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Experimental study on stabilization of a high plastic fine-grained soil soft subgrade using sugarcane bagasse ash

Estudio experimental para la estabilización de una subrasante blanda de suelo fino de alta plasticidad usando ceniza de bagazo de caña de azúcar

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ABSTRACT: Sugarcane bagasse (SCB) is a lignocellulose biomass of agricultural waste obtained from sugarcane processing and is estimated that its annual production globally is about 279 million metric tons. The main objective of the study was to assess the feasibility of using sugarcane bagasse ash (SCBA) as an eco-friendly natural ground improvement admixture for a soft, high plastic fine-grained subgrade. This paper presents results of an experimental study that included: 1) characterization of the base soil, and SCBA material, 2) evaluation of plasticity, compaction curves, and CBR for the compacted base soil treated with five levels of SCBA admixture, and 3) assessment of the unconfined compressive strength as a function of curing time ranging from 1 to 60 days for base soil samples treated with 20% SCBA by dry weight. This study shows that there is an improvement of the soft high plastic subgrade with an increase in CBR, a decrease of plasticity index, and a gain of unconfined compressive strength of up to 13% after 30 days of curing time. Study found SCBA is a viable, cost-effective, and practical way for improvement soft fine-grained subgrades, and it is a green solution as it helps recycle this abundant agro-waste byproduct and reduce use of carbon intensive admixtures such as cement.

KEYWORDS: stabilization, admixture, sugarcane bagasse ash.

1 INTRODUCTION

1.1 *Background and Rationale of the Study*

Since the 1990s decade, the agricultural industries growth around the world have generated waste byproducts of natural fibers which might affect the environment if there is an inadequate management of them (Demir 2006).

One of these natural fibers is sugarcane bagasse (SCB), which is a lignocellulose biomass of agricultural waste obtained from sugarcane processing (Ajala et al. 2021).

The annual production of sugarcane globally is about 1.6 billion tons and this generates about 279 million metric tons of SCB (Chandel et al. 2012). In Peru, where this study was performed, the annual sugar cane production was about 9.8 million metric tons in 2022 (Knoema 2024) thus there is a need to find recycling and reutilization alternatives for this agro-industry waste byproduct.

There are several reuse applications for SCB in the paper and textile industries, as feedstock, as biofuel, and in the civil engineering sector (Bilba et al. 2003).

Sales and Lima (2010) state that when the SCB is used as a source for biofuel in industry boilers, one metric ton produces 25 kilograms of ashes, which often is used primarily as a fertilizer.

Sugarcane bagasse ashes (SCBA) are composed mainly of silica (SiO_2) and aluminum oxide (Al_2O_3), therefore, is considered a pozzolanic material. However, to become a cementation material is required that ashes being mixed with lime, hence as the time increases the admixture will be hardened (Roland and Kiran 1993). Also, due to its pozzolanic properties SCBA might be used in mortars production (Camara et al. 2016).

This experimental study considers only the ashes as an admixture with the purpose of analyzing how the physical and mechanical properties of fine-grained soil change with different dosages of SCBA.

1.2 *Soil Stabilization*

The stabilization is a process that improves the physical and mechanical properties of soils (Das 2015). Kirsch and Bell (2019) define it as the modification of the existing engineering properties of the ground beneath a site to sufficient depth to enable effective, economic, and safe permanent or temporary construction in practical timescales.

According to Schaefer et al. (2016) when the subgrade has a CBR less than 8% is necessary a stabilization. This same criterion has been adopted by the Peruvian highway manual (MTC 2014) when the CBR of the subgrade is less than 6%.

Most subgrade stabilizations are either mechanical or chemical. Mechanical stabilization typically involves in-situ compaction, reinforcement with geosynthetics or soil substitution. Common subgrade chemical stabilization admixtures involve using Portland cement, lime, fly ash and asphalt.

Due to the large production of sugarcane in Peru and worldwide, in this paper we present an experimental study performed to investigate the feasibility of using sugarcane bagasse ash (SCBA) as an eco-friendly natural ground improvement admixture to improve soft fine-grained subgrades. If successful, it would not only help deal with this waste, but would also result in an economical and greener alternative to conventional admixtures such as lime or cement.

2 LITERATURE SURVEY ON USE OF SCBA

Several reuse and recycling alternatives for SCBA have been reported in the literature, such as additives in the production of concrete, mortars, bricks, and ground improvement.

Regarding the soil stabilization for pavement subgrades, the main findings from some studies are summarized below.

- Kumar-Yadav et al (2017) used rice husk ash (RHA), sugarcane bagasse ash (SCBA) and cow dung ash (CDA) in dosages between 0 and 12.5% by dry weight. After several laboratory tests, they found that CBR and UCS values increases.
- Delgado and Mendoza (2018) evaluated the effect of adding sugarcane bagasse ash (SCBA) to clays. Dosages used varied from 10 to 20% by dry weight, obtaining the soil improved by 20% in strength respect to the untreated sample.
- Hidalgo et al. (2020) found that 5% by dry weight addition of rice husk ash and sugarcane bagasse ash each, increases the value of CBR in a low plasticity clay.
- Sharma and Singh (2021) investigated the applicability of SCBA for clayey soil stabilization. They used different dosages of cement (between 3 and 12% by dry weight) and SCBA (between 2 and 8% by dry weight) and found an increase of compaction properties.

3 LABORATORY TESTING PROGRAM

3.1 *Experimental Methodology*

The feasibility of using SCBA was investigated through a comprehensive laboratory experimental program.

First, the base soil and SCBA were evaluated with classification and compaction tests. Also, for the base soil, CBR and UCS tests were conducted.

After that, to determine the optimum dosage of SCBA as an admixture for stabilization, the soil mixtures involved different dosages of the base soil (MH) and sugarcane bagasse ash (SCBA) in proportions by dry weight.

The experimental program included the following laboratory tests: sieve analysis, Atterberg limits, AASHTO soil classification, modified Proctor and CBR (California bearing ratio). The soil mixtures involved different SCBA dosages as shown in Table 1.

Table 1. Soil and SCBA mixtures (by dry weight)

MIXTURES	*% SCBA*	*ID*
Mix 1	*10*	*MH90SCBA10*
Mix 2	*15*	*MH85SCBA15*
Mix 3	*20*	*MH80SCBA20*
Mix 4	*25*	*MH75SCBA25*
Mix 5	*30*	*MH80SCBA20*

Finally, using the optimum dosage of SCBA, the influence of curing time in soil strength was analyzed.

In total, eighteen unconfined compressive strength (UCS) tests were conducted with different curing times: 1, 3, 7, 15, 30 and 60 days.

3.2 *Materials*

3.2.1 *Sugarcane Bagasse Ash (SCBA)*

For this experiment, SCBA has been donated from a sugar industry located in Laredo, department of La Libertad in the northern coast of Peru. According to INEI (2018), this department has the larger sugar production in Peru.

SCBA is generally black due to the burning process and presence of unburnt carbon particles. These particles of bagasse ash are irregular and rough textured. Figure 1 shows a photo of the SCBA used in this study. According to Agunsoye and Aigbodion (2013), SCBA chemical composition is primarily silica (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO).

Figure 1. Sugar cane bagasse ashes used for the experimental study.

The sugarcane bagasse ashes (SCBA) used for this study did not have plasticity with no measurable liquid nor plastic limits. The specific gravity, G_s, for the SCGA was 1.994.

The typical chemical composition of SCBA based on data reported by Bahurudeen et al. (2005), Kumar et al. (2007), Srinivasan and Satihiya (2010), and Camara et al. (2015), is summarized in Table 2.

Is important to mention that Puppala et al (2015) concluded in their investigation that calcium-based additives involve chemical processes in which pozzolanic reactions take place, inducing maximum bonding-induced soil strength and minimizing the swelling potential.

Therefore, the high content of silica in SCBA, typically ranging from about 70 to 80 %, and presence of some calcium oxide (1.2 to 6.6%) can help develop pozzolanic activity to improve fine-grained soft subgrades.

Table 2. Typical chemical composition of SCBA[1]

COMPOSITION (%)	*Range*	*Average*	*COV*
Silica (SiO_2)	70.9 – 78.3	75.4	4.2%
Aluminum oxide (Al_2O_3)	1.5 – 8.6	4.9	70.1%
Iron oxide (Fe_2O_3)	2.3 - 4.9	3.4	35.0%
Calcium oxide (CaO)	1.2 -6.6	3.4	70.0%
Potassium oxide (K_2O)	1.3 – 9.6	4.8	89.6%
Magnesium oxide (MgO)	0.1 – 3.3	1.8	90.8%

(1): Values based on Bahurudeen et al. (2005), Kumar et al. (2007), Srinivasan and Satihiya (2010), and Camara et al. (2015).

3.2.2 *Test soil*

The test soil was collected from a roadway construction site located in Tumbaden, in the department of Cajamarca in northern central Peru. The in-situ condition of this subgrade soil was soft with pocket penetrometer values between 30 and 40 kN/m^2. A photo of sampling site is shown in Figure 2.

Figure 2. Soil sampling site.

The base soil is a yellowish brown, high plastic fine-grained soil. A summary of the index properties of the base soil is presented in Table 3. The grain size distribution curve for the base soil is presented in Figure 3. This figure also shows the gradation curve of the SCBA described in the previous section. According to the AASHTO Classification System the base soil classifies as a A-7-5 (19) and MH for the Unified Classification System, which corresponds to a high plasticity silt.

Table 3. Index properties of the soil

PROPERTIES	*Value*	*ASTM Standard*
Water Content, ω (%)	44	D 2216
Liquid Limit	54	D 3418
Plastic Limit	42	D 3418
Plasticity Index	13	D 3418
Specific Gravity, Gs	2.626	D 854
% sands	4 %	D422
% silts	86 %	D422
% clays	10 %	D422
USCS Classification	MH	D422
AASHTO Classification	A-7-5 (19)	

4 LABORATORY TESTING RESULTS

4.1 *Influence of SCBA on gradation, plasticity, and classification*

The results of sieve analyses for the base soil, the SCBA and different mixtures of base soil and SCBA are shown in Figure 3. The SCBA has 26% of sand content and 74% of fines Mixtures of the MH base soil with SCBA in proportions of 10%, 15%, 20%, 25%, and 30% in terms of proportions of dry weight resulted in the grain size distribution curves shown in Figure 3.

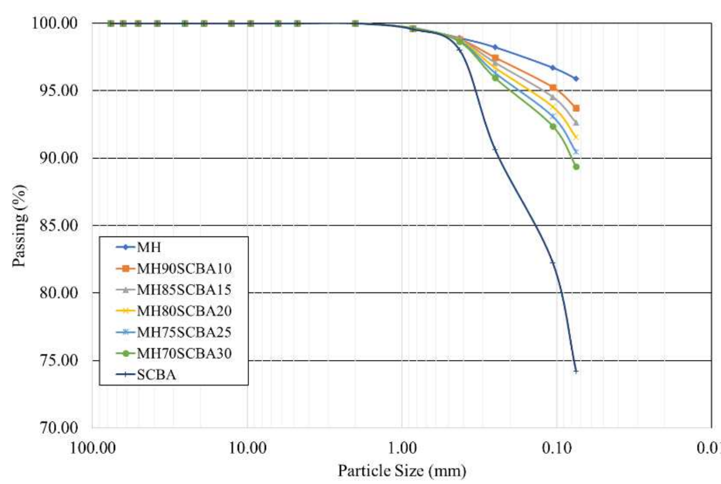

Figure 3. Grain size distributions of the MH base soil, the SCBA, and different base soil-SCBA mixtures.

The results presented in Figure 3 show that the addition of SCBA to the base soil (MH) resulted in a decrease of the fines content. For example, the mixture of 70% of MH base soil with 30% of SCBA (in terms of dry weight) (Mix ID MH70SCBA30) decreased the fine content from the original 96% of the base soil to 89%. This reduction of fines content is due in part due to the sand content of the SCBA.

The addition to change in gradation, adding SCBA to the MH base soil also helped decreased the plasticity index of the treated MH subgrade, thus improving its volume stability (Figure 4).

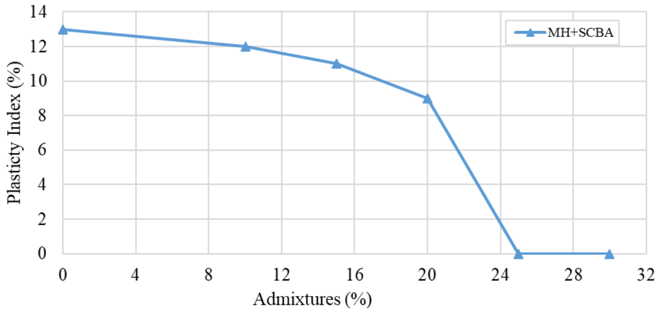

Figure 4. Decrease of plasticity index with increase of admixture dosage.

Results above show that addition of SCBA decreases the fines content and the plasticity. Therefore, the AASHTO soil classification changed for the different mixtures as summarized in Table 4.

Table 4. AASHTO classifications for the test soil and different soil mixtures

MIXTURES	*AASHTO*
MH (base soil)	*A-7-5 (19)*
MH90SCBA10	*A-7-5 (18)*
MH85SCBA15	*A-7-5 (18)*
MH80SCBA20	*A-5 (16)*
MH75SCBA25	*A-4*
MH80SCBA20	*A-4*

The values of the AASHTO group index (GI) are provided in parenthesis in Table 4. Results show a decrease in GI value with increasing dosage of SCBA admixture. According to AASHTO, a low GI value (10<GI < 20) corresponds to a "very poor" subgrade, and a value of GI below 1 corresponds to a "good" subgrade. This is consistent with the decrease in plasticity (PI) with increase of admixture dosage.

4.2 *Influence of SCBA on Modified Proctor compaction*

A series of Modified Proctor compaction tests on the base soil, the SCBA, and different mixtures of base soil and SCBA were performed to assess the influence of SCBA on the compaction test results. The compaction curves for the different materials and mixtures are shown in Figure 5. All these tests were performed in general accordance with ASTM Standard D1557. The compaction energy of the modified Proctor test is 2,700 kN-m/m^3.

The maximum dry unit weights obtained from Modified Proctor compaction tests for the MH base soil and the SCBA were 15.01 and 11.28 kN/m^3, respectively. The corresponding optimum water content values, for the same compaction test, were 20.15% and 51.41% for the MH base soil and SCBA, respectively.

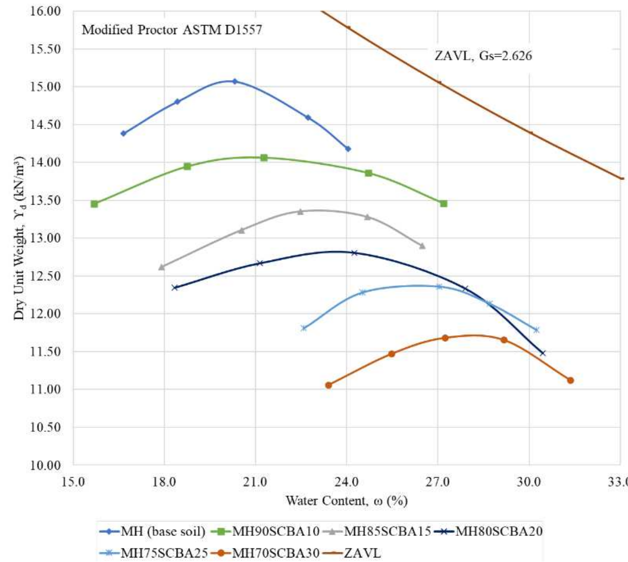

Figure 5. Modified Proctor curves for different SCBA admixture dosages.

As shown in Figure 5, increasing dosages of SCBA admixtures produced a decrease of the Modified Proctor maximum dry unit weight and an increase in the optimum water content. This a similar trend as observed in compaction curves of fine-grained soils treated with lime and cement.

4.3 *Influence of SCBA on CBR test results*

Although the CBR test is not being used as much in modern roadway design that is based on mechanistic approaches, the CBR test is still used, and for the purposes of this study allowed assessing the influence of the SCBA admixture on the CBR. Additionally, the Peruvian highway manual (MTC, 2014) specifies as a unique requirement for subgrade stabilization that the treated CBR value must be at least 6%.

The CBR test results for the treated MH subgrade with different percentages of SCBA are shown in Figure 6. All tests were performed in accordance of ASTM D1883. CBR results correspond to samples compacted to a relative compaction of 95% with respect to the maximum dry unit weight of the Modified Proctor.

The untreated MH soil had a CBR of 4.14%, corresponding to a poor subgrade. The addition of SCBA resulting in an increase of the CBR, with a greatest CBR value of 9.15% measured at 20% SCBA, which corresponds to a regular subgrade. Therefore, there is an increment of about 120% with respect to the soil untreated.

The CBR results showed that samples treated with at least 15% of dry weight of SCBA would meet the minimum CBR of 6% required by MTC (2014). For example, the addition of 20% of SCBA by dry weight resulted in a CBR of 9.15%

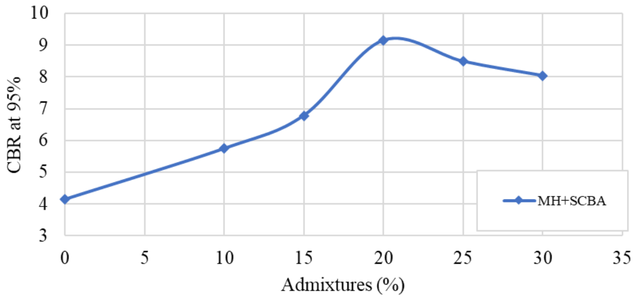

Figure 6. CBR test results for different SCBA dosages.

4.4 *Influence of kneading compaction*

The anticipated field compaction using a sheepfoot roller motivated the use of the Harvard miniature compaction device that uses kneading action for the soil compaction similar to the anticipated field conditions. The Harvard miniature equipment used is shown in Figure 7.

Figure 7. Miniature compaction equipment

The Harvard miniature compaction tests were performed following ASTM D 4647. The compaction energy applied by this method is 300 kN-m/m^3. A comparison of the compaction curves obtained using the Harvard miniature tests for the MH base soil and the MH soil treated with 20% SCBA are shown in Figure 8. This figure shows the addition of 20% SCBA results in a small decrease of about 5% in the maximum dry unit weight, and almost no change in the optimum water content for this type of compaction test (optimum moisture content about 35%).

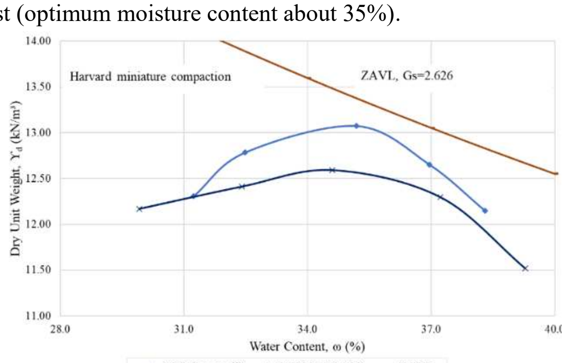

Figure 8. Compaction curves using Harvard miniature test

4.5. *Influence of SCBA on the unconfined compression stress-strain behavior*

4.5.1. *Effect of the unconfined compressive strength at young age*
The average unconfined compressive strength (UCS) obtained from three samples of the untreated MH base soil was 148.25 kPa. The average UCS measured from samples made with 80% MH base soil and 20% of SCBA, after a curing time of 1-day, was 149.49 kPa.

4.5.2. Effect on the stress-strain behavior at young age

The values of the unconfined compressive strengths of the untreated MH base soil samples compared to the values obtained from samples of MH base soil treated with 20% SCBA was small as indicated in the previous subsection.

The effect of the SCBA on the stress-strain behavior, and the peak strain, is shown in Figure 9. This figure shows two representative stress-strain curves for untreated and treated with 20% of SCBA.

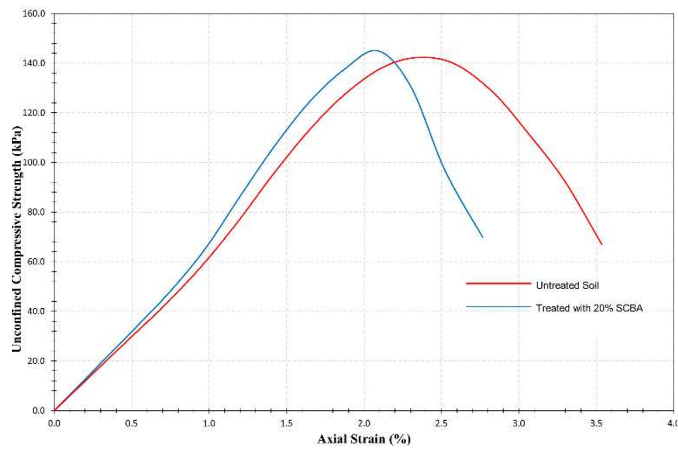

Figure 9. Representative UC tests for untreated MH soil and treated MH with 20% SCBA compacted with Harvard miniature

It can be seen that the curve for the treated sample has a higher initial stiffness, a slightly higher strength, and a lower peak strain. However, the peak strains are similar in nature, so the two samples have similar levels of brittleness. Therefore, at least based on unconfined compression testing, the addition of SCBA does not make the treated MH subgrade more brittle compared to the untreated.

However, for other geotechnical applications such as highway embankments, shallow foundations, or earth dams it would be recommendable to assess the effect of SCBA on stress-strain behavior using triaxial compression performed at the stress levels expected for the selected geotechnical application. For the focus of this paper on pavement application, the use of unconfined compression tests was considered sufficient to assess the effect of SCBA on the stress-strain behavior and its effect on brittleness was considered slight.

4.5.3. *Unconfined compression strengths versus curing time for MH base soil treated with 20% SCBA*

An evaluation of unconfined compressive strength variation versus curing time was done for samples of MH base soil treated with 20% SCBA. During curing, the samples were carefully wrapped with plastic and stored at room temperature (20 °C) inside enclosed containers such as the one shown in Figure 10 to minimize moisture loss.

Figure 10. Curing conditions

The water content after UCS testing was carefully checked and was found not to vary much. Photos of oven dried samples after UCS testing are shown in Figure 11.

Figure 11. Photos of dried oven samples after the UCS testing

Unconfined compressive strength (UCS) tests were conducted in triplicates after curing times of 1, 3, 7, 15, 30, and 60 days. Average unconfined compressive strength values obtained from three tests of MH base soil treated with 20% SCBA by dry weight as a function of curing time are shown in Figure 12. Results show that the strength increased with curing time during the first 30 days and beyond 30 days of curing there is no mayor increase in strength. This figure also shows as a baseline the average UCS of untreated soil. The results shown in Figure 12, indicate an increase of 13% of the UCS after 30 days of curing of the base soil treated with 20% SCBA compared with the untreated samples.

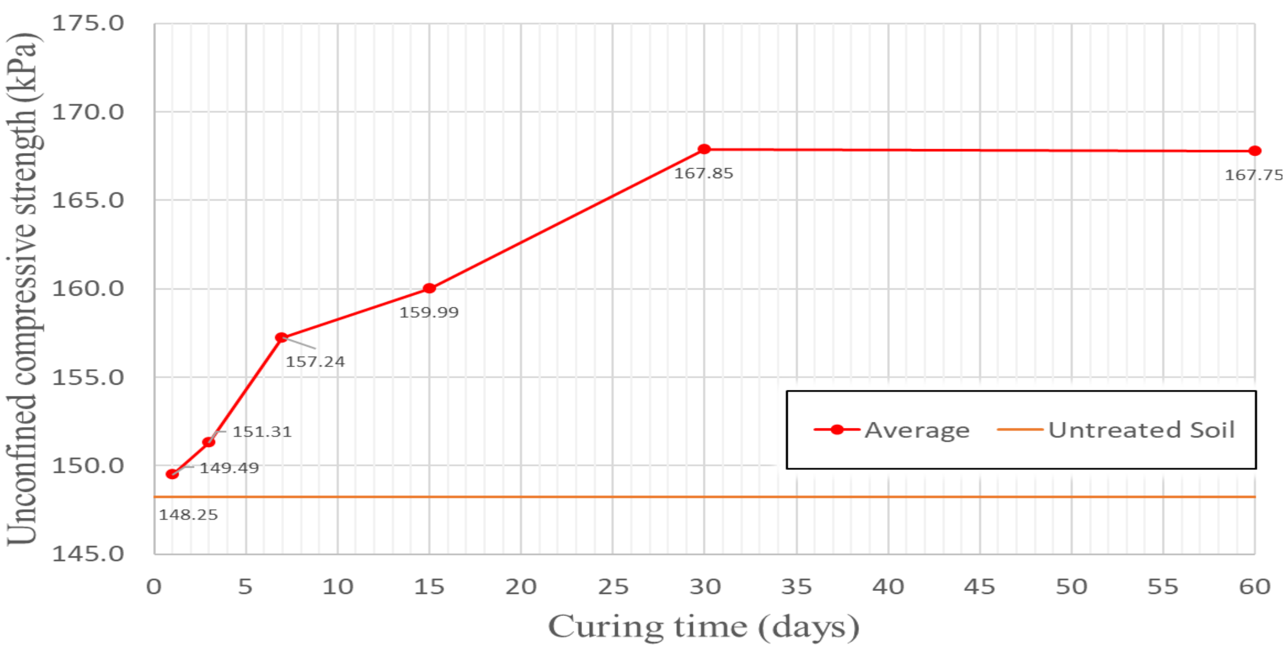

Figure 12. Variation of the unconfined compressive strength values with curing time for MH base soil of treated with 20% SCBA

5 CONCLUSIONS

Base on the results of the experimental study presented in this paper, the following conclusions are drawn:

- The study found that SCBA is a viable admixture for improvement of fine-grained soil subgrades.
- The mixture with the greatest increase in bearing capacity, assessed in terms of CBR, were for MH base soil with 20% by dry weight of SCBA (ID = MH80SCBA20).
- The AASHTO subgrade rating went from “poor” for the untreated soil condition to “regular” with 20% SCBA.
- The unconfined compressive strength of the MH base soil increased by adding 20% of SCBA. The treated MH soil samples increased initial stiffness slightly and showed a moderate decrease of the axial strain to failure.
- The unconfined compressive strength increased with curing time up to 30 days of curing. After 30 days, there was no increase of unconfined compressive strength observed. However, there was only a 13% increase of the unconfined compressive strength after 30 days of curing.
- Both CBR and UCS results show an increase in the values with 20% of SCBA by dry weight.

SCBA has some calcium oxide content that can improve engineering properties of fine-grained subgrades through pozzolanic reactions. The results of this study show that SBCA has potential to be used as a ground improvement admixture to gain moderate improvement in terms of lower plasticity, increased CBR, and a modest increase of unconfined compressive strength in the order of 13%. The results of this experimental study suggest SCBA could be used for subgrade improvements for local roadways with low volume of traffic. For roads with higher traffic loading demand SCBA may need to be mixed with other admixtures such as lime or cement in order to increase the levels of improvement. Furthermore, the use of SBCA is a green, cost-effective alternative as it helps reuse this sugar industry waste and can contribute to limit the use of typical admixtures such as cement and lime that are considered carbon-intensive.

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