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# Application of sugarcane bagasse ash in the production of low cost soil-cement brick

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**Abstract.** This work investigated the use of sugarcane bagasse ash (SCBA) generated by an energy co-generation process in sugarcane mill as an alternative raw material in soil-cement brick. The SCBA obtained from a sugarcane mill located in southeastern Brazil was characterized with respect to its chemical composition, organic matter content, X-ray diffraction, plasticity, and pozzolonic activity. Soil-cement bricks were prepared by pressing and curing. Later, they were tested to determine technical properties (e.g., volumetric shrinkage, apparent density, water absorption, and compressive strength), present crystalline phases, and microstructural evolution. It was found that the SCBA contains appreciable amounts of silica ($SiO_2$) and organic matter. The results showed that the SCBA could be used in soil-cement bricks, in the range up to 30 wt. %, as a partial replacement for Portland cement. These results suggest that the SCBA could be valorized for manufacturing low-cost soil-cement bricks.

**Keywords**: sugarcane bagasse ash; soil-cement brick; building material; recycling

## 1. Introduction

The sugarcane industry produces high amount of waste materials, including bagasse (Balakrishnan and Batra 2011). The sugarcane bagasse is a fibrous material essentially composed of cellulose (14-25%), hemicellulose (22-30%), and lignin (14-25%) (Shanmukharadhya and Ramachandran 2009, Balakrishnan and Batra 2011). This waste material has a high calorific value of about 8000 kJ/kg (Batra *et al*. 2013). For this reason, the sugarcane bagasse is very attractive to be used as renewable biomass fuel at the sugarcane mills for electrical energy co-generation (Shanmukharadhya and Ramachandran 2009, Stanmore 2010, Le Blonde *et al.* 2010). In Brazil, sugarcane bagasse biomass represents about 8 % of the total electrical energy consumed (Novacana 2016). However, as a result of this process a solid waste material known as sugarcane bagasse ash (SCBA) is produced in high amount in several countries. Brazil is the world's largest

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producer of sugarcane. In the 2014/2015 harvest, it is estimated that the sugarcane industry in Brazil is producing about 632.1 million tonnes of sugarcane to produce sugar and ethanol (UNICA 2016), resulting in about 3.95 million tonnes of SCBA.

The SCBA basically comprises two main components: inorganic fraction (rich in $SiO_2$ and minor amounts of Al, Fe, Ca, K, and Mg oxides) and organic fraction (charcoal and bagasse debris) (Balakrishnan and Batra 2011, Govindarajan and Jayalakshn 2011, Faria *et al.* 2012). In addition, it consists mainly of fine powder particles that may be easily dispersed in the environment. Most of the SCBA which is produced has been mainly disposed of as soil fertilizer (Khan and Qasim 2008, Balakrishnan and Batra 2011). However, this practical along the years may result in severe environmental degradation such as soil, air, and water pollution with negative impacts on human health (Hernandéz *et al.* 1998, Le Blonde *et al*. 2010). The disposal of SCBA in an ecological, social, and economical way is an urgent need that must be met. In particular, the valorization of SCBA is highly important and should be concentrated on the reuse of this abundant waste material for manufacturing value-added products.

Previous studies (Hernandéz *et al.* 1998, Cordeiro *et al.* 2011, Agredo *et al.* 2014) have shown the suitability of SCBA as a pozzolanic material, depending on factors such as the soil in which the sugarcane was planted and the energy co-generation process from which it has been produced. In fact, this waste material has been used as a partial replacement of cement for pastes, mortars, and concretes mixtures (Payá *et al.* 2002, Frías and Villar-Cocina 2007, Ganesan *et al.* 2007). However, little is known about reuse of SCBA for obtaining soil-cement brick (Valenciano and Freire 2004, Ramírez *et al.* 2012, Lima *et al.* 2012). The soil-cement brick is a cured compacted homogeneous mixture composed of soil, Portland cement, and water in adequate proportions (Souza *et al.* 2008). It is especially attractive as a building material due to the following factors: i) low cost (eliminates the firing step at high temperature with high-energy consumption); and ii) good technical properties (water absorption, mechanical strength, and durability).

In this work, the SCBA was incorporated as a partial replacement of Portland cement into a soil-cement brick used by the civil construction industry. The effects of the incorporation of SCBA on the technical properties and cured microstructure of soil-cement brick were shown.

## 2. Materiais and methods

The raw materials used were sandy soil, Portland cement, and SCBA. The SCBA sample from energy co-generation used for the present study was collected at a sugarcane mill located in southeastern Brazil (Campos dos Goytacazes-RJ). The waste sample was dried at 105 °C for 2h in an oven, crushed in a ball milling for 3h, and then sieved until a fraction that passed through a 200 mesh (<75 μm ASTM) sieve. Commercial sandy soil and Portland cement (type CP III-40RS) were used.

The chemical compositions of the raw materials were obtained using an energy-dispersive X-ray spectrometer (EDX 700, Shimadzu). The loss on ignition was obtained by calculating the wt.% difference between a dry sample at 110 °C and a calcined sample at 1000 °C for 2h. The crystalline phases present in the raw materials were detected via X-ray diffraction in a conventional diffractometer (XRD-7000, Shimadzu), using monochromatic Cu-Kα radiation ($\lambda$=1.5406 Å) at a scanning speed of 1.5° (2θ)/min. The crystalline phases were identified by comparing the intensities and positions of the Bragg peaks with those listed in the JCPDS-ICCD cards. The pozzolanic activity of the SCBA sample was determined in accordance with the electrical

Table 1 The proportions of the blends (in g) used in experiments

| Raw materials | TA0 | TA10 | TA20 | TA30 |
|---|---|---|---|---|
| Soil | 1080 | 1080 | 1080 | 1080 |
| Cement | 120 | 108 | 96 | 84 |
| SCBA | 0 | 12 | 24 | 36 |
| Total | 1200 | 1200 | 1200 | 1200 |

conductivity method (Luxán *et al.* 1989). The plasticity of the SCBA sample was evaluated in accordance with Atterberg method. The amount of organic matter has also been determined in accordance with the Walkley-Black method.

Four soil-cement brick compositions containing up to 30 wt.% SCBA were prepared (Table 1). In this work, the Portland cement was partially replaced with up to 30 wt.% of SCBA. In addition, a conventional soil-cement brick composition (soil:cement – 9:1) was used as a reference composition (TA0 sample).

Each soil/cement/SCBA brick composition (Table 1) was mixed and homogenized by using a mixer for 30 min. Then, the compositions were moistened with 14 wt.% of the total weight of water.

Cylindrical soil-cement bricks 37 mm in diameter and 56 mm in height were shaped by uniaxial pressing at 18 MPa in a steel die. The soil-cement bricks obtained were then subjected to a curing process for 28 days (usual curing time adopted in commercial soil-cement brick production) in a humid chamber with 95 % humidity at 24 °C, according to NBR standard 12024 (ABNT 2012a).

The soil-cement bricks bearing SCBA produced were characterized in terms of volumetric shrinkage, bulk density, water absorption, and compressive strength). Five samples were tested for each formulation (Table 1). Volumetric shrinkage values were determined from volume variations of the brick pieces. The bulk density was determined according to Da=m/Va, where m is the cured brick mass and Va is the apparent volume. Water absorption was determined from weight differences between the as-cured and water-saturated pieces after 24 h immersion in cold water. The compressive strength was determined based on the standard procedure NBR 8492 (ABNT 2012b) using a universal testing machine (model 5582, Instron) at a loading rate of 0.5 mm/min.

The identification of the mineral phases of the cured soil-cement bricks was done via X-ray diffraction. The microstructural analysis was performed by 3D-laser scanning microscopy using an Olympus Lext OLS 4000 confocal microscope.

## 3. Results and discussion

The raw materials play an important role on the technical properties and microstructure of soil-cement bricks. Table 2 gives the chemical composition and loss on ignition of the raw materials used to prepare the soil-cement bricks. The soil sample contained a large amount of silica ($SiO_2$), which is typical of sandy soil. The SCBA sample also contained a large amount of silica, and to a lesser extent calcium oxide (CaO), potassium oxide ($K_2O$), iron oxide ($Fe_2O_3$), and aluminum oxide ($Al_2O_3$). This result is in accordance with the mineral phases as revealed by X-ray diffraction (Table 3). The high loss on ignition (LOI) in the SCBA sample of about 9.32 wt.% is mainly attributed to the decomposition of organic matter. In fact, the SCBA may contain appreciable amounts of organic matter (Balakrishnan and Batra, 2011; Govindarajan and Jayalakshn, 2011; Faria *et al*. 2012). A comparison of the chemical compositions of SCBA and Portland cement shows that there are differences between them. The SCBA has higher silicon, aluminum, iron, and potassium oxides concentrations, higher loss on ignition value, and lower calcium oxide concentration. This indicates that the incorporation of SCBA into a traditional soil-cement brick formulation modifies its chemical and mineralogical compositions.

Table 4 gives relevant characteristics of the SCBA sample. It was observed that the SCBA used in this work was black in color. This indicates that the SCBA has high-unburned carbon amount, which is mainly attributed to defective burning of bagasse in the energy co-generation step. In fact,

Table 2 Chemical compositions (in wt.%) of the raw materials

| Oxides | Soil | Cement | SCBA |
|---|---|---|---|
| $SiO_2$ | 46.70 | 18.87 | 49.95 |
| $Al_2O_3$ | 26.63 | 7.11 | 8.10 |
| $Fe_2O_3$ | 7.40 | 1.21 | 8.86 |
| $TiO_2$ | 2.21 | 0.53 | 0.96 |
| $K_2O$ | 3.80 | 0.56 | 9.62 |
| CaO | 0.98 | 61.15 | 10.17 |
| MnO | 0.07 | 0.30 | 0.21 |
| SrO | 0.01 | 0.06 | 0.02 |
| $P_2O_5$ | - | - | 1.04 |
| $SO_3$ | 2.00 | 3.71 | 1.76 |
| LOI (1000 ºC) | 7.80 | 2.50 | 9.32 |

LOI-loss on ignition

Table 3 Mineralogical phases of the raw materials

| Raw material | Mineral phases |
|---|---|
| Soil | quartz, kaolinite, illite/mica, gibbsite, and goethite. |
| Portland cement | tricalcium aluminate, tetracalcium aluminoferrite, belite, alite, and gypsum. |
| SCBA | quartz, potassium carbonate, cristobalite, hematite, calcium phosphate, and mullite. |

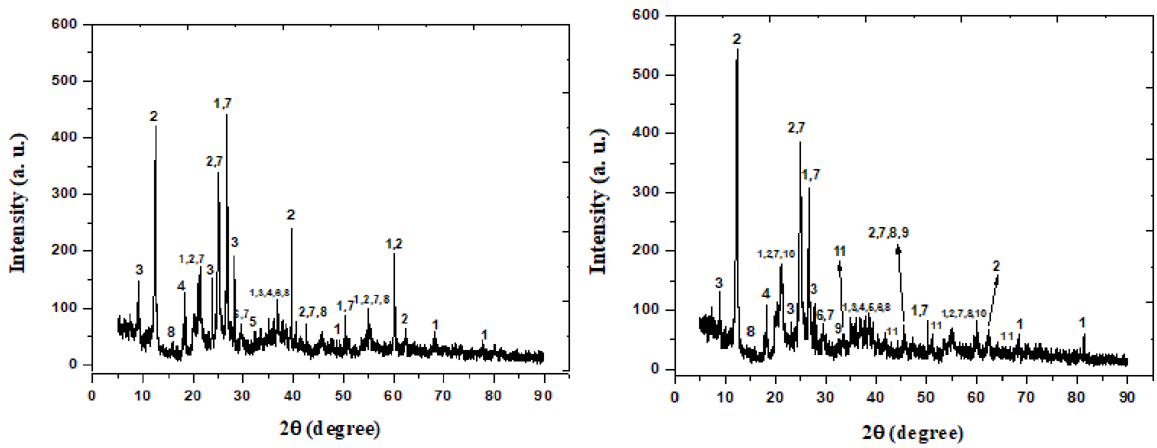
Table 4 Characteristics of the SCBA sample

| Characteristic | Range |
|---|---|
| Colour | Black |
| Organic matter, % | 10.3 |
| Density, $g/cm^3$ | 2.39 |
| Particle size range, μm | < 75 |
| Plasticity, % | Non plastic |
| Electrical conductivity, μS/cm | 0.44 |

the SCBA sample presented 10.3 % of organic matter. The real density of 2.39 g/cm$^3$ reflects its chemical and mineralogical compositions, and is lower than that of Portland cement (2.98 g/cm$^3$). The lower density of SCBA is determined by the presence of high amount of organic matter. The SCBA used in form of fine powder presented 100 % of the particles with sizes <75 μm. The Portland cement used also presented about 100 % of the particles with sizes <75 μm. However, the fineness index of the SCBA was found to be higher than that of Portland cement. This is important because it could contribute to improve the packing of soil-cement-SCBA mixtures. In terms of plasticity, it was found the non-plastic nature of the SCBA. The results indicated that the SCBA sample presented value of electrical conductivity of 0.44 μS/cm. This means that the SCBA used in this study can be classified as being a moderate pozzolanic material (Luxán *et al.* 1989). This moderate pozzolanic activity is caused by the presence of crystalline silica and organic matter in the SCBA.

The X-ray diffractograms of soil-cement bricks after curing for 28 days are presented in Fig. 1. As expected, the reference soil-cement brick (Fig. 1(a)) exhibited diffraction peaks associated with the following mineral phases: i) mineral phases linked with the sandy soil: mainly silica ($SiO_2$), kaolinite ($Al_2O_3.2SiO_2.2H_2O$), gibbsite ($Al_2O_3.3H_2O$), and goethite ($Fe_2O_3.H_2O$); and ii) mineral phases linked with hydrated Portland cement: mainly calcium silicate hydrate (C-S-H), ettringite (AFt), and portlandite (C-H). For soil-cement brick containing SCBA (Fig. 1(b)), the following additional mineral phases originated from SCBA were detected: potassium carbonate ($K_2CO_3$), hematite ($Fe_2O_3$), and cristobalite ($SiO_2$). The comparison of the XRD patterns indicated that the intensities of diffraction peaks of mineral phases tend to change with the partial replacement of Portland cement with SCBA. However, the results of XRD do not indicate that the incorporation of SCBA yield new cement hydration products in soil-cement matrix.

Fig. 2 shows the fracture surfaces observed via confocal images of soil-cement bricks containing SCBA cured for 28 days. Confocal micrographs show the typical sequence of microstructure with rising amounts of SCBA. All the soil-cement brick samples exhibited a dense




(a) TA0 sample (b) TA30 sample

Fig. 1 XRD patterns of the cured soil-cement bricks. 1-quartz, 2-kaolinite, 3-illite/mica, 4-gibbsite, 5-goethite, 6-ettringite, 7-calcium silicate hydrate, 8-portlandite, 9-potassium carbonate, 10-cristobalite and 11-hematite microstructure of the cured cementitious matrix. However, the microstructure of the TA30 sample (Fig. 2(d)) was more homogeneous, with a finer microstructure compared with the other samples. The particles are very closely connected together, resulting in a slightly more densified microstructure. This indicates that the incorporation of SCBA tends to improve the packing characteristics of soil-cement mixtures.

The quality of the soil-cement bricks after curing for 28 days was evaluated based on their physical and mechanical properties (volumetric shrinkage, apparent density, water absorption, and compressive strength). The soil-cement bricks with 0 wt. % SCBA (sample TA0) were used as reference brick pieces. It was found that all soil-cement bricks presented brown color, regardless of the added SCBA amount. In addition, all soil-cement bricks produced were free of surface stains, deformation cracks, and defects.

The dimensional variation in cured specimens is a prominent indicator for the soil-cement brick quality. It can be seen in Fig. 3 that the effect of incorporation of SCBA was to lightly increase the curing shrinkage of the soil-cement bricks. This effect is related to the chemical and mineralogical compositions of the SCBA. The volumetric shrinkage values for the specimens range from 0.02 to 0.41 %, indicating low dimensional variation property. This means that all soil-cement bricks produced have high dimensional stability. Additionally, all soil-cement bricks attended NBR 8491 standard (ABNT, 2012c) concerning dimensional variation for industrial soil-cement brick production. The apparent density of the cured specimens is shown in Fig. 4. The results indicate that only slight differences in apparent density (1.885-1.889 g/cm$^3$) with the incorporation of

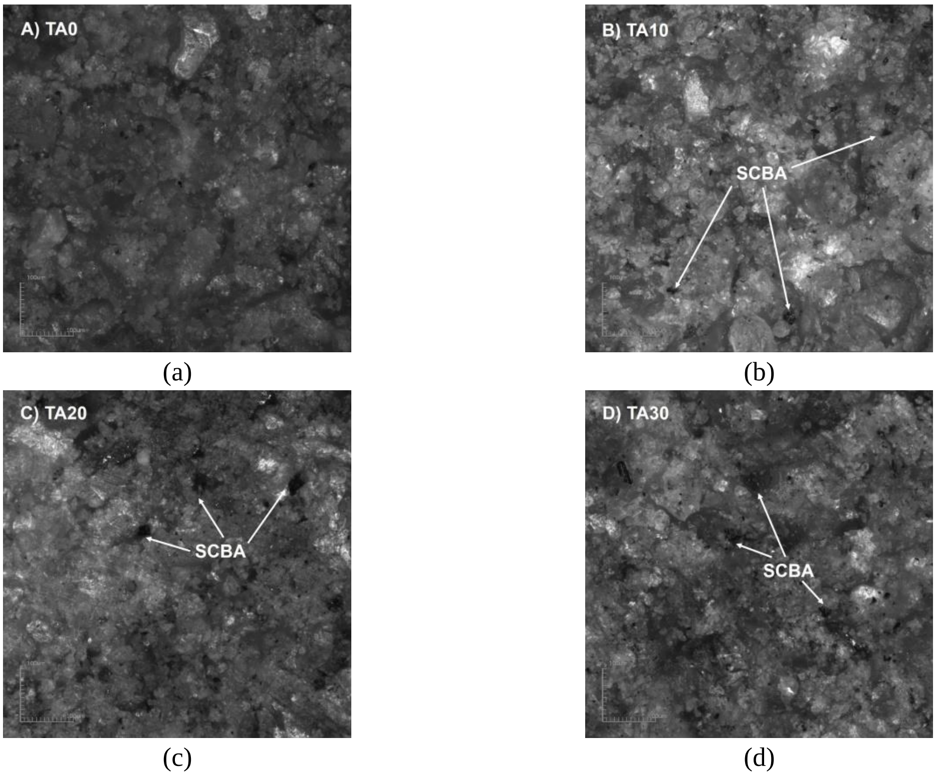



Fig. 2 Confocal micrographs of the cured soil-cement bricks

SCBA occurred. This is in agreement with the dimensional variation (Fig. 3).

The values of water absorption of the soil-cement bricks are presented in Fig. 5. The water absorption is related to the volume of open pores, and is an effective physical property in evaluating the technical quality of soil-cement brick used in civil construction. The results indicated that the SCBA positively provided a small but important reduction of the open porosity level in the soil-cement matrix. This finding suggests that the partial replacement of Portland cement with up to 30 wt.% of SCBA improves the packing of the cured soil-cement-SCBA mixture. This is in accordance with the microstructure (Fig. 2).

The compressive strength of the soil-cement bricks is shown in Fig. 6. The results indicate that there was a decrease in compressive strength of the soil-cement bricks containing SCBA, despite the reduction in open porosity level. Such a behavior is mainly attributed to the following factors: i) the SCBA sample presents moderate pozzolanic activity as compared with that of Portland cement; and ii) the organic fraction of SCBA tends to negatively influence the cement hydration reactions and increase the demand for water (Agredo *et al.* 2014). In particular, the formation of calcium silicate hydrate phase (C-S-H gel), that is the main compound of the mechanical strength development in cement paste, can be inhibited with SCBA addition. These results suggest that additions of high amounts of SCBA into conventional soil-cement brick body should be avoided, because it impairs the compressive strength of the cured bricks.

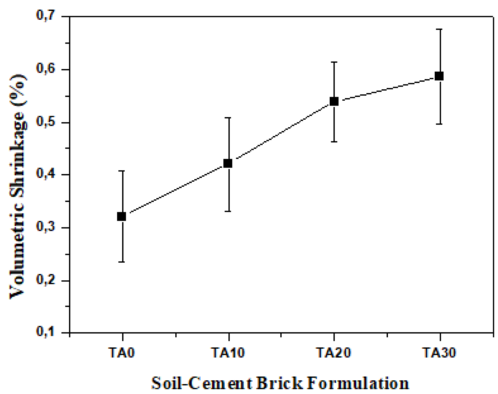



Fig. 3 Volumetric shrinkage of the soil-cement bricks

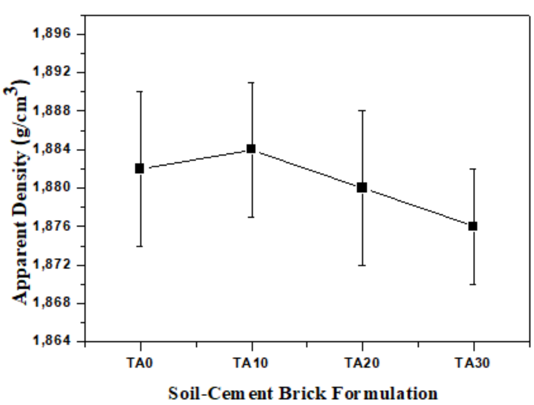



Fig. 4 Apparent density of the soil-cement bricks

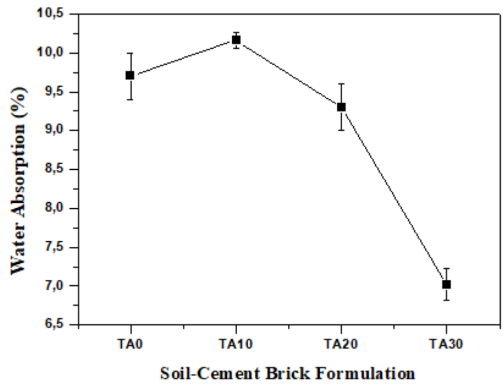



Fig. 5 Water absorption of the soil-cement bricks

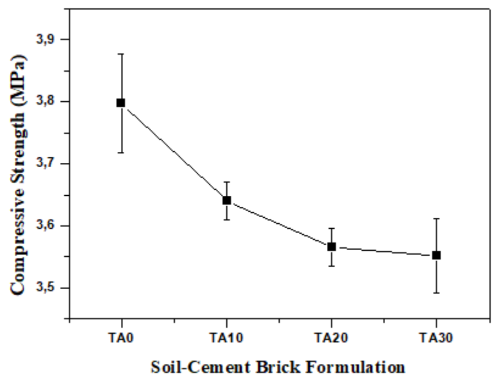



Fig. 6 Compressive strength of the soil-cement bricks

It is very important to evaluate the technical quality of the soil-cement bricks containing SCBA after curing for industrial application. According to NBR 8491 standard (ABNT, 2012c), the values of water absorption and compressive strength are used for specification of soil-cement bricks for civil construction. The requirements of water absorption and compressive strength are: i) mean water absorption ≤20 % and individual water absorption <22 %; and ii) mean compressive strength ≥2.0 MPa and individual compressive strength ≥1.7 MPa. As can be observed in Fig. 4 and Fig. 6, all soil-cement bricks bearing SCBA met water absorption and compressive strength values prescribed by the Brazilian specification for industrial soil-cement bricks production. This result is very important because it clearly indicate that SCBA produced in the sugarcane mills during electrical energy co-generation could be used as partial replacement for Portland cement in the production of soil-cement bricks. In addition to the industrial use of the SCBA, there are environmental and economical benefits associated with the safe disposal of this abundant waste material and reduction of Portland cement consumption. Thus, the valorization of SCBA in this application could serve as sustainable technological solution to traditional disposal methods.

## 4. Conclusions

The following conclusions may be drawn from the experimental results and their discussion:

• This study has demonstrated that the SCBA could be used as an alternative raw material for partial replacement of Portland cement in the production of soil-cement brick.

• The obtained results indicate that the composition of the used SCBA sample is chemically rich in silica ($SiO_2$) with appreciable amount of organic matter. The SCBA behaved as a non-plastic material with moderate pozzolanic activity. In addition, the organic fraction in SCBA tends to influence the cement hydration reactions.

• It was found that the replacement of Portland cement with SCBA, in the range up to 30 wt.%, allows the production of soil-cement bricks with technical properties compatible with those specified in the NBR 8491 standard. The use of higher amount of SCBA is not recommended because of the decreased compressive strength of the resulting soil-cement bricks.

• It is feasible to valorize SCBA for the production of low-cost soil-cement bricks. The reuse of SCBA in this application could serve as important technological solution to the environmental impacts caused by the energy co-generation in the sugarcane industry.

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