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Analysis of the mechanical properties of compressed earth block masonry using the sugarcane bagasse ash

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HIGHLIGHTS

- ▶ Industrial waste (sugarcane bagasse ash, SBA) reuse.
- ▶ Proposal of a new sustainable compressed earth block.
- ▶ Study of the optimum SBA content in the blocks.
- ▶ Mechanical and physical characterization of the proposed blocks with SBA.
- ▶ Mechanical characterization of masonry prisms.

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ABSTRACT

The cultivation of sugarcane and production of its derivatives are closely linked to Brazil's history and development. The factory managers face the problem of discarding the sugarcane bagasse ash (SBA), as these ashes are the final waste resulting from the industrial processes, with no possibility to reduce it. The objective of this study is to analyze the effect of adding SBA to compressed earth blocks (CEBs). Two sets of blocks were prepared with 6% and 12% of cement in addition to the earth and with the addition of SBA at ratios of 0%, 2%, 4% and 8% each. Compressive strength and absorption tests were performed on the blocks. Additionally, masonry prisms were produced with the set of blocks that showed the best preliminary test results. The results showed that the SBA can be incorporated into the CEBs and masonry without damage to the mechanical properties.

1. Introduction

Brazil has traditionally planted sugarcane since the 18th century. Alcohol as a viable energy option was only discovered in the 20th century in Brazil. The country currently produces about 60% of ethyl alcohol (ethanol) consumed worldwide and is the world's largest sugar producer. The cultivation of sugarcane bagasse represents one of the main agricultural activities in Brazil, occupying a planted area of about 6.5 million hectares [1]. The production of cane sugar has been on the rise since 2000 and reached over 600 million tons in the 2009/2010 harvest, according to the Department of Sugarcane and Agroenergy of the Ministry of Agriculture, Cattle Raising and Supply.

The demand for sugarcane ethanol is expected to continue growing over the next 10 years, according to the Ministry of Mines and Energy (MME). Generating electricity by burning bagasse and cane straw may exceed the capacity of the largest hydroelectric plant in Brazil, the Itaipu Dam [2].

Nonetheless, the sugar–ethanol industry is still seeking solutions for the disposal of waste generated in the sugar and alcohol production. The ash that remains after the bagasse is burned is the last residue generated by the sugarcane chain. 25 kg of ash are generated per ton of bagasse burned. For the 2010/2011 crop in Brazil, the production of ash was over 10,000 tonnes per day [1,3].

The practice of using the ashes as fertilizers, mixed with the sugarcane filter cake and/or vinasse, is common in the sugarcane plantations of São Paulo. The producers claim that all of the waste is used in the supply chain. This practice of using ash as fertilizer

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overlooks the use of pesticides in the plantations and the persistence of these products in the earth [3,4].

Moreover, these ashes are used as fertilizers on crops, but lack the adequate nutrients for this purpose [5]. Research conducted by the Brazilian Agricultural Research Corporation showed that the amount of potassium, the main nutrient required for sugarcane plantation, is of about 80–150 kg of K_2O/ha, for the cane plant as well as for rootstocks [6]. The amount of K_2O on the SBA does not exceed 2% [7], thus a nutrient-poor ash.

The use of SBA as a stabilizing material in components made from raw earth can be evaluated as an alternative to its use as fertilizer. In addition to being an environmentally safe practice, since the SBA would be encapsulated in components, it could improve the properties of components made from raw earth.

Thus, the SBA was incorporated to the compressed earth blocks (CEBs), with SBA addition levels between 0% and 8%, aiming at application in non-structural components of masonry. Due to their smaller particle size, the SBA tends to occupy the voids between the earth and kaolin, permitting increased density and improved mechanical properties of CEBs. For the evaluation of the former application, structural characterization was performed in this work.

2. Waste incorporation in compressed earth blocks

This section addresses the use of waste in construction material, especially in the components produced by raw earths.

Earth, as a building material, has been used since ancient times, together with wood and stone. The construction technologies using earth may change according to the geographical area and the historical period. Some advantages of earthen constructions are their thermal and acoustic insulating properties [8,9], therefore they can also be used for non-structural elements in modern buildings.

Compressed earth blocks (CEBs) are one of many possibilities for the use of earth for construction. Over the past 50 years, the production technology of CEBs has increased, especially in developing countries [10].

CEBs can be considered the modern descendant of the thick earth blocks, more commonly known as adobe blocks [11]. However, the idea of compressing earth to improve the performance of thick earth blocks is not new. The first compressed earth blocks were produced using wooden tamps, a process that is still used in some parts of the world [12].

CEBs can also be considered as an alternative to burnt clay bricks. The advantage of this brick is that there is no need for high curing temperatures to produce it, as is required for clay, and their degree of compaction can be achieved with hydraulic equipment or hand levers [8].

If the earthen material does not have the ideal characteristics for CEB production, it can be improved by adding one or more stabilizers, which means modifying the earthen characteristics by means of such applications [13].

Cement is one of the best and most widely used stabilizers in CEBs. The cement not only reacts chemically with water to form cementitious agents, but also with fine earth particles. The stabilizer ratio depends on the type of earth that will be used. If there is much clay in it, at least 6% of cement by weight is required. If the earth is too sandy, higher rates of stabilizers may be required. If the earth is well graded, 4% cement can result in high-quality blocks [13].

Replacing natural earths, aggregates, and cement with solid industrial by-product is highly desirable. In some cases, a by-product is inferior to traditional earthen materials. Due to its lower cost, however, this is an attractive alternative given that adequate performance can be obtained [14].

The rice hull ash (RHA) was studied as an earthen stabilizer and the mixtures with 8% RHA and cement had the highest compressive strength. It was also concluded in the same study, that the compressive strength of stabilized earth cement increased by adding RHA to the mix [14,15].

The fluidized bed combustion ashes were used as raw material in the production of CEBs. The fluidized bed combustion ash is a method that involves burning coal in a layer (bed) of heated particles suspended in flowing air. It was concluded that the mixtures containing lime, as binder, and fly ash showed the best results of compressive strength, specific mass and water absorption for the blocks [16].

The incorporation of kraft paper fibers (composite) from discarded cement bags, was studied for the production of CEBs. Blocks and prisms were tested with the addition of 6%, 9% and 12% of cement. After the analysis, it was found that the prisms prepared with the CEBs manufactured with the composite had better results regarding simple and diagonal compressive strength, shrinkage and fire resistance. However, when compared to the reference blocks, the composite addition increased the water absorption rates [12].

The use of waste together with the production of raw earthen components can be considered a technically feasible application as it uses a well established technique of building with earth – which does not need the components' final burning, hence avoiding environmental pollution from ceramic materials. In addition, when using waste to replace the conventional materials, the construction industry offers a substantial environmental contribution to society.

3. Objectives

The objectives of this research with the CEBs are the following:

- To analyze the effect of adding SBA to compressed earth blocks, stabilized with cement, by compressive strength and water absorption tests.
- Determine the optimal SBA addition ratio in compressed earth blocks.
- Compare the levels of axial and diagonal compressive strength prisms produced with SBA to the reference prisms.

Focusing on non-structural masonry component applications, the SBA's technical implementation feasibility, regarding the CEBs, was determined after the completion of these steps.

4. Materials and experimental methodology

4.1. Materials properties

To produce the blocks, a sandy earth from the region of Aveiro, Portugal was used. Before being mixed with the other materials, the earth underwent a separation process of any organic waste and other debris, and uniformity of particle size using a sieve No. 4 (# 4.8 mm) according to the standard recommendations of NBR 10832 [17].

As the earth had a very high coarse sand fraction (above 70%), the particle size was corrected with a clay, kaolin, which was chosen due to its regional availability. After some analysis regarding the molding and compacting of the CEB, the ratio of one part of kaolin for seven parts of earth was chosen (1:7).

The mineralogy and chemical composition of kaolin is closely related to particle size. The kaolin used in this study met the requirements of the ceramic industry, which specify that the high grade washed kaolin must have: (i) white color after firing at 1400 °C; (ii) content of Al_2O_3 > 36% (>34% for second quality kaolin); (iii) content of TiO_2 < 1.1% (<1.5% for second quality kaolin) [18]. Regarding physical properties, kaolin presented unit mass of 570 kg/m^3 [19] and specific density value of 2412 kg/m^3 [20]. Table 1 shows the chemical composition analysis, obtained by fluorescence spectrometry X-ray of the earth.

The plastic limit and liquid earth testing was not performed since the in the earth used in this study the clay fraction was inferior to 30%. Table 2 shows the results of the sieve analysis.

Table 1
Chemical analysis of soils.

Elements (%)	SiO_2	Al_2O_3	K_2O	Na_2O	Fe_2O_3	CaO	MgO	MnO	P_2O_5	LOI	Total
Soil	91.18	4.28	0.21	<0.01	1.37	0.06	<0.01	<0.01	0.03	2.53	99.68
Kaolin	48.33	36.63	1.99	0.04	0.87	0.06	0.32	<0.01	0.12	12.14	100.57

Table 2
The granulometric compositions of the soil used in the production of CEB's.

Soil – sample #1			Soil – sample #2		
Sieves (mm)	% Retained	% Retained accumulated	Sieves (mm)	% Retained	% Retained accumulated
4.76	0.00	0.00	4.76	0.06	0.06
2.00	14.70	14.70	2.00	20.14	20.20
0.85	55.51	70.21	0.85	60.17	80.37
0.425	16.23	86.44	0.425	13.00	93.37
0.250	5.88	92.32	0.250	3.00	96.37
0.106	5.22	97.54	0.106	2.09	98.46
0.075	1.08	98.62	0.075	0.48	98.94
Bottom	1.36	99.98	Bottom	1.05	99.99
Total	99.98		Total	99.99	
Clay + silt		1.4%	Clay + silt		1.1%
Sand	Thin	6.3%	Sand	Thin	2.6%
	Medium	5.9%		Medium	3.0%
83.9%	Coarse	71.7%	78.7%	Coarse	73.2%
Gravel		14.7%	Gravel		20.2%

The binder used as an earth stabilizer was limestone Portland Cement CEM II/B-L 32.5 N, from CIMPOR – Indústria de Cimentos, S.A. Table 3 shows the chemical composition of this cement.

The sugarcane ash bagasse (SBA) was used in addition to the total earth + cement mass. The SBA samples were collected from the mills in the State of São Paulo, Brazil, near São Carlos, SP. The ash was sieved (#4.8 mm) and crushed for 3 min in a mechanic mill (mortar/pestle), as shown in Fig. 1, before the analyses.

The characterization of the sugarcane ash bagasse used showed these results: specific mass of 2650 kg/m^3; unitary mass density of 1390 kg/m^3; maximum dimension of 0.60 mm and fineness modulus of 1.23 [3]. Table 4 shows the chemical analysis values of the SBA.

4.2. Production and characterization of the CEBs

For the analysis of the blocks, two series were produced, with 6% and 12% of cement in addition to the earth, with SBA addition levels of 0%, 2%, 4% and 8%. The amount of water was adjusted for each series and it increased as the amount of SBA was increased in the mixture, for the same kneading and molding consistency. Table 5 shows the amount of material used in each series of blocks.

The mixture of the materials to produce the blocks was carried out in a portable concrete mixer with an 80-liter capacity, which enabled producing a mixture volume equivalent to twelve earth-cement blocks at a time. Some precautions were taken to obtain homogeneous mixtures using the concrete mixer. If the mixture spins longer than the time necessary to homogenize the composite, it produces "lumps", or small nodules usually comprised of a single material. The higher the occurrence of lumps in a mix, the less homogeneous it will be [12].

The molding of the blocks was performed in a manual Appro-Techno TERSTARAM press. This press produces two blocks at a time, has no storage compartment for the mixture, and no system to place the material into the compacting molds. After molding, the blocks were placed in a room with controlled ventilation and no direct sunlight, as shown in Fig. 2, until the test date.

The compressive strength and absorption tests of the bricks were carried out following the recommendations of the Brazilian standards NBR 8491 and NBR 8492 [22,23], with some adaptations.

Table 3
Properties of cement used in CEB's production. Source: producer.

Chemical composition – CEM II/B-L cement	
Element	% of cement, in terms of mass
Clinker of Portland cement	45–100
Limestone	0–35
Fly ashes	0–55
Specific gravity	2750–3200 kg/m^3
Bulk density	900–1500 kg/m^3
Average particle size	5–30 μm

For the compressive strength test, some changes in the standards were made. The first related to the submersion of the blocks in water before rupture, for which we adopted the same methodology as Buson et al. [12]. And secondly, regarding the number of specimens submitted to testing, three blocks were tested in each series, not ten, as the standard requires.

After the curing time of 28 days, the blocks were cut in half and attached with a cement paste. After 48 h of drying the paste, the surface of the blocks was capped with a paste of fresh earth to improve the fit and to regulate the press platens, as presented in Fig. 3.

The Brazilian standards proposes a method similar to that proposed by the Technical Committee 164 (RILEM), in which the two halves of a block are tested together with a mortar bond, forming a small prism. The results have shown that the performance of this type of test does not dependent much on the geometry of the blocks, in addition to greatly relying on the performance of mortar and on the quality in preparing the prisms [10].

For the absorption test, given that the NBR 10832 [17] stipulates that the blocks have to be used with a minimum age of 14 days, the absorption measurement was done at such age.

The CEBs with and without the added SBA were also characterized by optical microscopy (OM) and scanning electron microscopy (SEM). The first enables to distinguish the minerals that compose the earth used in the block due to the color information provided. The latter was performed in order to access the cement hydration and the bonding of the binder with the components of the block: clay, earth and the SBA. To prepare the samples to be analyzed, small bits of each block type where milled and diffused in ethanol.

The OM was carried out in a Nikon Eclipse LV150 equipped with a digital image acquisition system and dark and bright field illumination techniques. SEM was done on a Hitachi S-4100 SEM system.

Fig. 1. Milling of the sugarcane bagasse ash.

Table 4
Chemical analysis of SBA used on CEB's and prisms.

Elements (%)	SiO_2	$Fe_2O_3 + Al_2O_3$	$K_2O + Na_2O$[a]	CaO	P_2O_5	MgO	SO_3	LOI
SBA	96.2	1.9	0.3	0.1	0.1	<0.1	0.1	1.04

[a] Alkalis.

Table 5
Materials used in the preparation of CEB's.

Group	Cement content (in mass)	Proportion of materials – % (in mass)			Water content (%)
		Soil	Cement	SBA	
CP6-C0	6% CP	1.00	0.06	–	10.85
CP6-C2		1.00	0.06	0.02	10.88
CP6-C4		1.00	0.06	0.04	11.36
CP6-C8		1.00	0.06	0.08	11.40
CP12-C0	12% CP	1.00	0.12	–	12.72
CP12-C2		1.00	0.12	0.02	12.81
CP12-C4		1.00	0.12	0.04	12.84
CP12-C8		1.00	0.12	0.08	13.33

Fig. 2. Drying of the CEB's after molding.

Fig. 3. Compressive strength test of CEB's.

4.3. Production and mechanical characterization of the prisms

This section will present the materials used in the tests and the techniques applied to the analysis of blocks and prisms produced from the sugarcane bagasse ash.

Upon completing the characterization tests and defining the best SBA content to be added to the CEBs, two series of masonry prisms, including one without the SBA, were produced and analyzed for diagonal and axial compressive strength after 28 days. The Peruvian standard for adobe buildings, the NTE E0.80 [24], and the technical notes TC76-LUMB1 and TC76-LUMB6, of RILEM, were used as Refs. [25,26].

According to the NTE E0.80, the compressive strength of masonry can be determined by tests with low walls (prisms) composed of a sufficient number of rows to obtain a slenderness ratio (height/thickness) of about 3, with 4 as the minimum number of rows. The curing time of the prisms is 30 days and the minimum number to be tested is three samples.

TC76-LUMB1 recommends that the prism's slenderness coefficient remains within 3 and 5 and the number of rows of at least 5. It also describes the minimum number of blocks should be 3 and adds that the relationship between height and length of the wall must be greater than or equal to 1. Thus, taking these requirements into account, the dimensions of the prisms were of approximately 34.0 cm wide (1 ½ block) × 34.0 cm height × 11 cm width. The variation of these measures was ±1 cm due to the height variation of the blocks. Fig. 4 shows the schematic drawing of the prisms.

For each set of blocks (with or without SBA) six prisms were produced, three for axial testing and the others for diagonal testing. The blocks were seated with earth-cement mortar with 9% of SBA and the thicknesses of the rows were of approximately 10 mm horizontally and 15 mm vertically, as shown in Fig. 5.

The amount of cement to be used in the seating mortar was determined by compressive strength and tensile strength tests in mixtures with 9%, 12%, 24% and 36% of cement with regards to the earthen material. The content of 9% was chosen because the compressive strength of this mortar, after 28 days, was the closest to that of the blocks, as presented in Fig. 6.

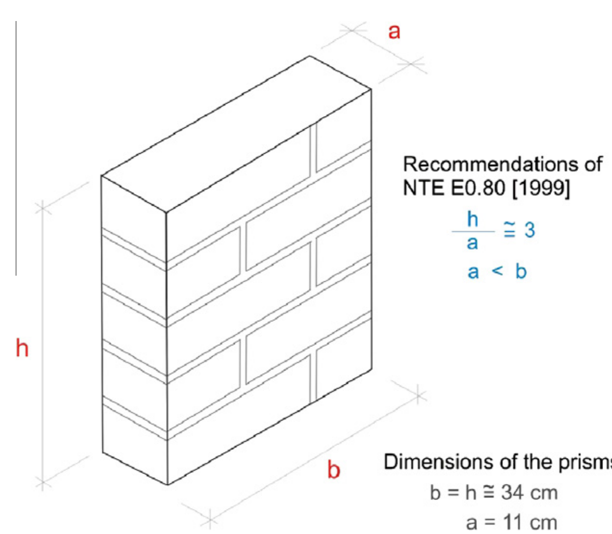

Fig. 4. Dimensions of the prisms.

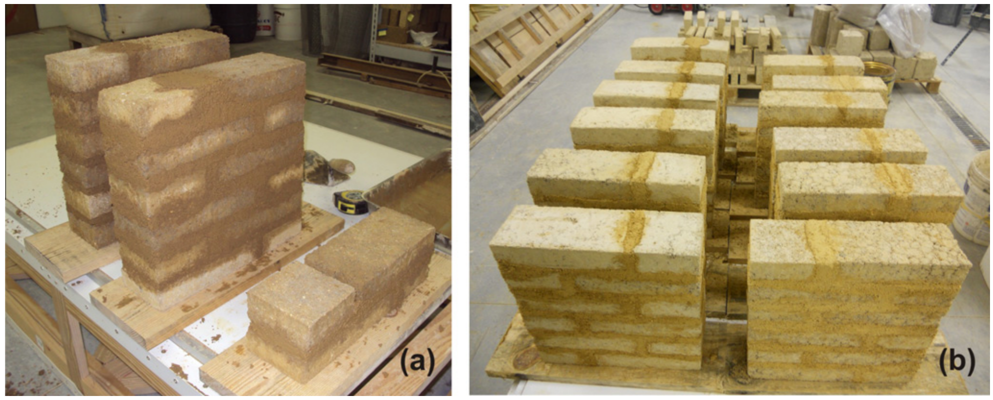

Fig. 5. Production of the prisms (a); and mortar joint curing period, with controlled temperature and wind conditions (b).

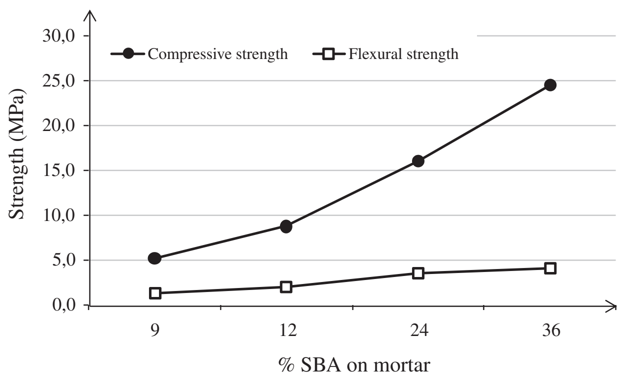

Fig. 6. Compressive and flexural strength of mortars tested for the prisms construction.

The axial compression test was conducted with a load cell of 100 kN in conjunction with a fixed support. And the diagonal test was performed in a digital press ELE Multiplex 50-E.

A setting and support system to place the extensometers was designed to measure the deformation of the material during the tests. This device enabled an aluminum circular section bar to be supported at two points. The extensometer was fixed onto this bar and the strain measurements were performed using the top anchor bolts as a base. Three vertical bars to measure the parallel bending deflections, and one additional horizontal bar were installed. With these bars, as shown in Fig. 7a, it was possible to verify if the loads were uniform.

To measure the deflection in both directions during the diagonal test, two bars were placed, a vertical and a horizontal bar, as shown in Fig. 7b. The test was conducted by subjecting a masonry square panel to a compressive force applied to two opposite corners along a diagonal until the panel cracked. The shear force can be deduced from the diagonal compression force based on a theoretical distribution of normal and shear tensile for a continuous, homogeneous and elastic amount of material.

To facilitate the uniform load transmission and distribution through the metal sheets, and also to reduce the interference of small irregularities in the faces of the prisms, a thin layer of fresh mortar was used with the same composition as the seating mortar. The plates were laid in place before the mortar lost its plastic consistency, or rather, before the prisms absorb the water from the mortar. For the diagonal test, two metal supports with angles were used to place and align the prisms in the compression equipment. For a better distribution of the loads, a thin layer of mortar was used in the corners with the same composition of the placing mortar.

During the diagonal test, the prisms were wrapped with a layer of transparent plastic film in order to prevent its collapse during rupture. The plastic film did not provide any form of support structure, serving only for the safety of the press operators during the tests.

5. Analysis of test results

5.1. CEB blocks

In this section, the results of the axial compressive tests, of absorption and of the electron microscopy analysis of the series of CEBs with 0% and 8% of SBA are also analyzed and discussed.

Table 6 shows the compressive strength results of the blocks. In the series produced with 6% of cement (CP6-Cx), the increased SBA (C0–C8) addition resulted in the blocks' increased maximum compression strength of up to 54% but the average values of the series did not exceed the value of 1.54 MPa at 28 days. Only the blocks with 12% cement (CP12-Cx) had values above 2.00 MPa [22].

For the series with 12% cement, the reference blocks (CP12-C0) reached a mean value of 3.13 MPa at 28 days, while the blocks with 8% of SBA (CP12-C8) reached 2.89 MPa. The coefficient of variation was much lower in the blocks with 12% cement. This fact can be explained by the higher amount of fine particles dispersed in the

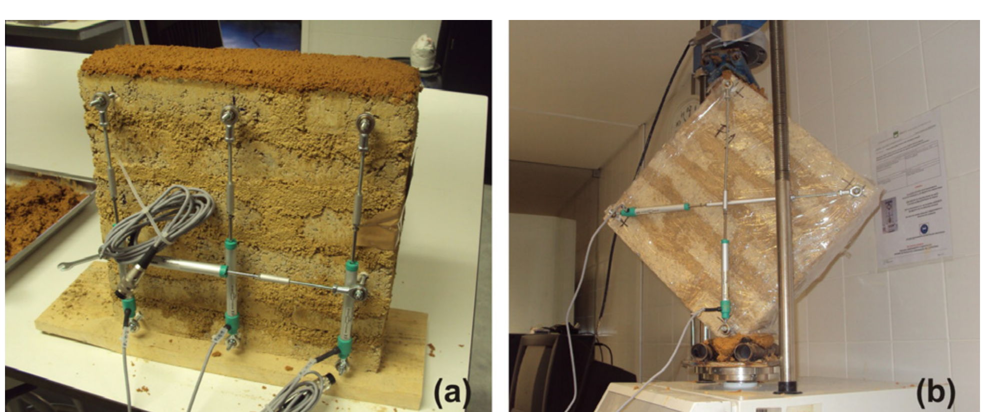

Fig. 7. Extensometers adapted for testing of prisms: compressive strength test (a) and compressive diagonal test (b).

Table 6
Test results of compressive strength at 28 days.

Group	Mean compressive strength (MPa)	Standard deviation	Coefficient of variation (%)
CP6-C0	0.70	0.08	11.16
CP6-C2	0.92	0.19	20.67
CP6-C4	1.44	0.15	10.36
CP6-C8	1.54	0.16	10.16
CP12-C0	3.13	0.21	6.63
CP12-C2	2.77	0.11	3.81
CP12-C4	2.62	0.10	3.72
CP12-C8	2.89	0.11	3.81

Table 7
Results from absorption at 14 days.

Groups	Absorption (%)	Dry specific gravity (kg/m^3)
CP6-C0	12.41	1930
CP6-C2	12.61	1950
CP6-C4	13.79	1980
CP6-C8	11.86	2020
CP12-C0	11.94	2020
CP12-C2	12.20	2010
CP12-C4	11.57	2030
CP12-C8	12.11	2040

mixture, which may have resulted in more homogeneous blocks, and therefore denser and more resistant.

All mean compressive strength values of the series with 12% cement were above the minimum stipulated by Brazilian standards, hence emphasizing the series produced with 8% of SBA by weight. For this series (CP12-C8), it was analyzed whether the average could be considered statistically equal to the average reference value (3.13 MPa). Then a Student's *t*-test was applied and it determined that there are not sufficient data to reject the hypothesis of equality between the average values obtained, hence concluding in this test that the addition of SBA in 8% did not influence the compressive strength of the CEBs.

For the absorption test, the values for the earth-cement bricks can reach up to 20% on average, starting at 7 days [21]. The results presented in Table 7 indicate that increasing the content of SBA provides a specific density increase of 6% in the dry state of the blocks, but that the absorption values remained very close, around 12% for all samples.

The series produced with 12% of Portland cement and 8% of SBA (CP12-C8), by weight, showed a value above the minimum that is recommended by the Brazilian standards for this type of component. The value obtained for this series is somewhat lower than the value of the reference sample specimen, but considering the level of water absorption obtained, the results of these properties validate the use of SBA for the production of compressed earth blocks.

Fig. 8 exhibits the optical microscopy images of both samples under investigation. These images were acquired by means of dark field illumination technique. Although the images are not completely clear due to different focusing plains (some grains appear somewhat tarnished), it is possible to clearly identify the quartz, moreover mica, limestone and feldspars have some of the constituents of the earth used. The sand particles range in diameter as high as 0.3 mm to particles with just a few micrometers. Comparing the OM images of the samples without SBA addition and

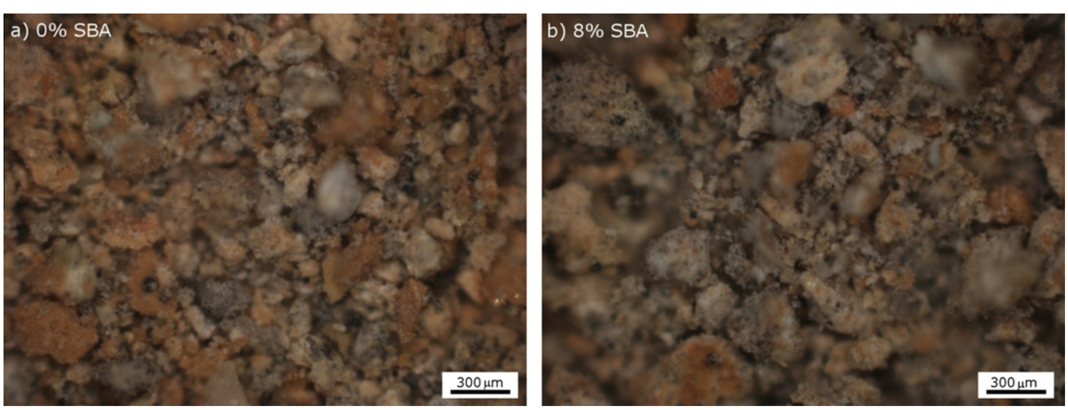

Fig. 8. OM dark field images of: (a) sample without SBA; (b) sample with SBA.

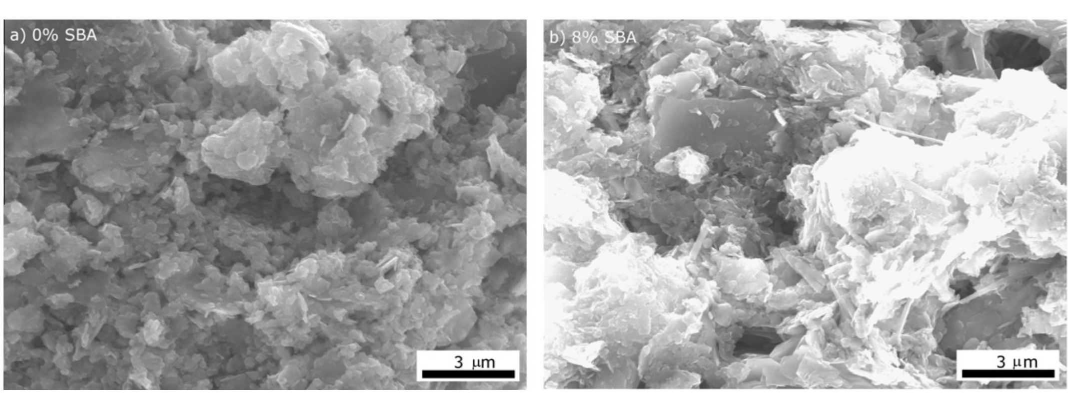

Fig. 9. SEM images of: (a) sample without SBA; (b) sample with SBA.

samples with 8% SBA, Fig. 8a and b, respectively, show no evident differentiation.

Fig. 9 shows the scanning electron microcopy images of the two samples analyzed. Here again there is no relevant difference between the samples with the SBA and without it. In the samples with 8% of SBA there are some traces of the milled carbonized sugarcane, but at a very low number. Both samples present a very homogeneous distribution of the components of the blocks (clay, earth and the SBA, in the sample with it) and a good binding of these components.

5.2. Mechanical characterization of prisms

In this section, the results of the materials' axial compression and diagonal tests are analyzed and discussed.

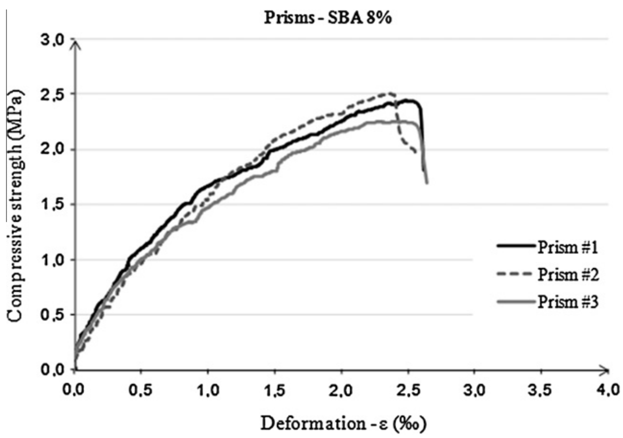

Fig. 10. Compressive strength versus deformation of the prism with 8% SBA.

Fig. 10 shows the behavior of the prisms with 8% of SBA in the axial compression test. The measurements in terms of deformation for the reference prisms (SBA 0%) were not consistent, due to the discrete number of relative displacement transducers adopted in these tests. However, the strength of the reference prisms was consistent between them and the average value is used for comparison with the prisms with 8% of SBA.

Regarding the rupture stress, the reference materials showed an average compressive strength of 2.42 MPa, while for the SBA materials the average was of 2.36 MPa, very close values to those obtained by the CEBs. A Student's *t*-test was performed to infer about two small and independent samples. In this case, the variances are close for the samples, confirmed by an *F* test. The Student's *t*-test determined that there is insufficient data to reject the hypothesis of equality between the mean values, which may be one of the indications that the incorporation of the SBA did not influence the average compressive strength of the masonry prepared with the CEBs.

The coefficient of variation (CV) was 10.63% for the reference prisms and 4.60% for the prisms with SBA, which again showed the best homogeneity for the CEBs made with ash. These CV values are compatible with TC76-LUMB1, which stipulates that the minimum number of prisms tested have to be raised to 10 samples if the CV is higher than 20%. Table 8 presents detailed data on the prisms' axial compression test.

The distributions of cracks in the prisms indicated that the ruptures were due to crushing in all cases and that the load was distributed uniformly. No shear cracks were reported, which could mean a poor support of the prism in the test apparatus or defects when working the prisms, such as the lack of verticality.

Figs. 11 and 12 show the diagonal test results of the prisms. Although the maximum stress values reached by both groups (SBA 0% and SBA 8%) were very close, a greater horizontal and

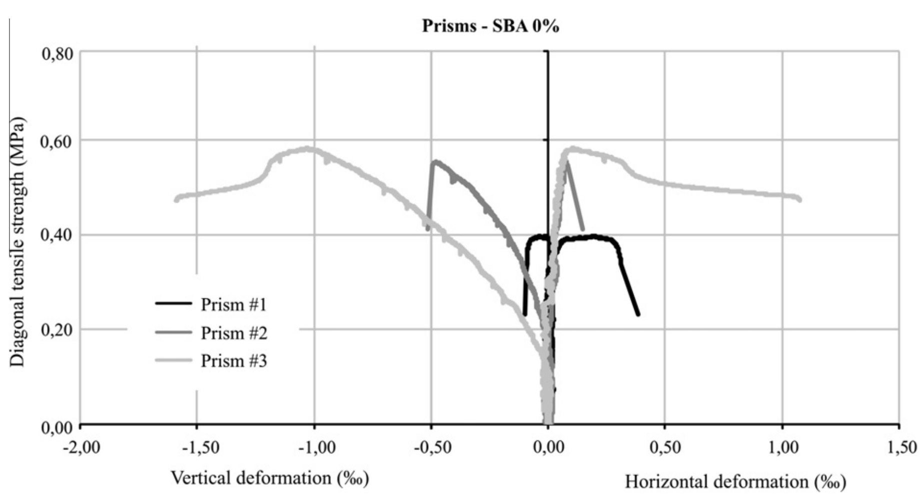

Fig. 11. Vertical and horizontal deformation versus tensile strength of the prisms without SBA.

Table 8
Results of the compressive strength test of the prisms.

Group		Dimensions – $h \times w \times t$ (mm)	Height to thickness ratio (>3)	Maximum strength (MPa)	Average (MPa)	Coefficient of variation (%)
SBA 0%	1	345 × 345 × 110	3.14	2.24	2.42	10.63
	2	348 × 345 × 110	3.16	2.71		
	3	340 × 345 × 110	3.09	2.30		
SBA 8%	1	360 × 345 × 110	3.27	2.24	2.36	4.60
	2	350 × 345 × 110	3.18	2.44		
	3	350 × 345 × 110	3.18	2.41		

Table 9
Results of the diagonal tensile strength tests of the prisms.

Sample		Dimensions – $h \times w \times t$ (mm)	Height to thickness ratio (>3)	Shear strength (MPa)	Average (MPa)	Coefficient of variation (%)	Shear strain – γ	Shear modulus – G (GPa)
SBA 0%	1	345 × 345 × 110	3.14	0.27	0.34	19.23	0.000223	1202.83
	2	330 × 345 × 110	3.00	0.37			0.000628	595.21
	3	340 × 345 × 110	3.09	0.38			0.001249	312.45
SBA 8%	1	357 × 345 × 110	3.20	0.39	0.33	15.97	0.000492	786.78
	2	353 × 345 × 110	3.21	0.32			0.000482	669.48
	3	345 × 342 × 110	3.14	0.28			0.000485	582.82

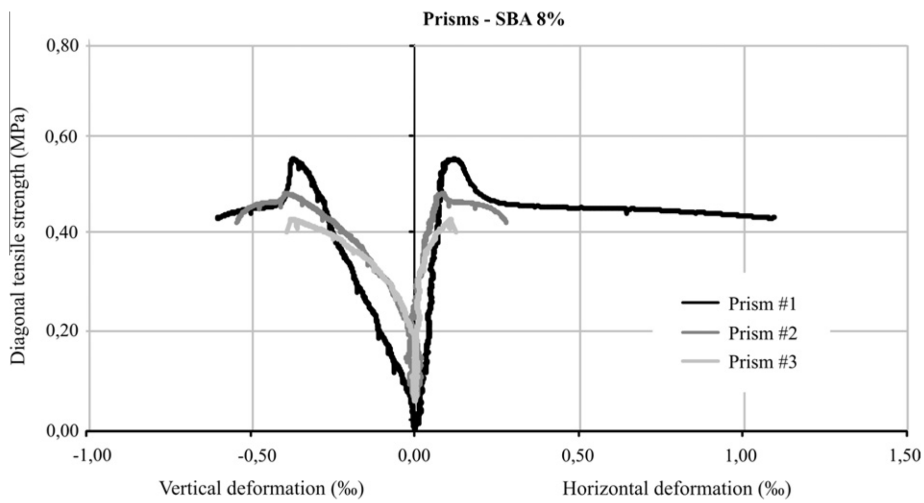

Fig. 12. Vertical and horizontal deformation versus tensile strength of the prisms with SBA.

vertical deflection can be noted for the prisms belonging to the reference group. Additionally, the three prisms prepared with 8% of SBA, as shown in Fig. 10, showed a similar behavior among themselves, just as during the axial compression test with the prisms of the same group.

All prisms show cracks very close to the normal loading line, with fragile-type cracks. The cracks occurred mostly between the mortar and block. The low mortar-block adherence may be because the earth used in the mortar is not appropriate, as it has a very high fraction of coarse sand (above 70%). However, we chose to use this placing mortar earth as it was the same one used to produce the CEBs.

Table 9 presents data on the diagonal compression test of the prisms. Regarding the tensile stress rupture, the reference materials obtained a diagonal tensile stress of 0.34 MPa, while for the SBA materials the average was of 0.33 MPa. The Student's *t*-test was also applied to the diagonal rupture test, which determined that there is insufficient data to reject the hypothesis of equality between the mean values. Despite the statistical equality, the CV of the group without the ash was slightly higher (19.23%) than the group of prisms made of ash (15.97%), which reinforces the fact that the CEBs as well as the prisms prepared with SBA had a higher structural homogeneity.

6. Conclusions

The results showed that:

- The compressive strength of the samples with 12% cement was satisfactory and met the values stipulated by the Brazilian standards.
- The addition of SBA did not affect the mechanical strength and water absorption of the compressed earth blocks made with earth and cement, and this waste residue can be incorporated into such components.
- The prisms produced with SBA had better structural performance in the axial and diagonal compressive strength tests than the reference prisms, produced without ash.
- The mean values observed in the mechanical compressive strength tests of the prisms, with and without SBA, were very close to each other; although the reference values were slightly higher, they cannot be considered statistically different.
- The series produced with 12% of Portland cement and 8% of SBA, by weight, can be used in the manufacture of nonstructural masonry components, which proves the technical feasibility of this material.

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