [18]. SCSA samples have a loss of matric suction, decreasing the retention capacity compared to natural soil samples, so the ash does not provide apparent cohesion to the material [21]. The suction generated by the materials was found with the WP4C equipment in Figure 8, which is compared with the characteristic curve in the clays described by VAN GENUCHTEN [22–24].

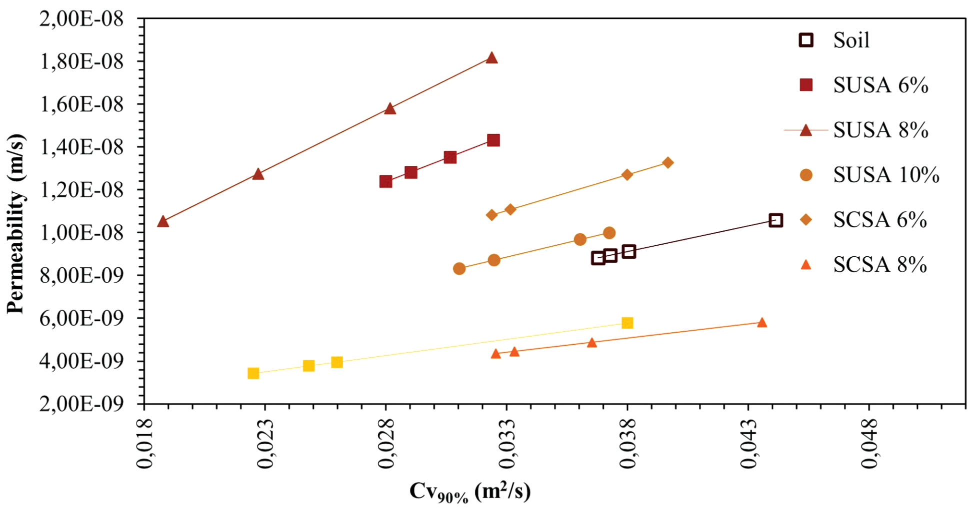


Figure 7: Consolidation coefficient vs permeability in soil samples, SUSA and SCSA.

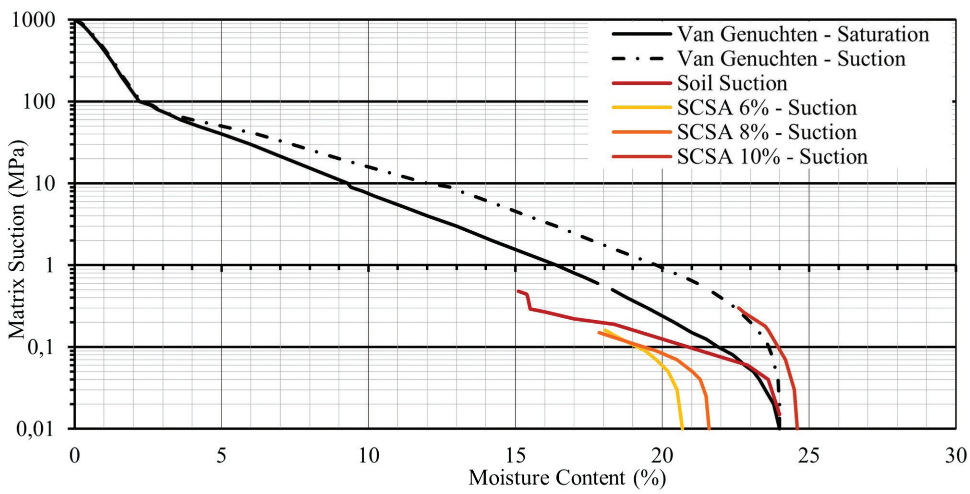
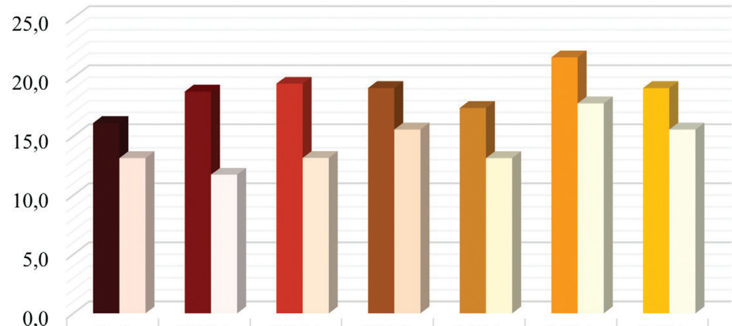


Figure 8: Van Genuchten water characteristic curve for soil and SCSA.



	Soil	SUSA 6%	SUSA 8%	SUSA 10%	SCSA 6%	SCSA 8%	SCSA 10%
ϕ (°)	16,1	18,8	19,4	19,1	17,4	21,7	19,1
C (kN/m²)	13,1	11,7	13,2	15,6	13,1	17,8	15,6

Figure 9: Friction and cohesion angle in soil samples, SUSA and SCSA.

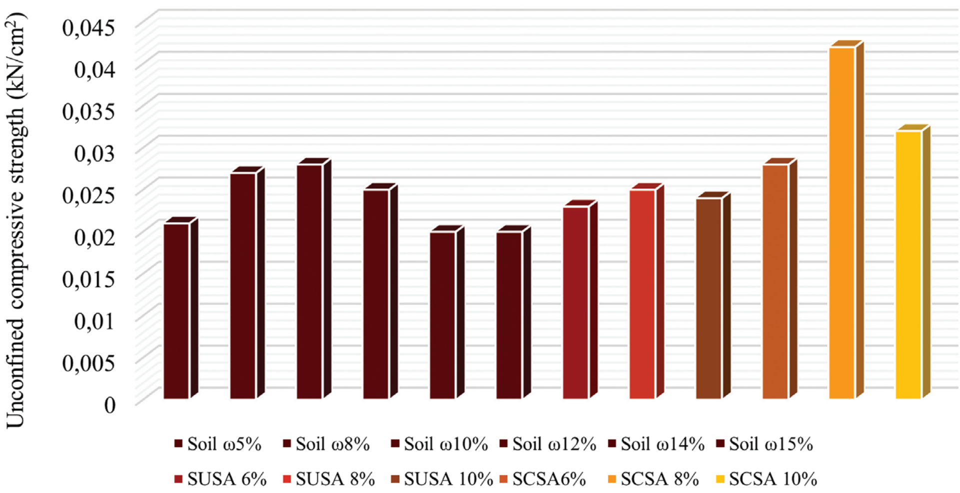


Figure 10. Unconfined compressive strength in soil samples, SUSA and SCSA.

3.3. Effect of USA and CSA ash on mechanical properties of clay

Direct friction angle and cohesion measurements were made using the shear strength test. To evaluate the improvement of the geotechnical properties in the soil samples, SUSA and SCSA, as can be seen in Figure 9. Each sample was manufactured with 98% of the optimum moisture carried out in the Proctor tests; the properties of the SUSA samples improved slightly, while the SCSA samples significantly increased. The SCSA sample went from 17.4 to 21.7° of friction angle and from 13.1 kN/m^2 to 17.8 kN/m^2 of cohesion, obtaining the best results in the test. The virgin soil has a friction angle of 16.1° and cohesion of 13.1 kN/m^{2,} while the best SCSA 8% specimen had a friction angle of 21.7° and cohesion of 17.8 kN/m^2. This is because the ash generates cementation between the particles of the mineral skeleton of the soil, improving cohesion and friction angle with curing time [25].

Finally, the shear strength of the soil was evaluated at different moisture percentages, the samples of SUSA and SCSA were manufactured with 98% optimal moisture of each. The unconfined compressive strength in the SCSA samples increased, while in the SUSA samples it decreased, as can be seen in Figure 10. These results demonstrate the cementitious and mechanical properties of the soil samples, with calcined ash having a better adherence between particles [13]. The specimen that obtained the highest unconfined compression is SCSA 8%, which reached 0.042 kg/cm^2 because adding ashes to the soil and silicon content generates the formation of cementitious compounds that bind the particles of the mineral skeleton of the soil [2, 26]

4. CONCLUSIONS

The mixture of clay soil with sugarcane bagasse ash generally improves some physical and mechanical qualities; however, there is a substantial difference between SUSA and SCSA. As shown in the past statements, the

SCSA ash has pozzolanic properties that behave better than the SUSA mixture since it contains 11.04% Silicon, a chemical element that favors the union between soil particles and ash.

- The soil had a specific gravity of 2.73, the USA of 1.5, and CSA 1.6, while the SUSA specimens were from 2.5 to 2.67, and the SCSA from 2.2 to 2.7, the reduction of this value occurred because ash has a lower specific gravity compared to virgin soil. The decrease in specific gravity indicates a lower density of the material concerning the water absorption capacity; however, this difference is slight, so it is not reflected in the compaction tests.
- The soil sample was classified as clay with a plasticity index (PI) of 47.2%, and the SUSA and SCSA samples decreased considerably their PI, which indicates a reduction in the water adsorption capacity, demonstrating that both USA and CSA can reduce the swelling process of soils with expansive characteristics.
- In some of the SCSA samples, the maximum density increased or at less kept the same density of the virgin soil. On the other hand, all the SUSA samples showed a decrease compared to the natural soil sample, which could be affirmed that USA is not an excellent option for improving physical properties referring to compaction and optimum moisture. It is essential to ratify that CSA does not decrease soil physical properties, does not archive, and a significant increment of this soil qualities.
- About the soil consolidation process, the Cv decreased in both USA and CSA, concluding that this sort of cementitious material probably increases the time of soil consolidations, making it essential that this parameter be considered when some of those ashes are going to be used in an improvement process. However, it is essential to mention that SCSA 8% decreases its Cv in the first loading process, but in the end, it returns a similar consolidation coefficient compared with virgin soil.
- Also, in the consolidation process was obtained the permeability coefficient, and the results indicate that USA contributes in some way to the improvement of soil permeability through it cannot be considered an actual betterment. Due to the decrease in permeability, the suction test was performed on the SCSA samples using the SWCC curve, which defines the relationship between suction and soil moisture. Suction is directly related to permeability. The lower the permeability, the higher the suction due to the size of the ducts in the porous medium. However, the suction in the ash samples decreased, indicating a reduction in the hydraulic properties. In conclusion, USA does not contribute to the soil's hydraulic properties. On the other hand, CSA hurts this kind of soil quality.
- The purpose of soil laboratory testing is to quantify physical, hydraulic, and mechanical properties to determine values for geotechnical design. The angle of friction and the cohesion of the materials are the main geotechnical parameters used, so their evaluation is considered necessary. The SUSA and SCSA samples increased friction and cohesion angle parameters; however, the SCSA samples significantly improved. The 8% SCSA sample passed from 16.1° of friction angle in natural soil to 21.7° and 13.1 kN/m^2 to 17.8 kN/m^2 in cohesion, which obtained the best test results, demonstrating that CSA can contribute to the mechanical strength of clays soils.
- Unconfined compressive strength is one of the most critical parameters that demonstrate the improvement of the geotechnical properties of soils. The 8% SCSA sample obtained an increase in resistance from 0.025 kg/cm^2 of natural soil to 0.042 kg/cm^2, the increase in resistance is due to the cementitious properties of the USA ash.
- It is important to mention that soil mixed with sugar cane bagasse ash has an essential plasticity reduction with 20% of PI, which considerably decreases the volumetric changes due to the increase in moisture content. On the other hand, the best improvement in resistance parameters was evidenced by the SCSA 8% material, which showed an increase of 15% in unconfined compressive strength, friction angle, and cohesion.

5. ACKNOWLEDGMENTS

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