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The use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks

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ABSTRACT

This study analyzes the use of lime and sugar cane bagasse ash (SCBA) as chemical stabilizers in compacted soil blocks. The blocks were tested for flexure and compression in a dry and a saturated state. The tests were performed at 7, 14 and 28 days of age in order to evaluate the effects of the addition of lime and SCBA on the mechanical properties of the compacted soil blocks. The results indicate that blocks manufactured with 10% of lime in combination with 10% of SCBA showed better performance than those containing only lime. Nevertheless, the addition of lime improved the strength of the blocks when compared with blocks fabricated with plain soil. According to SEM and DRX analyses, considerable improvement of the matrix was observed due to the formation of strong phases, such as CSH and CAH for the mixtures with additives. It was also concluded that the combination of SCBA and lime as a replacement for cement in the stabilization of compacted soil blocks seems to be a promising alternative when considering issues of energy consumption and pollution.

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1. Introduction

The compacted soil block emerged as an improved version of adobe which allowed soil to be reconsidered as a valuable building material, since innovations in the manufacturing and compacting processes improved the mechanical properties of the material [1]. Despite these advances in the field, further studies are needed in order to improve the durability and mechanical properties of compacted soil blocks.

Many additives such as cement, lime, asphalt emulsions, bituminous materials, and natural and industrial byproducts have been tested to improve the mechanical properties and to enhance the durability of the compacted blocks [2–7].

Portland cement has been by far the most used material for soil stabilization [2,6,7]; however, as a consequence of the high energy consumption necessary for its manufacture and the consequent environmental damage caused by the release of high quantities of greenhouse gases during its production, the cement industry has been pointed out as one of the major contributors of anthropogenic CO_2 emissions with about 5% globally [8,9]. In view of the above mentioned, several research activities have been directed towards partial or total substitution of Portland cement by pozzolanic binders, e.g. lime, fly ash, and natural pozzolans among others.

For instance, previous studies have found the use of 4–10% lime increased the mechanical strength of soil while significantly reducing water absorption [10,11]. Three types of chemical reactions have been identifying to occur in the soil: when lime is added, when ion exchange occurs, and when the pozzolanic reaction and carbonation of lime occur [10,12].

Regarding the use of fly ash, a study of the formation of the hydraulic products during the curing of clay, which contained fly ash with high calcium content as a stabilizing agent, shows that a significant amount of tobermorite is formed leading to a denser and more stable structure of the clay samples. The free CaO of fly ash reacts with the clay constituents (SiO_2 and aluminum silicates) leading to the formation of tobermorites and calcium aluminum silicate hydrates as well. The mechanical properties such as compressive and flexural strengths are considerably enhanced [13].

When the availability of fly ash is limited, the use of other waste materials is necessary, for example, the physical and mechanical properties of a sandy soil mixture with rice husk ash (RHA) and lime cured during 28 days, has been reported. Compressive strength of the mixture containing the RHA was several times higher than the control, whereas, wetting and drying testing results showed improvement with the use of RHA. XRD results confirmed the

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formation of cementing products such as CSH as a result of the reaction between the Ca ions with the amorphous silica of the ash. These products were suggested to be the responsible for the stabilization of the soil [14].

Sugar cane bagasse ash (SCBA), produced in the boilers of the sugar industry, has also been studied as a promising pozzolanic material. In spite of the fact that most of the research on SCBA has focused on its use as a supplementary material in concrete, there is a great potential for its use in other applications. Some of the major findings on its use as cement replacement are summarized next.

Recent research indicates that up to 20% of ordinary Portland cement can be replaced with well-burnt bagasse ash without any adverse effect on the desirable properties of concrete, such as, the development of high early strength, and reduced water permeability and reduced chloride penetration, all of which have a direct bearing on the durability of reinforced concrete structures [15]. However, it has been proposed that factors such as the high temperatures and incomplete combustion that take place in the boilers, influence the reactivity of SCBA. These factors affect the degree of crystallinity of the silica present in the ash, and the presence of impurities, such as carbon and unburned material. Such impurities could limit the contact between Calcium Hydroxide (CH) and reactive silica and prevent them from forming stable compounds [16].

In order to produce SCBA with pozzolanic activity, which will give amorphous silica, low carbon content and high specific surface area, controlling the temperature of calcination is required [17]. Reduction of particle size of SCBA by grinding also has a significant effect on the pozzolanic activity. This hypothesis has been corroborated in a recent study, where concrete containing up to 30% ground bagasse ash, showed a higher compressive strength and lower water permeability than the control concrete without ground bagasse ash, both at ages of 28 and 90 days [18]. In another study [19], the replacement of cement (up to 20%) with an ultrafine, ground SCBA, produced by vibrating grinding, allows for the production of high-performance concrete with the same mechanical response as the concrete prepared solely using Portland cement.

In summary, SCBA is a pozzolan that can partially replace clinker in cement production and consequently, its use tend to reduce emissions of CO_2 into the atmosphere. SCBA is an agro-industrial residue available in several countries. It has been proven by previous comprehensive studies that its use generally improves the behavior of the cementitious construction materials and can contribute, according to the methodology of United Nations Framework (UNFCCC), in reducing an estimate of 519.3 kilotonnes of CO_2 per year [20].

Nowadays, in spite of the increasing interest in the potential use of SCBA as a supplementary material of Portland cement, there is no evidence in the current literature of its use as a soil stabilizer. Therefore, conduct research on the use of SCBA, with low-energy consumption post-treatment, is appropriated.

In the present study, the combination of lime plus sieved SCBA, lime and cement were used in the stabilization of compacted soil blocks. The samples were tested for both flexural and compressive strength. For the latter, samples were tested both in a dry state and in a water-saturated state to evaluate the effects of moisture on the performance of the mixtures. Furthermore, SEM and DRX techniques were employed to study the microstructural modifications of the compacted soil blocks. Finally, energy consumption, CO_2 emissions and energy in transportation of the materials were estimated.

2. Materials and methods

2.1. Experimental design

An experiment was developed to evaluate the effects of the admixtures on the mechanical properties of compacted soil blocks. Some of the variables of the study were the type of mixture and the time elapsed (also age) since the production of the blocks. The levels of the type of mixture variable were NA, CAL, CEM and CALBA, referring respectively to the compacted soil blocks, those with no additives, those with 10% lime, those with 10% cement and those with a combination of 10% lime plus 10% sugar cane bagasse ash. In regards to the elapsed time variable, or age, the mixtures were tested at 7, 14 and 28 days after production. The response variables were flexural strength, axial compressive strength and the axial compressive strength of some of these blocks soaked in water for 24 h. Experimental design details are shown in Table 1.

Microstructural modifications in the matrix of the compacted soil blocks were analyzed by using SEM and DRX techniques. Furthermore, an estimate of energy consumption and CO_2 emissions during the block production is presented.

The additive percentages chosen were those which have been reported to improve the mechanical properties of compacted soil blocks. For example, 10% of cement for soil stabilization has been proved to be an optimum value [2]. For lime, 10% of replacement of soil showed the best performance [11]. In the case of the SCBA of interest in this research, it has been characterized in a previous study [21]. Details on the properties of the SCBA proposed are given in the following section on materials.

2.2. Materials

Sandy soil from the Southern Pacific Coastal Area of Oaxaca State, Mexico, was used for this study. The soil was sieved through mesh #4 prior to the determination of its particle size distribution curve and consistency limits (Table 2).

Fig. 1 compares the size distribution curve of the soil used with the limits recommended for soil with good graduation and easy compaction [22].

As can be seen in the figure, the amount of fine particles was relatively low, indicating soil that is less sensitive to water, and consequently less likely to undergo considerable expansion [23]. However, a lack of fine particles can limit both the pozzolanic reaction and the filler action. The cementing and pozzolanic materials had a significant amount of fine particles to compensate for this absence; therefore, no grading correction was applied. The soil's liquid limit was 25.28% and its plasticity index was 12%; it can therefore be classified as sandy clay or SC type, according to the Unified System of Soil Classification [24]. Prior to the preparation of the compacted soil blocks, the optimum moisture content of the soil was determined using the ASSHTO Standard test [25]. Fig. 2 shows the maximum specific weight and optimum moisture content for each mixture: plain soil had values of 18.27 kN/m^3 and 9.4%; soil + cement had values of 19.06 kN/m^3 with 12.1%; soil + lime had values of 18.39 kN/m^3 with 12.8%; and soil + lime + SCBA had values of 16.66 kN/m^3 with 17.6%, respectively.

Hydrated lime, pozzolanic Portland cement CPP-30R (which meets the specifications of the NMX-C-414-ONNCCE-2004 for Cement [26] and the American Standard ASTM C-595 [27]), and SCBA obtained from the sugar mill "Providencia", located in Tezonapa, Veracruz, Mexico, were used to chemically stabilize the blocks. The burning temperature of the bagasse for the SCBA production was from 700–900 °C. Tap water from the local supply was used in the preparation of the soil block mixtures. The chemical compositions of the admixtures are presented in Table 3.

Table 1
Variables tested in this study.

Variable	Levels	Description	Repetitions	Response
Type of Mixture	4	NA CAL CEM CALBA	5	Flexural strength, compressive strength 1 (dry block), compressive strength 2 (water saturated block)
Time Elapsed Since Production	3	7,14, 28 days	5	

A: soil with no admixture, CA: 90% soil + 10% lime, CEM: 90% soil + 10% cement, CALBA: 80% soil + 10% lime + 10% sugarcane bagasse ash.

Table 2
Identification and characteristics of soil used.

Property		
Atterberg limits	Liquid limit (w_L)	25.28
	Plastic index (Ip)	12
Grain size distribution (%)	Gravel (>4.75 mm)	0
	Sand (0.074–4.75 mm)	72.6
	Silt and clay (<0.074 mm)	23.1–4.3
Surface area	BET (m^2/kg)	47.2
Normalized proctor test	Optimum water content (%)	9.4
	Maximum dry density (kN/m^3)	19.81

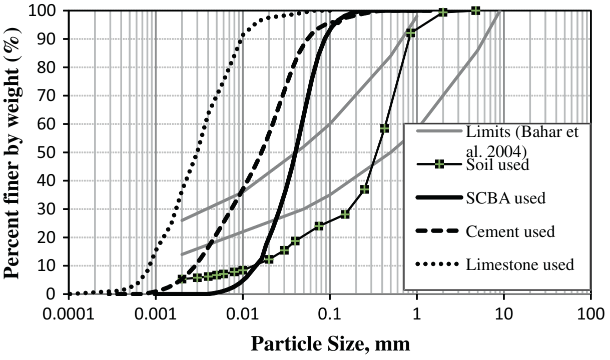


Fig. 1. Grain size distribution.

The SCBA used in this research was chosen based on a previous study [21], where low-energy consumption post-treatment methods, including sieving and grinding, were implemented; furthermore, different cement replacement and curing times were evaluated at different ages. The Strength Activity Indexes (SAIs), which is an indication of the pozzolanic activity of the SCBA using the ASTM C311-04 recommendations, were determined [28]. From that work, it was found that according to the SAIs values the most effective and less energy demanding treatment was sieving the material through #200 sieve. It was also found that by adding 10% of SCBA cement replacement, the SAIs obtained for all the mixtures were much higher than 75%, even for early ages (Table 4) [29]. Based on this, it was decided to use only 10% of SCBA for the soil stabilization in the present study.

2.3. Mixture proportions and sample preparation

Soil preparation for the block making process consisted of desegregating and sieving the material through #4.5 mm mesh. Experimental mixture proportions are summarized in Table 5.

After sieving, the components were mixed in a rotating mixer for 10 min, making sure that the aggregates did not clump together, then the calculated amount of water was added mixing all the ingredients together for five more minutes. The resulting material was placed in the mold of a motorized hydraulic press where it was compacted by a 24 ton load (Fig. 3). Sixty 30 × 15 × 12 cm blocks were fabricated. All the blocks were cured in a curing room at 90% relative humidity until the time of the test.

2.4. Mechanical properties

Mechanical testing was carried out to determine the flexural and compressive strength of the blocks. To establish compressive strength, the blocks were tested in both a dry state and a saturated state (i.e. after being soaked in water for 24 h prior to testing). The mechanical tests were carried out at three different elapsed times, according to the experimental design.

Table 3
Major oxides of the admixtures used to chemically stabilize the compacted soil blocks.

Element/compound	Lime (%)	Cement (%)	SCBA (%)	Soil (control) (%)
Al_2O_3	N.D	6.3	9.92	13.7
CaO	68.83	53.52	2.59	1.55
Fe	0.4	2.92	2.7	4.57
Fe_2O_3	0.14	2	2.32	5.0
FeO	0.39	1.96	1.39	1.38
K_2O	0.22	1.19	2.1	2.59
MgO	0.42	2.26	1.44	0.59
MnO	N.D	0.04	0.14	N.D
Na_2O	N.D	1.89	1.23	2.05
P_2O_5	N.D	0.04	0.9	N.D
LOI to 950 °C	29.84	4.04	24.15	5.28
SiO_2	0.31	26.64	51.66	65.33
TiO_2	N.D	0.18	0.74	1.47
Density (KN/m^3)	21.97	29.62	21.48	19.81

N.D. = not detected.

Table 4
Strength activity index of mixtures with SCBA under different curing times (%) from [29].

Mixture	Curing time (days)	Age (days)				
		3	7	14	28	90
10% SCBA	0	77	97	94	87	83
	7	97	95	100	97	94
	28	97	95	92	103	100
20% SCBA	0	60	75	76	76	72
	7	68	69	82	85	78
	28	68	69	77	89	87

For flexural tests, the blocks were dried to constant mass using an electric oven set at 110 °C for 3 days, following the Mexican Transportation and Communications Board Recommendations (SCT) [30]. Subsequently, the bending moment and cross-section of each block were determined in order to calculate flexural strength. The equipment used for this test was a multi-load machine with a 5 tons capacity, fitted with a 2.5 ton capacity ring (Fig. 4). Each sample was supported at its edges and a concentrated load applied in the center (less than 10 kN/min), utilizing a three point bending load [31].

The two fragments resulting from the flexural tests were carefully resized with a diamond saw. One fragment was measured and sulfur capped to determine the axial compressive strength of the material [32]. A hydraulic press with a 120 ton capacity equipped with an electric pump, that made it possible to maintain loads at constant speed (50% of the load to a convenient speed to condition the block and the rest of the load applied between 1–2 min), was employed as recommended by the standard (Fig. 5).

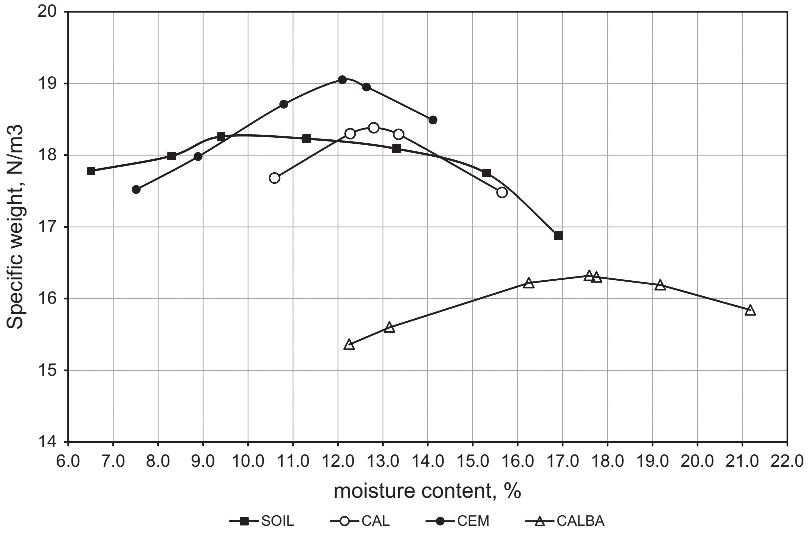


Fig. 2. Optimum moisture content.

Table 5
Details of mixture proportions (by weight, kg).

Mixture	Soil	Water	Lime	Cement	SCBA
NA	1863.0	175.1	–	–	–
CAL	1704.6	240.0	170.5	–	–
CEM	1766.4	235.1	–	176.6	–
CALBA	1387.5	293.0	138.75	–	138.8


CEM, CAL and NA blocks

CALBA blocks

Fig. 3. Block preparation machine and specimens.

The second fragment was submerged in water for 24 h in order to estimate the decrease in compressive strength as a result of water-saturation [33]. Based on the above-mentioned methodology, the first test is referred to as compressive strength-dry, and the second as compressive strength-saturated.

2.5. XRD and SEM analysis

Fragments were obtained from the samples in order to identify the phases formed. The fragments were ground in a planetary grinder, equipped with two mortars and three agate balls; they were then analyzed using a diffractometer using CuK radiation at a wavelength of 1.5418 A, passage of 0.03, and a time of incidence of 2 s per step, maintaining a range of 2 sweeping of 7–65θ.

Micrographs and microstructural analysis of selected samples was carried out to study impurities or apparently unreacted particles using a Scanning Electron Microscope. The operating conditions of the microscope were 20 kV, with a working distance ranging from 10.3 to 11.5 mm.

2.6. Energy consumption (EC), CO_2 emissions (CO_2) and energy in transportation (ET)

The methodology used for evaluating the energy consumption and pollution on materials production was adopted from Morel et al. [34]. In that research, it is emphasized that the use of local materials can decrease substantially the environmental impact in the production process and the amount of transported raw materials used for the production of building materials.

EC and CO_2 estimates for the production of NA, CAL, CEM and CALBA materials were calculated based on the values reported by Arguello-Méndez and Cuchí-Burgos [35]. ET, which is also a major factor in the cost and energy of a building, was adopted from the work carried out by Venkatarama and Jagadish [36]. The authors consider in this study that the bulk of the building materials in rural and semirural areas are transported by trucks.

3. Results

3.1. Flexural and compressive strength

Table 6 shows the flexural strength results for all four mixtures 7, 14 and 28 days after production. As expected, the blocks prepared with no admixture (NA) had the lowest strength values, mostly achieved by the soil compaction process; these values did not increase over the testing period.

Samples containing lime (CAL) and cement (CEM) displayed considerably higher strengths than NA and they increased 25% and 8% over time, respectively; whereas no increase with time was registered for the mixture lime + SCBA (CALBA). The order of performance of the mixtures from best to worst for all elapsed times was as follows: CEM > CALBA > CAL > NA.

For compressive strength results a trend similar to the one observed in flexural strength was found (Table 7). The order performance of the mixtures from best to worst for all elapsed times was also: CEM > CALBA > CAL > NA.

The results also indicate that there was a slight increase in strength over time in the samples containing any of the tested admixtures CEM, CAL, or CALBA, which is attributable to the progressive densification of the matrix as a result of hydration and pozzolanic reactions, as well as the effects of the admixtures acting as filler, as will be discussed later.

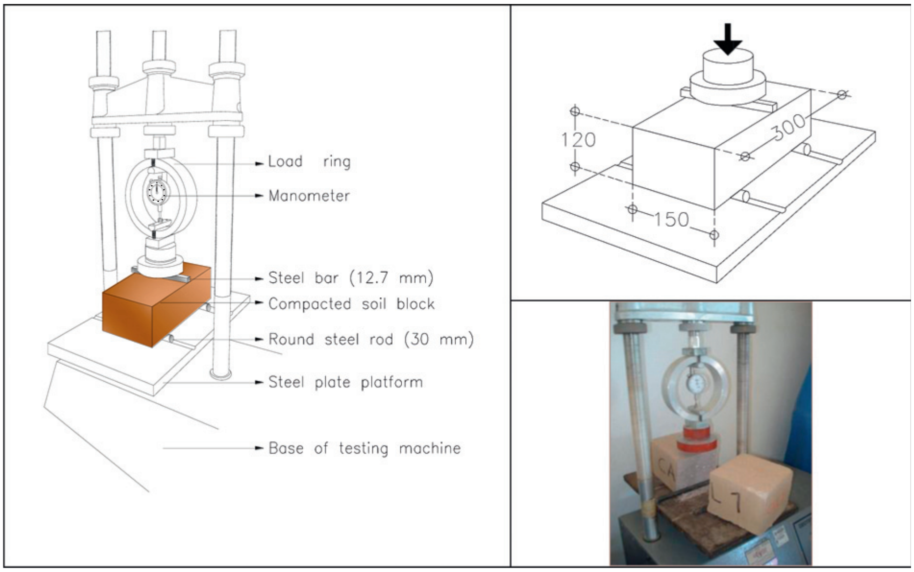


Fig. 4. Arrangement of specimen for flexural strength test.

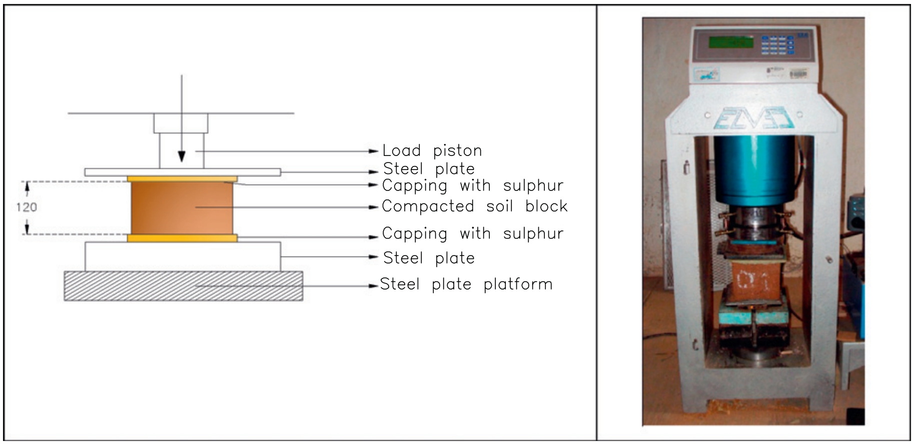


Fig. 5. Arrangement of specimen for compression test.

Table 6
Flexural strength results (MPa).

Mixture	NA			CAL			CEM			CALBA		
Elapsed time	7	14	28	7	14	28	7	14	28	7	14	28
1	0.12	0.12	0.11	0.71	1.16	1.02	1.79	1.82	1.91	1.04	1.34	1.10
2	0.13	0.12	0.10	0.86	1.12	0.99	1.81	1.80	1.96	1.57	1.39	1.32
3	0.11	0.14	0.11	0.88	1.20	1.06	1.80	1.74	2.00	1.57	1.52	1.60
4	0.12	0.10	0.12	0.81	1.12	1.26	1.73	1.70	1.97	1.40	1.42	1.98
5	0.10	0.11	0.09	0.84	1.17	1.26	1.83	1.76	1.96	1.66	1.35	1.02
Mean (MPa)	0.12	0.12	0.11	0.82	1.15	1.12	1.79	1.76	1.96	1.45	1.40	1.40
SD (MPa)	0.011	0.015	0.011	0.067	0.034	0.132	0.038	0.048	0.032	0.247	0.072	0.393
CV (%)	9.8	12.6	10.8	8.1	3.0	11.8	2.1	2.7	1.7	17.0	5.2	28.0

Table 7
Compressive strength results of dry blocks (MPa).

Mixture	NA			CAL			CEM			CALBA		
Elapsed time	7	14	28	7	14	28	7	14	28	7	14	28
1	0.78	0.64	0.62	14.5	13.6	16.0	20.4	23.1	24.6	15.8	21.5	20.9
2	0.68	0.69	0.60	14.7	16.6	16.4	21.0	23.1	23.4	18.0	15.7	21.7
3	0.58	0.62	0.64	15.2	16.5	16.3	22.0	22.7	22.7	18.7	22.6	21.6
4	0.61	0.67	0.69	13.7	15.9	17.1	20.9	22.7	23.3	20.3	21.8	22.8
5	0.75	0.62	0.66	12.7	16.5	16.5	20.5	22.4	23.5	15.8	22.3	19.6
Mean (MPa)	0.68	0.65	0.64	14.2	15.8	16.5	21.0	22.8	23.5	17.7	20.8	21.3
SD (MPa)	0.086	0.031	0.035	1.00	1.29	0.40	0.61	0.29	0.67	1.94	2.88	1.16
CV (%)	12.7	4.8	5.4	7.0	8.2	2.4	2.9	1.3	2.8	11.0	13.9	5.4

The results for the axial-compressive strength of water-saturated samples are presented in Table 8. In this test, it was not possible to take strength measurements for the samples without admixtures (controls), due to the disintegration of the blocks after only half an hour of immersion in water. Once again, the results of this test clearly show the beneficial effects of lime, SCBA and cement; the order of performance based on this test can be given as follows: CEM > CALBA > CAL > NA (Table 8).

In this case, the results indicate that CAL and CALBA blocks lost nearly 65% of their compressive strength as a result of the detrimental effect of water inside the pores of the material, regardless the date of testing; whereas CEM blocks lost approximately 45% (Fig. 6).

The improvement of the strength of the blocks can be attributed to various processes. In the first place, the improvement caused by packing, i.e. the addition of fine particles to the soil matrix. Also, chemical reactions occurring between the additions and soil can contribute to improving the mechanical and durability properties of the matrix [37].

In the case of the CAL mixture, the strength value increase was most likely due to a chemical reaction between lime and silica and alumina available in the soil, resulting in the formation of calcic silicates (CSH) and aluminates (CAH), which are stable compounds [38].

For the CALBA mixture, in addition to the reaction occurring in the CAL mixture, some additional reactions are expected to occur between lime and SCBA, producing additional CSH and CAH.

In the CEM mixture there is, in addition to the cement hydration reaction, another reaction which can occur between the hydration products of cement (portlandite) and silice and alumina from the soil producing CAH and CSH.

Testing results indicate that the additions improved the microstructure of the mixtures leading to higher values of strength. Scanning electron micrographs confirm this, showing a more uniform and dense structure of CEM when compared to CAL, CALBA mixtures (Fig. 7).

In spite of the benefits achieved by using the additions, the matrix is made up, in a large percentage, of soil which contains of a

Table 8
Compressive strength results of saturated blocks (MPa).

Mixture	NA			CAL			CEM			CALBA		
Elapsed time	7	14	28	7	14	28	7	14	28	7	14	28
1	–	–	–	6.93	5.83	5.88	12.3	11.9	13.1	6.20	8.19	8.05
2	–	–	–	5.86	5.47	5.56	11.4	12.2	12.6	5.91	6.66	8.14
3	–	–	–	5.86	4.96	5.49	13.0	13.0	12.4	6.22	8.32	7.26
4	–	–	–	4.85	4.67	5.40	12.2	12.5	12.9	5.62	6.47	6.78
5	–	–	–	5.80	5.07	5.41	12.6	12.3	12.5	6.14	8.12	8.37
Mean (MPa)	–	–	–	5.86	5.20	5.55	12.3	12.4	12.7	6.02	7.55	7.72
SD (MPa)	–	–	–	0.74	0.45	0.20	0.58	0.42	0.28	0.25	0.91	0.67
CV (%)	–	–	–	12.6	8.7	3.5	4.7	3.4	2.2	4.2	12.0	8.7

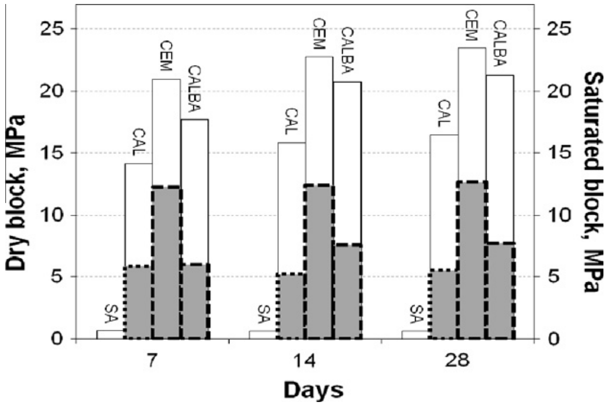


Fig. 6. Compressive strength (gray bars are results for saturated blocks).

low content of fine particles and it is apparently mostly crystalline in structure. This could be the cause of all the mixtures did not display a considerable increase in strength over time.

Besides, as a result of the complex nature of the soil, a high variability in the measurements was observed in some tests (see coefficients of variation in Tables 6–8).

It is worth noticing that all blocks containing admixtures reached compressive strengths higher than those commonly used for flooring construction in the Southern region of Mexico and those containing soil + cement and soil + lime + CBC even reached the compressive strengths used for some structural applications.

3.2. Results for XR-diffraction

The mineralogical composition of the sandy soil used in this study was determined by XRD technique; the results are presented in Fig. 8. The coarse-ground fraction consists of quartz, while the low fine fraction in the soil is predominantly kaolinite and montmorillonite.

Mineralogical analysis of the SCBA used are shown in Fig. 9. The material essentially consists of an amorphous silica structure with small quantities of crystal-phases such as quartz and crystobalite are present [16].

Some of the ash had a crystalline structure, which can affect pozzolanic activity. Only amorphous silica is able to react chemically with calcium ions in the lime, forming cementitious compounds that stabilize sandy soil. The presence of carbon can another cause of the low pozzolanic activity observed in the SCBA mixture [15,39].

The sugar cane bagasse ash (SCBA) used in the research was dark in color, as is burnt in boilers at temperatures varying from 700 to 900 °C, depending on the moisture content of the bagasse. Dark color can also indicate that the ash used has high carbon content due to incomplete calcination of the bagasse as corroborated by the SEM-EDS elemental analysis shown in Fig. 10.

Figs. 11–13 show the X-ray diffractograms of the CAL, CEM and CALBA mixtures. Carbon tends to react with valence 4, thus when there is excess carbon, the tendency is to form planar structures due to the ease of forming double bonds. The interplanar distance is large and can induce water absorption, decreasing the amount of water available for the cement hydration process and pozzolanic reaction. As a result, this can inhibit the formation of cementing compounds such as CSH and CAH.

For the CAL mixture, small fractions of amorphous fine soil reacted with lime to make quartz crystals [14,39]). The contribution of the pozzolanic reaction, involving kaolinite and montmorillonite to CSH formation seems to be insignificant [39].

In the case of the CEM mixture, the formation of strong phases (CSH) over time corroborated the improvement of the matrix [40–42]. In terms of the CALBA mixture, the peaks corresponding to quartz are suspended in the matrix, as the quartz from the coarse fraction of the sandy soil and the crystalline quartz from the SCBA cannot react with the lime. New peaks can be observed at different elapsed times. However, the combination of SCBA and lime in some cases was insufficient for the formation of cementitious compounds in the quantities necessary to allow their identification in the diffractograms of early stages.

New peaks are identified in the CAL mixtures, mostly of portlandite, which is a type of calcium hydroxide [15]. This mineral is associated with cementitious compounds, indicating that after

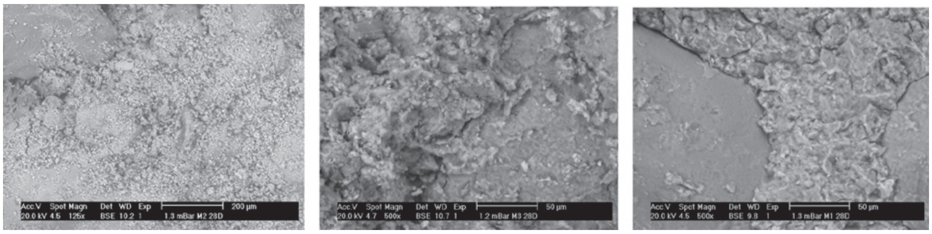

(a) CAL (b) CALBA (c) CEM

Fig. 7. Example of the matrices for the different mixtures at 28 days.

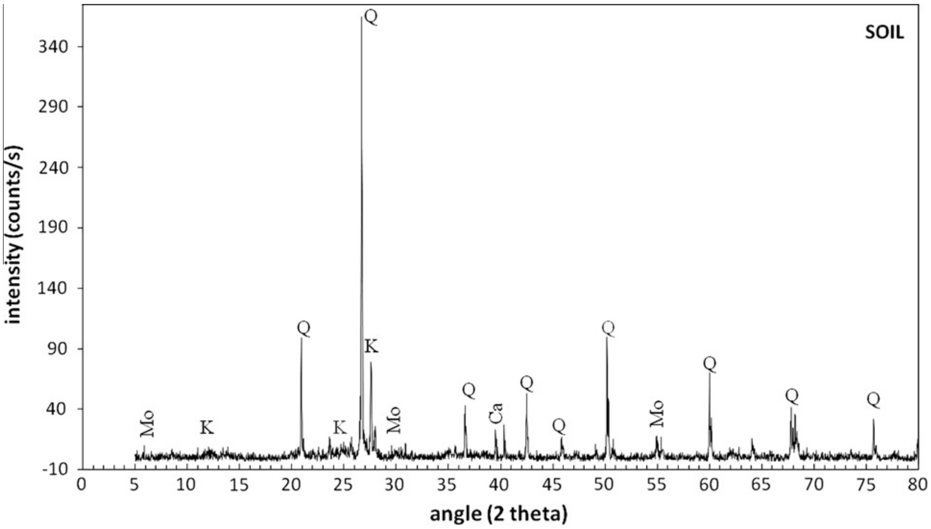


Fig. 8. XRD diagram for the soil used in the present study (Q = quartz, K = caolinite, Mo = montmorillonite, Ca = calcite).

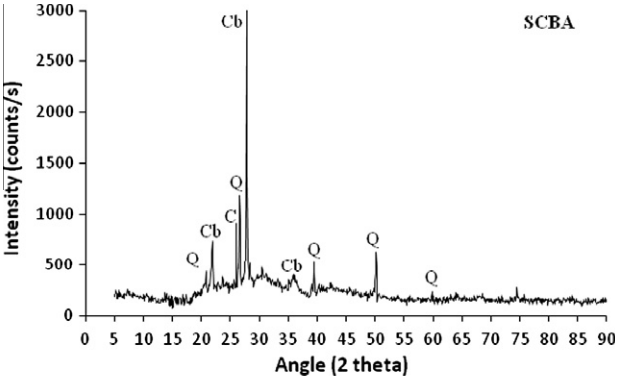


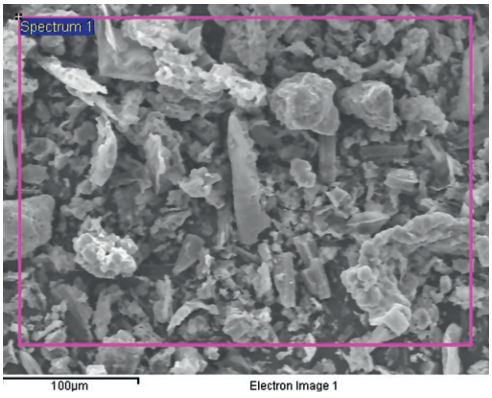
Fig. 9. XRD diagram for the SCBA used in the present study (Q = quartz, C = carbon, Cb = cristobalite).

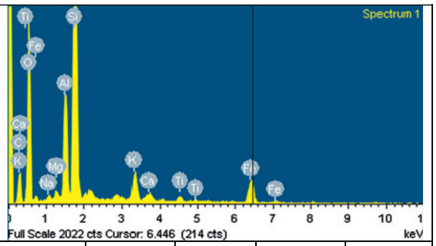
28 days of curing, reactions had taken place between the amorphous silica and the calcium ions of the hydrated lime. The kaolinite and montmorillonite peaks disappear in the mixtures, most likely as a result of reactions between them and portion of the lime, thereby contributing to the formation of cementitious compounds [14]. The main products in the lime-pozzolana reaction are CSH and CAH, which is formed when silica and alumina in an amorphous state reacts with CH.

The XRD diagrams for CALBA confirm the formation of new compounds with properties that match well with those of CSH and CAH. The compounds were detected during the first 7 days after hydration of the pastes. As the reaction evolved, the intensity of the main and secondary peaks of CSH and CAH increased, leaving no doubt as to the nature of the compounds.

Large quantities of carbon and organic material can be found together with the reaction products as well as unreacted material (Fig. 14). It is assumed that these substances slow down the reaction product formation process, as they decrease the amount of contact between CH and silica-rich grains.

It has been reported that morphological similarities can be found between such material and the reaction products formed in the hydration of ordinary Portland cement [15]. On the other hand, it has been reported that SCBA presents high pozzolanic reactivity despite the high carbon content and crystallinity [43]).





Element	Weight %	Atomic %	Compd %	Formula
C K	12.17	18.08	44.60	CO_2
Na K	0.39	0.30	0.52	Na_2O
Mg K	0.40	0.30	0.67	MgO
Al K	4.88	3.23	9.22	Al_2O_3
Si K	16.43	10.44	35.15	SiO_2
K K	1.92	0.88	2.31	K_2O
Ca K	0.52	0.23	0.72	CaO
Ti K	0.61	0.23	1.02	TiO_2
Fe K	4.50	1.44	5.79	FeO
O	58.18	64.89		
Totals	100.00			

Fig. 10. SEM micrograph and elemental analysis of SCBA used in the present study.

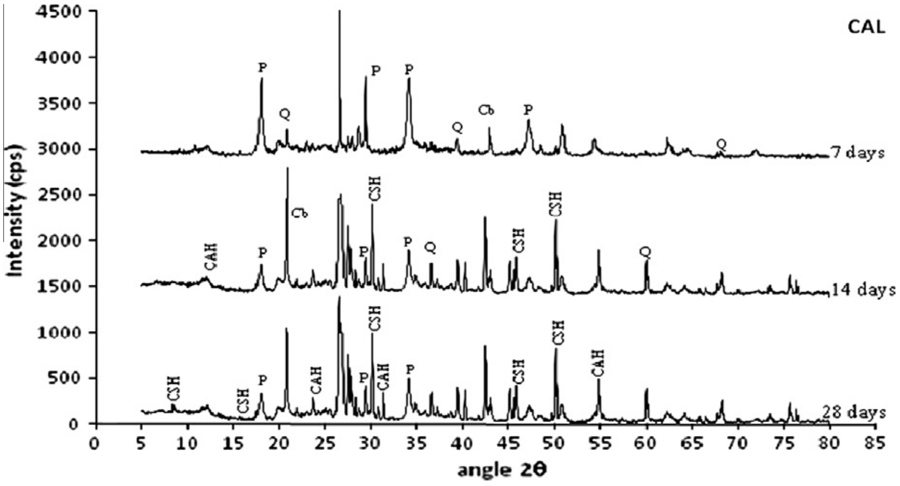


Fig. 11. XRD diagrams of the CAL mixture (P, portlandite; Cb, cristobalite; Q, quartz; CSH, calcium silicate hydrate; CAH, calcium aluminate hydrate).

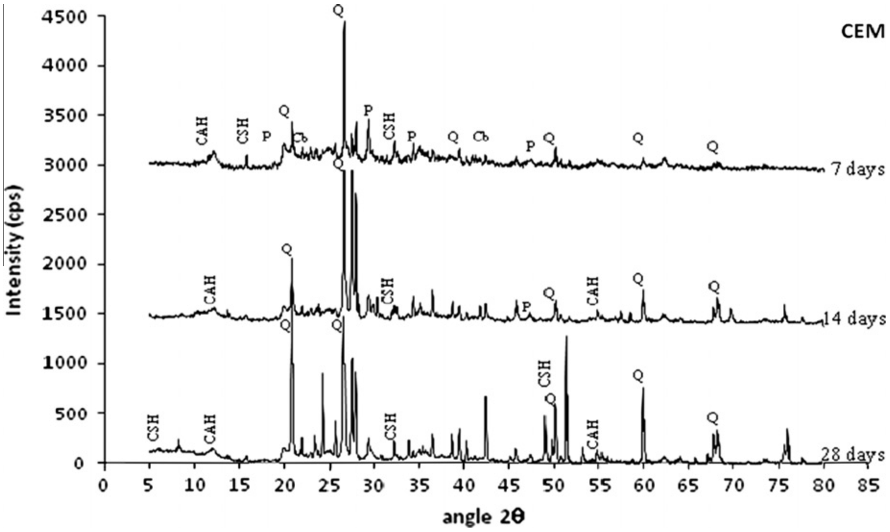


Fig. 12. XRD diagrams of the CEM mixture (P, portlandite; Cb, cristobalite; Q, quartz; CSH, calcium silicate hydrate; CAH, calcium aluminate hydrate).

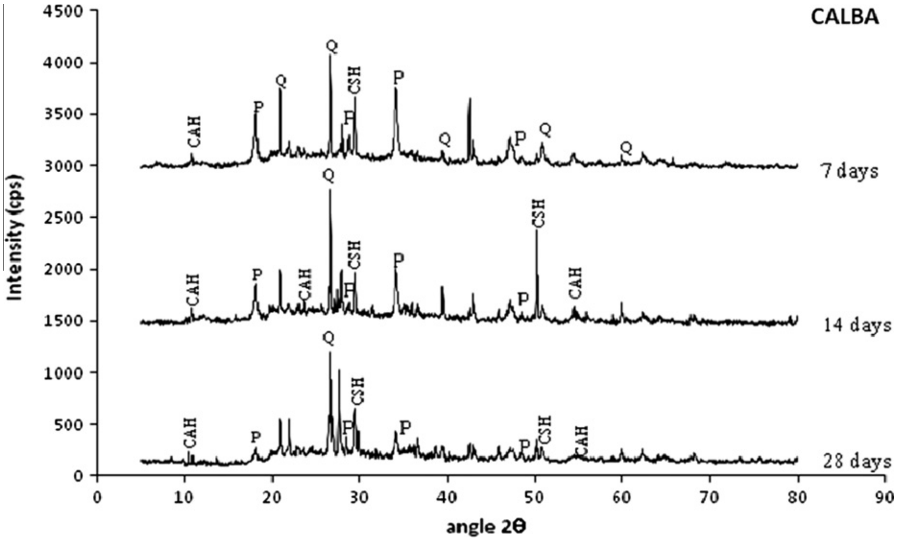


Fig. 13. XRD diagrams of the CALBA mixture (P, portlandite; Q, quartz; CSH, calcium silicate hydrate; CAH, calcium aluminate hydrate).

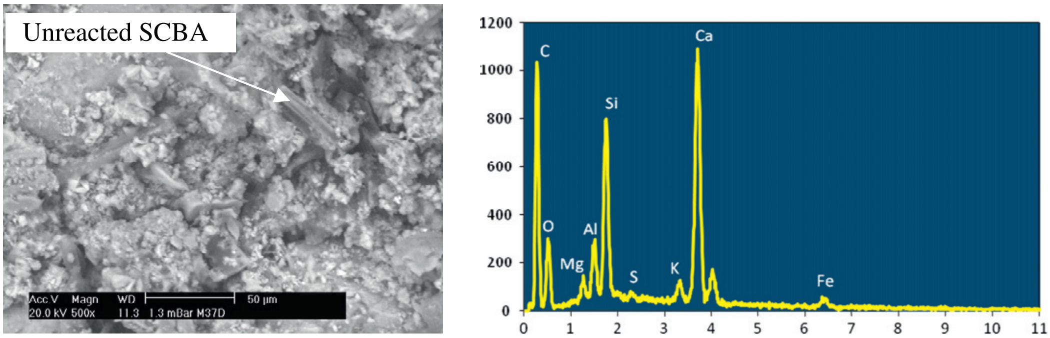


Fig. 14. Micrograph for the CALBA mixture at 28 days of age.

The XRD patterns confirm that after 28 days of curing, cementitious compounds are formed when calcium ions present in the lime react with the amorphous silica of SCBA [44]. These products are responsible for the stabilization of the sandy soil, thus improving its durability and mechanical properties.

3.3. Energy consumption, CO_2 emissions, and energy in transportation

For the energy consumption and pollution estimates the order performance of the mixtures from best to worst was: NA < CALBA < CAL < CEM, whereas for the energy in transportation was: CALBA < NA < CAL < CEM (Table 9).

When comparing the results, regarding the energy needed for the material production and CO_2 emissions and energy in transportation, it can be seen that there is a reduction of 19% for all factors when using SCBA + lime instead of lime alone. Regarding the comparison CALBA versus CEM, the difference is even more notorious, with 38%, 40% and 21% of reduction for energy, CO_2 emissions and energy in transportation, respectively.

Results indicate that the combination of SCBA + lime, as a replacement for cement, or used instead of lime alone, seems to be a promising alternative in the stabilization of compacted soil blocks and significantly reduce the energy used for its production and transportation, as well as carbon dioxide emissions.

4. Conclusions and recommendation

Based on the analysis of results, the following conclusions can be drawn:

- The addition of 10% of sugar cane bagasse ash in combination with 10% of lime significantly improves the mechanical and durability properties of compacted soil blocks.
- The addition of SCBA improved the flexural, compressive strength and compressive strength of water saturated compacted blocks prepared with only soil + lime.
- Observations of the XRD diagrams for the SCBA + lime mixture confirm the formation of chemical stable compounds. The compounds are mainly CSH and CAH, resulting from the reaction between lime and SCBA, as well as between lime and soil.
- No significant strength increase over time was observed for all the mixtures, which can be influenced presumably by the low content of fine particles in the soil and the high carbon content of the SCBA.

Table 9
Energy, CO_2 emissions and transport for the production of 1 m^3 of material.

Materials	NA	CAL	CEM	CALBA
Soil (ton)	1.863	1.705	1.766	1.388
Transport (MJ)	(1863/*d*) *a* = 80.70	(1705/*d*) *a* = 73.86	(1766/*d*) *a* = 76.50	(1388/*d*) *a* = 60.12
Cement (ton)	–	–	0.177	–
Energy (MJ)	–	–	177 × *b* = 771.72	–
CO_2 emissions(kg)	–	–	177 × *c* = 72.57	–
Transport (MJ)	–	–	0.177 × *e* = 17.70	–
Lime (ton)	–	0.171	–	0.139
Energy (MJ)	–	170 × *f* = 583.10	–	139 × *f* = 476.77
CO_2 emissions (kg)	–	170 × *g* = 54.4	–	139 × *g* = 44.48
Transport (MJ)	–	0.170 × *h* = 17.00	–	0.139 × *h* = 13.90
SCBA (ton)	–	–	–	0.139
Energy (MJ)	–	–	–	–
CO_2 emissions (kg)	–	–	–	–
Transport (MJ)	–	–	–	–
Total				
Energy (MJ)	–	583	772	477
CO_2 emissions (kg)	–	54	73	44
Transport (MJ)	81	91	94	74

d = 2020 kg/cm^3 (density of soil).
a = 87.5 MJ (energy needed for transporting 1 m^3 of soil to a distance of 50 km) [35].
b = 4.36 MJ (energy needed for producing 1 kg of cement) [34].
c = 0.41 kg of CO_2 for producing 1 kg of cement [34].
e = 100 MJ (energy needed for transporting 1 ton of cement to a distance of 100 km) [35].
f = 3.43 MJ (energy needed for producing 1 kg of lime) [34].
g = 0.32 kg of CO_2 for producing 1 kg of lime [34].
h = 100 MJ (energy needed for transporting 1 ton of lime to a distance of 100 km) [35].

- Blocks containing CALBA mixture lost nearly 65% of their compressive strength as a result of the detrimental effect of water, regardless the date of testing.
- Sieved SCBA produced in industrial sugar boilers can be classified as a probable material for the stabilization of compacted soil blocks; however, its use can be optimized by testing different types of soils and some other low-energy consumption post-treatments to the ash.
- The combination of SCBA and lime as a replacement for cement in the stabilization of compacted soil blocks seems to be a promising alternative when considering issues of energy consumption and pollution. There is a significant reduction on the energy needed for its production, diminution of carbon dioxide emissions and decrease of energy needed for the transportation of the materials.

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