Available online at www.sciencedirect.com

ScienceDirect

Cement & Concrete Composites 30 (2008) 410–418

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars

G.C. Cordeiro [a,*], R.D. Toledo Filho [b], L.M. Tavares [c], E.M.R. Fairbairn [b]

[a] Laboratory of Civil Engineering, Universidade Estadual do Norte Fluminense Darcy Ribeiro, Campos dos Goytacazes, Brazil
[b] Department of Civil Engineering/COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
[c] Department of Metallurgical and Materials Engineering/COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Received 26 April 2007; received in revised form 7 January 2008; accepted 9 January 2008
Available online 15 January 2008

Abstract

Sugar cane bagasse ash (SCBA) is generated as a combustion by-product from boilers of sugar and alcohol factories. Composed mainly of silica, this by-product can be used as a mineral admixture in mortar and concrete. Several studies have shown that the use of SCBA as partial Portland cement replacement can improve some properties of cementitious materials. However, it is not yet clear if these improvements are associated to physical or chemical effects. This work investigates the pozzolanic and filler effects of a residual SCBA in mortars. Initially, the influence of particle size of SCBA on the packing density, pozzolanic activity of SCBA and compressive strength of mortars was analyzed. In addition, the behavior of SCBA was compared to that of an insoluble material of the same packing density. The results indicate that SCBA may be classified as a pozzolanic material, but that its activity depends significantly on its particle size and fineness.

Keywords: Sugar cane bagasse ash; Pozzolan; Pozzolanic activity; Filler effect; Packing density

1. Introduction

Mineral admixtures are commonly employed in many applications that range from high-performance concrete of bridges, tall building and offshore structures, to mass concrete of dams. It is well known that mineral admixtures such as silica fume, fly ash and rice husk ash are by-products of industrial or agroindustrial processes. The application of these by-products in concrete production brings positive effects to the environment once it reduces the problems associated to their disposal. Several benefits will be attained regarding greenhouse gas emissions resulting from the use of mineral admixtures as cement replacement, since their use allows reducing cement production. Moreover, in the case of agroindustrial mineral admixtures, their use has the additional advantage of reducing methane emissions generated by the disposal of the by-products. This is particularly important when the agroindustrial by-products contain elevated content of carbon in their composition.

Regarding their use as cement replacement, mineral admixtures affect the performances of paste, mortar and concrete owing to both physical and chemical effects. The physical effects are primarily associated with their influence on the packing characteristics of the mixture, which depend on size, shape and texture of the particles. The chemical effects are associated with their capability of providing siliceous/aluminous compounds that will chemically react with calcium hydroxide in the presence of water. According to Goldman and Bentur [1], the capability of pozzolanic materials of enhancing the strength of concrete is more closely associated with physical than chemical effects.

Sugar cane bagasse ash (SCBA) is one of the main by-products generated worldwide and can be used as a mineral admixture mainly due to its high content in silica

* Corresponding author. Tel.: +55 22 2726 1517 (r. 43); fax: +55 21 2562 8484.
E-mail address: gcc@coc.ufrj.br (G.C. Cordeiro).

0958-9465/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2008.01.001

(SiO_2) [2–5]. Several studies have been conducted to investigate the chemical effect or pozzolanic activity of SCBA. According to Martinera Hernández et al. [2] the main products from the reaction between calcium hydroxide and SCBA are calcium silicate hydrates (C–S–H). In another work, Singh et al. [4] studied the reactivity of SCBA with Portland cement. These authors observed a decrease in free lime values in pastes and associated it to the pozzolanic activity of SCBA. Further, results of differential scanning calorimetry (DSC) showed that large amounts of C–S–H were formed in the presence of SCBA. Another evidence of chemical effect of SCBA was shown by Payá et al. [3], who determined the pozzolanic activity of SCBA/calcium hydroxide and SCBA/Portland cement pastes. The authors indicated that SCBA presents a high pozzolanic activity and can produce an increase in strength when used as a hydraulic binder. In a recent study, Cordeiro [5] verified, using the Chapelle test [6], that the reactivity of SCBA depends directly on the conditions used in burning the bagasse. Fig. 1 shows the variation in SCBA reactivity as a function of bagasse burning temperature. Although caution should be used in using the Chapelle test to assess reactivity of a pozzolanic material, given that the test is carried out at high temperature [7], Fig. 1 clearly demonstrates the existence of maximum at around 500 °C. Recently, the influence of different mechanical grinding configurations in laboratory and pilot-scale mills on the physical characteristics of the SCBA was investigated [8]. The results indicate that the SCBA grinding to values of D_{80} (80% passing size) below about 60 μm and Blaine fineness above 300 m^2/kg resulted in products that can be classified as pozzolans.

In spite of studies and evidence of advantages of using SCBA as cement replacement, the actual mechanisms that are responsible for these are not yet understood. It is not clear if the advantageous use of SCBA is due to physical or chemical effects. This difficulty is partially due to the fact that both effects are coupled to influence the results from most commonly used evaluation methods. For instance, if the particle size distribution of the SCBA is refined it can increase the packing density of the mixture as well as the chemical reactivity of the ash due to the increase in the specific surface area. The present study aims to evaluate the chemical and physical effects of a residual SCBA on the properties of cement mortars. At first, the influence of SCBA particle size distribution on the compressive strength, pozzolanic activity indices, Chapelle test result and packing density is investigated. In this case, the effect of cement dilution is maintained constant; however, the chemical and physical effects are distinct for different SCBAs. In the final part of the paper, the aim is to compare the performance of mortars containing SCBA and crushed quartz (CQ) – considered as an insoluble or low-reactivity material – with the same packing density. Under these conditions the physical effect of both mortars is approximately equalized and the actual pozzolanic activity of SCBA can be estimated.

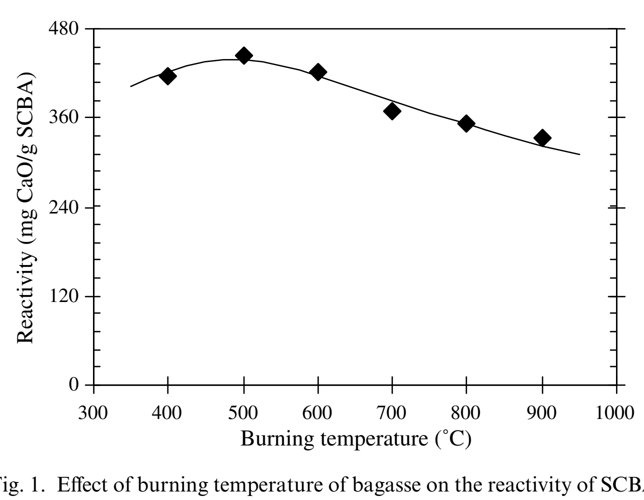

Fig. 1. Effect of burning temperature of bagasse on the reactivity of SCBA using the Chapelle test [5].

2. Materials

The SCBA (as-received) used in the present study was collected at a local sugar and alcohol factory in the State of Rio de Janeiro, Brazil. In the factory, the sugar cane bagasse is burnt in boilers at temperatures varying from 700 to 900 °C, depending on the moisture content of the bagasse. Fig. 2 shows the X-ray powder diffraction pattern of as-received SCBA, where the predominance of cristobalite and quartz in the SCBA is evident and representative of biomass burnt at high temperature. Quantitative XRD analysis based on the Rietveld method was performed using Bruker's Topas v. 3 software [9] to determine the amorphous content of this SCBA. We found a content of

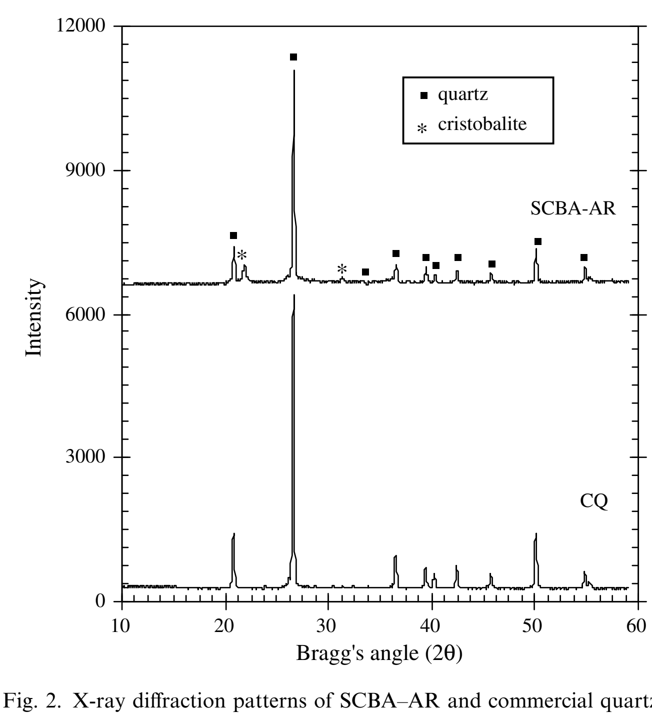

Fig. 2. X-ray diffraction patterns of SCBA–AR and commercial quartz.

Table 1
Chemical composition of materials (in mass)

Compound	SCBA (%)	Quartz (%)	Portland cement (%)
SiO_2	78.34	98.80	20.85
Al_2O_3	8.55	0.20	4.23
Fe_2O_3	3.61	0.11	5.25
CaO	2.15	0.30	63.49
Na_2O	0.12	–	0.16
K_2O	3.46	–	0.40
Ignition loss	0.42	0.40	1.05

amorphous material of 24% with an estimated error of ±4%. Besides that, the proportions of cristobalite and quartz were estimated as 16% and 59% (in mass), respectively. The presence of quartz in the SCBA is ultimately due to the sand adhered to the sugar cane and that is harvested along with it. Even after washing of the harvested sugar cane, the factory reports [5] that sand can represent as much as 2% in weight of the material that is processed. After the loss of organic matter during burning the bagasse, this proportion increases significantly, reaching values as high as those found for quartz (the main constituent of the sand in the region) in the present study. Another evidence of presence of reactive material in SCBA is the result of ^{29}Si nuclear magnetic resonance spectroscopy of hardened cement pastes [5], which indicated that the intensity of the Q^4 peak, characteristic of amorphous silica (chemical shift of -110 ppm), decreased with the hydration development.

Fig. 2 also shows the X-ray powder diffraction pattern of as-received commercial high-purity quartz, which was selected as insoluble material. Portland cement without mineral addition, similar to ASTM type I, with 308 m^2/kg Blaine fineness, chemically pure calcium hydroxide and deionized water were used in the mortar mixtures. Table 1 presents the chemical composition determined using X-ray fluorescence method and loss on ignition of the mineral admixtures and Portland cement. The fine aggregate, which was also employed in mortars, was standard quartz sand [10] with particle size ranging from 0.15 mm to 2.36 mm.

3. Methods

3.1. Grinding procedures

Grinding of SCBA was carried out in vibratory and tumbling mill, whereas CQ was processed by tumbling grinding. A mill manufactured by Aulmann and Beckschulte Maschininfabrik (Germany) was used for vibratory grinding, which was carried out in batch mode, simulating continuous open circuit operation with grinding times varying from 8 to 240 min in accordance to Cordeiro et al. [8]. Tumbling grinding simulating closed circuit operation with classification was performed for processing of SCBA and CQ with nearly identical particle size distributions. In this case, a tumbling mill was used with a bowl rotation speed of 70 rpm and 20% filling of steel balls as grinding media. The grinding products were classified by dry sieving (sieve size 45 μm) using a rotational and tapping shaker (Ro-Tap® shaker). After sieving, the coarse material returned to the mill, which was filled with SCBA to maintain the constant feed. This set-up used in the grinding tests allowed a close control of product size distribution.

In this paper the following nomenclature has been adopted:

- As-received SCBA is denominated SCBA–AR.
- Vibratory ground SCBAs are named SCBA-V-*t*, where *t* is the grinding time in minutes.
- SCBA and CQ ground by tumbling grinding are denominated SCBA-T and CQ-T, respectively.
- The reference mortar composed of Portland cement, sand and water, is named MPC.
- For mortars composed of SCBA or CQ, Portland cement, sand and water, the prefix M is used before the designation of the mineral admixture.

3.2. Physical characteristics

Particle size distributions were measured using a laser diffraction particle analyzer (Malvern Mastersizer®) in liquid mode with analytical-grade ethyl alcohol as dispersant and ultrasonic agitation for 60 s. The particle size distributions generated were characterized using D_{50}, which is the 50% passing size in the cumulative distribution. Blaine fineness was determined according to ASTM C 204. Particle morphology was characterized qualitatively with the aid of scanning electron microscope (SEM) images, obtained using a Jeol® JXA 840-A.

3.3. Packing density

The compressible packing model (CPM) [11] was used to characterize the packing density of the grain mixtures. In this model, the packing density depends on the size and shape of the grains, and on the method of packing adopted. The CPM allows making the transition from virtual packing density (γ) to the actual packing density (ϕ) of the mixture, which is in accordance with the energy applied at the time of placing. A scalar K, called compaction index, enables connecting γ with ϕ. This scalar is strictly dependent on the protocol implemented for the particular mixture, such that as K tends to infinity, ϕ tends to γ. The general form of equation that reports ϕ to γ is given by

$$K = \sum_{i=1}^{n} \frac{y_i/\beta_i}{\frac{1}{\phi} - \frac{1}{\gamma^{(i)}}} \quad (1)$$

where n is the number of grain classes; y_i is the volumetric fraction; β_i is the virtual packing density of the ith class. It represents the volume of grains contained in a unitary volume, compacted with an ideal compaction energy that corresponds to a maximum virtual packing; and $\gamma^{(i)}$ is the virtual packing density when i is the dominant class. The index K assumes a value of 4.5 when the compaction process is simple pouring, 6.7 for water demand and 9.0 when the placing process is vibration followed by compression with 10 kPa of pressure. It is evident that when the Eq. (1) is used with $n = 1$, it is possible to determine β_i for a given single class using

$$\beta = \frac{1+K}{K}\phi \tag{2}$$

De Larrard [11] suggests to determine the packing properties of sand from the vibration and compaction test ($K = 9$) and fine materials (cement, SCBAs and CQ) from water demand test ($K = 6.7$).

3.4. Compressive strength and pozzolanic activity

Mortars containing mineral admixture were prepared in a laboratory bench mixer according to Brazilian standards in order to examine the pozzolanic activity of the mineral admixtures/cement and mineral admixtures/lime. The pozzolanic activity index with lime [12] was obtained from the average compressive strength of mortar after 7 days of curing. Mortars were prepared using a constant 1:9:2 (weight basis) calcium hydroxide-sand-mineral admixture ratio. The amount of water required to achieve a consistency index [13] in the range of 225 ± 5 mm was equivalent to 14–18% in weight of the solid materials.

The compressive strength (after 7, 14 and 28 days of curing) and the pozzolanic activity index with Portland cement [14] were obtained from the mortar mixtures with 1:3 (weight basis) cement–sand ratio and amount of water required to achieve a consistency index in the range of 225 ± 5 mm. In the mixtures with pozzolan, 35% in volume of the Portland cement was replaced by the pozzolanic material. In this investigation, the water/cementitious material ratio for all mixtures could be kept constant at 0.52, which allowed achieving consistency values within the specified range. These compressive strengths were based on testing cylinders of 50 mm diameter and 100 mm height. After mixing and moulding, specimens were maintained in a moist chamber during the first 24 h at a temperature of 22 °C and 100% relative humidity. Then, specimens were demolded, sealed with plastic film and stored in hermetically-closed air-tight containers at a temperature of 38 °C ± 2 °C for curing. At the end of the curing process, the specimens (4 per mixture) were tested in a servo hydraulic press (Shimadzu® UH-F1000kNI) operating at 0.1 mm/min. The compressive strength results were evaluated by analysis of variance (ANOVA) and Duncan's multiple range tests [15]. Significant differences were considered when the probability was smaller than 0.05. Results were expressed as average of 4 specimens ± standard error. After 28 days of curing, the pozzolanic activity index with Portland cement was calculated from the ratio between the compressive strengths of mortars with mineral admixture and a reference mortar, prepared with cement, sand and water.

The pozzolanic activity was also assessed using the modified Chapelle method [6]. This test consisted of placing the 1.000 g of mineral admixture and 1.000 g of calcium oxide in a water volume of 250.0 ml. The solutions were kept for 16 h in an oven at 90 °C. At the end of the period, the CaO content was determined for titration with hydrochloric acid (HCl) solution and using phenolphthalein as indicator. The results were expressed by fixed CaO, which is equal to the difference between 1.000 g and the mass of CaO obtained from titration.

4. Results and discussion

4.1. Effect of particle size distribution

Particle size distributions of the SCBAs ground in the vibratory mill during different times and the SCBA–AR are shown in Fig. 3. The ashes present a wide range of particle sizes, with D_{50} values ranging from 1.65 μm to 76.3 μm. The reduction in particle size with the increase in grinding time is evident; however, the shapes of the particle size distributions are fairly complex, presenting two populations of particles (bimodal). The mode (and also the average size) of the coarser population of particles, predominantly formed by those larger than about 1 μm, clearly becomes finer as grinding time increases. On the other hand, the mode of the finer population of particles remains relatively constant at about 0.3 μm, while the relative proportion of this population increases with time. The distinction between these two populations start to disappear at longer grinding times, as they tend to overlap. This appearance of poly-modal distributions has already been observed by Palaniandy et al. [16] in vibratory grinding of silica and has been attributed to the tendency of fine particles to agglomerate.

As can be seen in Fig. 4a, the SCBA-V-8 presents an heterogeneous mixture of coarser quartz particles and particles with cellular structures, typical for organic materials. Quartz particles are characterized by their distinctive con-

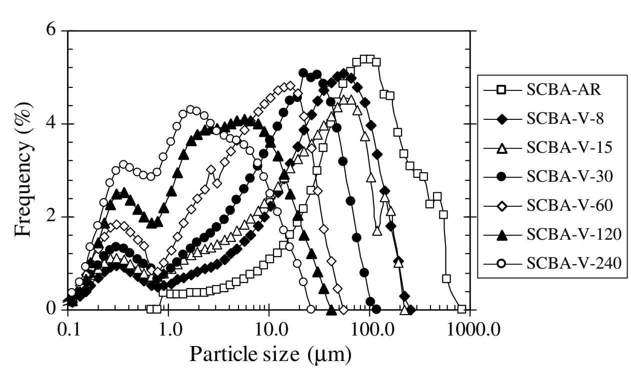

Fig. 3. Particle size distributions of SCBA–AR and ground SCBAs.

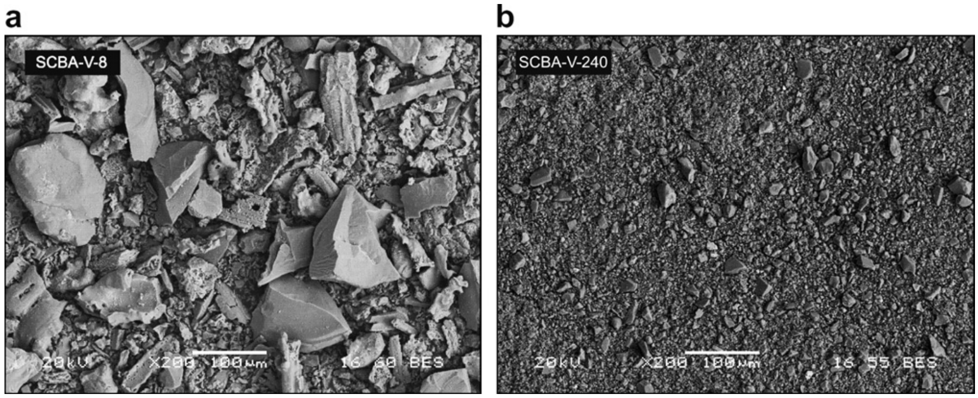

Fig. 4. SEM images of SCBAs produced after 8 min (a) and 240 min (b) of vibratory grinding.

choidal fractures. After 240 min of grinding, the SCBA also presents coarser particles of quartz; however, the cellular grains were totally broken by the mechanical action of the grinding media (Fig. 4b). Table 2 summarizes the values of D_{50}, virtual packing density (β_i) and Blaine fineness of SCBAs. As expected, the Blaine fineness increases with grinding time. Moreover, the virtual packing density also increases with grinding time. These observations indicate that the reduction in particle size is responsible for changes in the intrinsic capacity of the particles to pack.

In relation to pozzolanic activity, the reduction in particle size results in an improved performance of SCBA, as shown in Table 2. It is evident that the pozzolanic activity index with cement increases as D_{50} of SCBA decreases. SCBA–AR presents a pozzolanic index of 49%, while the SCBA-V-240 presents an index of 103%. The Brazilian standard NBR 12653 [17], in analogy to the American standard ASTM C 618-05 [18], establishes that 75% is the minimum value required to classify a material as pozzolan. Therefore, SCBA presents a pozzolanic index higher than the minimum requirement after only 15 min of grinding. The pozzolanic activity index with lime of the SCBA increases with an increase in grinding time. SCBA–AR presents a pozzolanic index with lime equal to 3.9 MPa, which is lower than the NBR 12653 [17] minimum requirement of 6.0 MPa. The decrease of SCBA D_{50} by grinding is also accompanied by an increase of pozzolanic activity index with lime. Thus, a D_{50} below about 12.0 μm is required to satisfy the standard requirement (Table 2). The higher fineness of SCBAs, SCBA-V-120 and SCBA-V-240, exhibited pozzolanic indices of 8.5 MPa and 8.6 MPa, respectively. These values are approximately 40% higher than the minimum established by the standard. From these results, it is clear that particle size reduction influences positively the behavior of SCBA-cement and SCBA-lime systems. The analysis of pozzolanic activity of the SCBA using the modified Chapelle method [6] shows a similar trend. The increase in lime fixed during the reaction with SCBA is inversely proportional to the Blaine fineness, as shown in Fig. 5. The pozzolanic activity caused by the SCBA is in general agreement with that observed on several studies [2,4,5].

Fig. 6 shows the effects of grinding time and curing time (7, 14 and 28 days) on the compressive strengths of mortars prepared using SCBA. As expected, strengths increase with both curing and grinding time for all mixtures. However, the replacement of cement by SCBA results in a decrease in compressive strength, compared to the MPC (reference mortar), due to the negative effect resulting from cement replacement by mineral admixture. This effect, so called dilution effect [19], is continually reduced by the increase of SCBA fineness. In accordance to statistical analysis,

Table 2
Physical and pozzolanic characteristics of materials

Material	D_{50} (μm)	Virtual packing density	Blaine fineness (m^2/kg)	Pozzolanic index with cement (%)	Pozzolanic index with lime (MPa)	Chapelle activity (mg CaO/g)
Sand	900	0.65[a]	–	–	–	–
Cement	16.9	0.61[b]	308	–	–	–
SCBA–AR	76.3	0.54[b]	196	49	3.9	36
SCBA-V-8	27.5	0.56[b]	277	71	5.1	45
SCBA-V-15	19.8	0.59[b]	395	77	5.3	93
SCBA-V-30	12.0	0.58[b]	444	79	6.2	101
SCBA-V-60	5.6	0.60[b]	640	89	6.7	141
SCBA-V-120	2.7	0.61[b]	893	100	8.5	279
SCBA-V-240	1.7	0.65[b]	1197	103	8.6	298

[a] Compaction index $K = 9$.
[b] Compaction index $K = 6.7$.

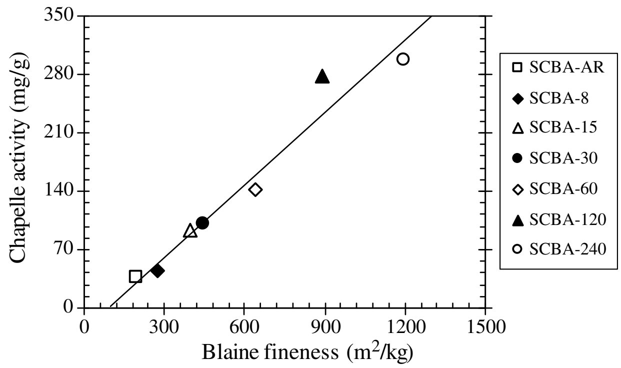

Fig. 5. Relationship between Chapelle activity results and Blaine fineness of SCBAs.

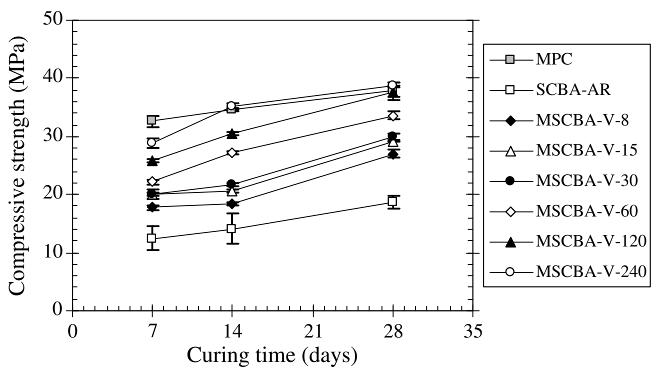

Fig. 6. Compressive strengths of reference and ground SCBAs mortars.

no significant difference exists in compressive strength of the mortar prepared using MSCBA-V-15 and MSCBA-V-30, after 7 days of curing. The other mixtures present different values of compressive strength, increasing with fineness of SCBA. After 14 days of curing, all mortars present significantly different strengths, according to Duncan's test, with the exception of MSCBA-V-240 and MPC mixtures, which are statistically equal. After 28 days, it can be observed that the compressive strength of MSCBA-V-15 and MSCBA-V-30 are not different. The same trend is observed with MSCBA-V-120, MSCBA-V-240 and the MPC. The results indicate than the production of mortar with high cement replacement (35% in volume) by SCBA with the same compressive strength of cement mortar was possible, given that the ash presented D_{50} below 3 μm and Blaine fineness of about 1000 m^2/kg.

The compressive strength and the pozzolanic activity results present similar behavior. This can be well observed by comparing compressive strengths of MSCBA-V-240 and MPC mixtures for different times of curing. After 7 days, the strength of MPC is 13% higher than that of the MSCBA-V-240. Nevertheless, the results obtained after 14 and 28 days of curing are statistically equal, which represent a rise not associated with the filler effect. Moreover, the increase in strength between 7 and 14 days is more significant for MSCBA-V-60, MSCBA-V-120 and MSCBA-V-240, when compared to the other mixtures with SCBA. This indicates that this behavior of SCBA mortar is in accordance with the pozzolanic activity results, which increase significantly after longer grinding times.

In order to investigate if this improvement in pozzolanic activity could be associated to a mechanochemical activation of SCBA during vibratory grinding, the X-ray diffraction pattern of the SCBA–AR is compared to that of the material ground for 240 minutes. Mechanochemical activation during grinding is often attributed to the fact that, besides breaking the particles, impacts from grinding media may also be responsible for creating microdefects and electrostatic charges on the particles, increasing their surface energy [20]. This activation was observed, for example, by Kanno [21] in vibratory grinding of quartz powder for 120 h. Fig. 7 shows, however, that the widening of peaks, which would be characteristic of amorphization, is not observed in the present study, even after the longest grinding time studied (240 min). This contrasts with results from Kitamura et al. [22] from grinding of $Al(OH)_3$ and from Palaniandy et al. [16] from oscillating grinding of silica that show evidence of amorphization at grinding times that are comparable to the ones used in the present study. It is important to note that an increase in compressive strength of mortars generated by vibratory grinding of the silica powder was observed by Benezet and Benhassaine [23]. However, no structural changes in silica could be detected, and the authors pointed out that the crystalline structure of silica can not be considered as an obstacle to its reactivity with lime, since the particles are of very fine sizes. The authors also reported that in the particle size range below 5 μm, the reactivity of the material depended closely on particle size. The results for the SCBA studied in this research

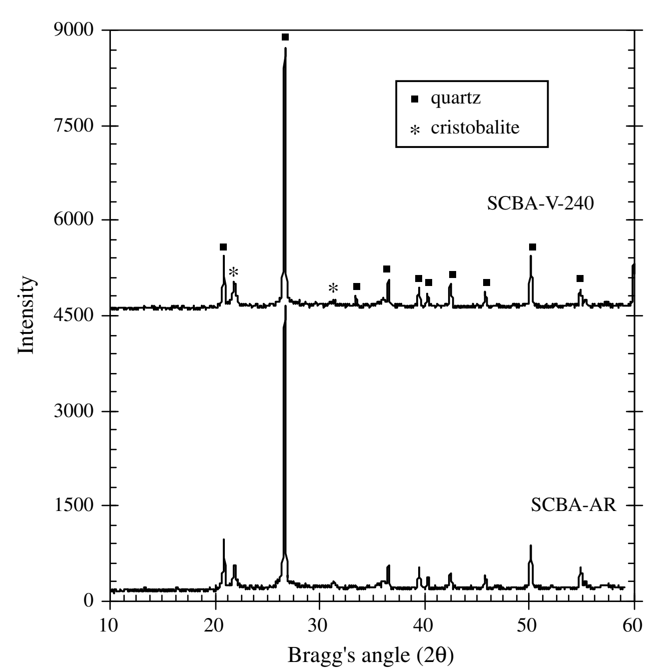

Fig. 7. X-ray diffraction patterns of SCBA–AR and SCBA ground for 240 min.

suggest the same trend, since the ash presents low amorphous content (24%) due to high quartz contamination.

In spite of the apparent absence of mechanochemical changes, the reduction of SCBA particle size causes an increase in the packing density of mortar. These packing densities were quantified using the CPM, taking as input the experimental data presented in Table 2, and computing the values of φ with $K = 9$, given in Fig. 8. This figure also indicates that the compressive strength of SCBA mortars studied in the present research is directly proportional to the packing density. Breakage of SCBA particles possibly allows interstices left between coarse grains be filled by the ultrafine particles that are produced in large amounts, so that the packing density increases progressively. The results suggest that the increase in compressive strength of the SCBA mortars is closely linked to the filler effect proportioned by the ultrafine particles of SCBA.

It is also worth noting that no significant changes were observed on the mortar water demand in spite of the increase of SCBA Blaine fineness. This behavior can be explained with the following: while the SCBA fineness increases, the proportion of regular-shaped particles also increases (Fig. 4), mainly due to the high quartz content in the residual mineral admixture and the internal porosity of SCBA particles is probably destroyed by grinding.

4.2. Comparison of mineral admixtures with the same packing density

In order to better evaluate the pozzolanic activity of SCBA, its properties are compared to those of an insoluble material (CQ-T). Fig. 9 presents the particle size distributions obtained for the two mineral admixtures SCBA-T and CQ-T (both materials ground in tumbling mill). It shows that both materials present very similar particle size distributions, with D_{50} of about 30 μm. Table 3 summarizes values of D_{50}, virtual packing density and Blaine fineness of SCBA-T and CQ-T. The difference between Blaine fineness is likely to be associated with the greater microporosity of the particles from burning the bagasse, evident in Fig. 10. This photomicrography also allows comparing particle shapes of the admixtures, demonstrating a reasonable similarity between them, although particles in SCBA-T tend to present smoother surfaces and while CQ-T particles are more uniform, with distinctive conchoidal fractures. As a result of their similarity in particle size, shape and, to a lesser extent, surface texture, virtual packing densities are very similar for both mineral admixture investigated, as shown in Table 3. Thus, it can be considered that both SCBA-T and CQ-T present the same packing behavior, that is, the same filler effect is expected from the two mineral admixtures when they partially replace Portland cement.

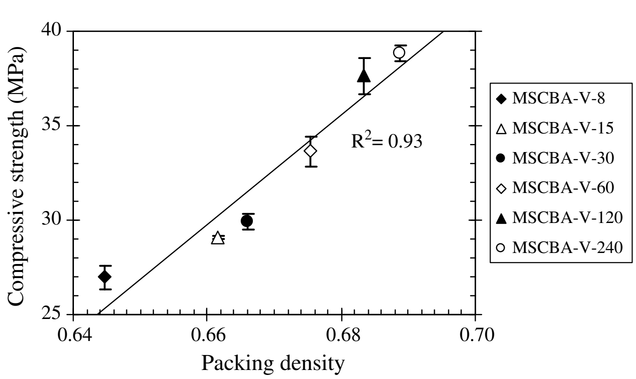

Fig. 8. Relationship of packing density and compressive strength of SCBA.

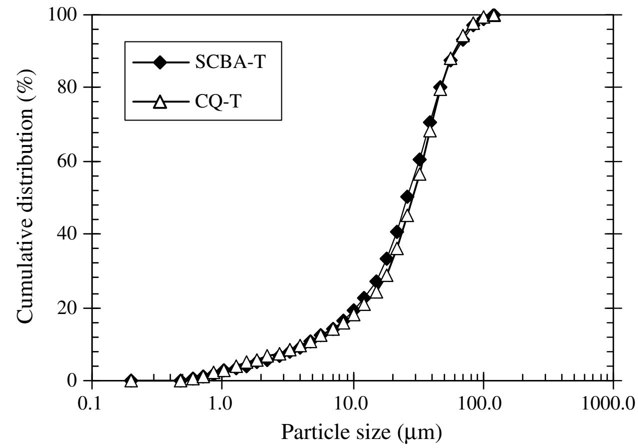

Fig. 9. Particle size distributions of SCBA-T and CQ-T.

Table 3
Physical and pozzolanic characteristics of SCBA-T and CQ-T

Material	D_{50} (μm)	Virtual packing density	Blaine fineness (m^2/kg)	Pozzolanic index with cement (%)	Pozzolanic index with lime (MPa)	Chapelle activity (mg CaO/g)
SCBA-T	26.6	0.66[a]	295	81	5.20	173
CQ-T	29.1	0.66[a]	210	62	0.14	32

[a] Compaction index $K = 6.7$.

The results of the pozzolanic activity of SCBA-T and CQ-T are shown in Table 3. CQ-T presents a low pozzolanic activity index with cement (62%), lower than that specified by NBR 12653 [17] as the minimum required. As expected, the values of pozzolanic activity index with lime and Chapelle activity, equivalent to 0.14 MPa and 32 mg CaO/g, respectively, are insignificant and typical of inert materials. In relation to SCBA-T, the pozzolanic activity index with cement of 81% confirms the chemical activity of SCBA. The SCBA-T investigated does not show high pozzolanic activity due to burning bagasse conditions and high quartz content contaminating the sample. However, its pozzolanic index with cement is similar to that which was observed for the other pozzolans, as for example low-calcium fly ash (ASTM "Class F" fly ash) [24]. In the evaluation of two other methods, the ash presents a pozzolanic activity index with lime of 5.20 MPa and Chapelle activity of 173 mg CaO/g. These values are significantly

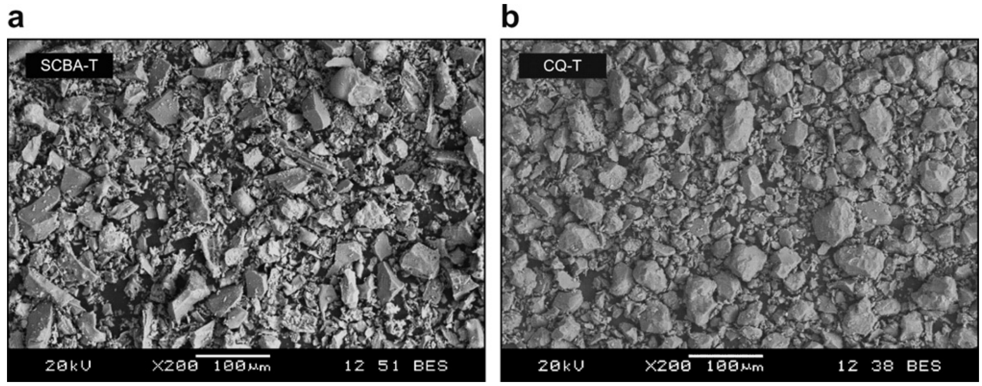

Fig. 10. SEM images of SCBA-T (a) and CQ-T (b).

higher than those obtained for the CQ-T. Moreover, the results show that both grinding procedures (vibratory and tumbling mill) are appropriate to produce mineral admixture from SCBA.

The packing densities of mortars were computed using CPM with $K = 9$. It is important to point out that these packing densities are nearly identical, with values of 0.67 for MPC and MSCBA-T and 0.68 for MCQ-T. Therefore, the packing (filler) effects of SCBA-T and CQ-T mortars are similar. The average values of mortar compressive strength developed over time are presented in Fig. 11, where SCBA-T, CQ-T and MPC mixtures are compared. It can be seen that the three mortars present different trends in time. Specifically, the mortars prepared using mineral admixtures exhibit very different behaviors. After 7 days, both mortars present compressive strength lower than that of the MPC (30% lower); and no statistical difference is observed between them. After 14 days, the strength of SCBA-T mortar is significantly higher than that of the CQ-T mortar, which demonstrates the reactivity of SCBA. At 28 days, the progressive increase in compressive strength of SCBA-T, responsible for the significant difference in relation to CQ-T mortar, is evident. At this curing time, the difference between MPC and SCBA-T mortars is approximately 20%, while the difference between MPC and CQ-T mortars is larger than 40%. The parallelism between MPC and CQ-T strength against curing time curves confirms this behavior, as can be seen in Fig. 11. Furthermore, the dilution effect after 28 days of curing is responsible for the strength differences of MPC and CQ-T mixtures and the difference between both SCBA-T and CQ-T mortar strength can be attributed to the pozzolanic activity of SCBA. Thus, it can be assumed that the compressive strength of the SCBA mortars, in the replacement volume used, depends on both chemical and physical effects, in spite of the low amorphous silica content in the SCBA.

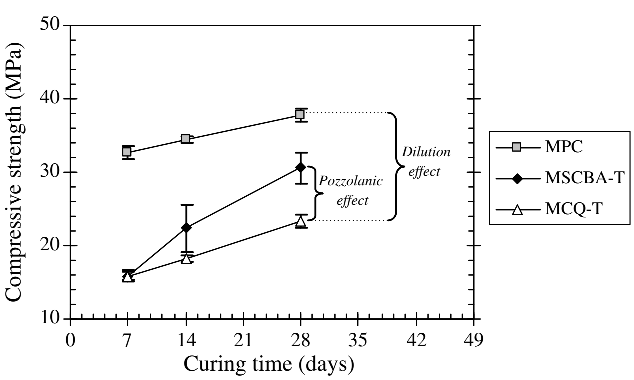

Fig. 11. Average values of compressive strength of mortars.

5. Conclusions

The results from the investigation of the physical and pozzolanic effects of SCBA on the mortar properties allowed concluding that:

- A direct relationship exists between the compressive strength of mortar containing SCBA and the Blaine fineness of the ash. On the other hand, the compressive strength of mortar containing SCBA is inversely proportional to SCBA's particle size. According to the investigation of the SCBAs produced by vibratory grinding, the finest SCBA provided the highest packing density of mortar, which generated a higher compressive strength and pozzolanic activity. Moreover, a clear correlation was observed between Chapelle reactivity and fineness of SCBA.
- The pozzolanic activity of SCBA was established from the comparison with an insoluble material at the same packing density. In that case, a different behavior was verified in relation to compressive strength of mortars produced with the mineral admixtures, SCBA and quartz. After 28 days of curing, the compressive strength of SCBA mortar was 31% higher than the strength of CQ-T mixture. This discrepancy was also observed in pozzolanic activity, mechanical response, as well as in results from the modified Chapelle method. Thus, the results suggested that the SCBA presents physico-chemical properties appropriate for its use as mineral admixture and its reactivity was mainly dependent on particle size and fineness.

Acknowledgments

The authors wish to thank the Brazilian agencies FAPERJ, CNPq and CAPES for the financial support to this investigation and also thank Companhia Açucareira Usina Barcelos for providing the sugar cane bagasse ash used in the investigation.

References

[1] Goldman A, Bentur A. Properties of cementitious systems containing silica fume or nonreactive microfillers. Adv Cem Based Mater 1994;1(5):209–15.

[2] Martinera Hernández JFM, Middeendorf B, Gehrke M, Budelmann H. Use of wastes of the sugar industry as pozzolana in lime-pozzolana binders: study of the reaction. Cement Concrete Res 1998:1525–36.

[3] Payá J, Monzó J, Borrachero MV, Ordóñez LM. Sugar-cane bagasse ash (SCBA): studies on its properties for reusing in concrete production. J Chem Technol Biotechnol 2002;77(3):321–5.

[4] Singh NB, Singh VD, Rai S. Hydration of bagasse ash-blended Portland cement. Cement Concrete Res 2000;30(9):1485–8.

[5] Cordeiro GC. Utilização de cinzas ultrafinas do bagaço de cana-de-açúcar e da casca de arroz como aditivos minerais em concreto. D.Sc. Thesis, COPPE/Universidade Federal do Rio de Janeiro, Brazil; 2006 [in Portuguese, http://www.coc.ufrj.br].

[6] Raverdy M, Brivot F, Paillère AM, Bron R. Appréciation de l'activité pouzzolanique de constituents secondaires. In: Proceedings of 7e Congrés International de la Chimie des Ciments, Paris, France; 1980. p. 6–41.

[7] Sabir BB, Wild S, Bai J. Metakaolin and calcined clays as pozzolans for concrete: a review. Cement Concrete Res 2001;23(2):441–54.

[8] Cordeiro GC, Toledo Filho RD, Fairbairn EMR, Tavares LM, Oliveira CH. Influence of mechanical grinding on the pozzolanic activity of residual sugarcane bagasse ash. In: Proceedings of International RILEM Conference on the Use of Recycled Materials in Building and Structures, Barcelona, Spain; 2004. p. 731–40.

[9] Bruker. Topas version 3.0: diffract plus tutorial. Karlsruhe: Bruker; 2005.

[10] ABNT NBR 7214, Standard sand for cement test, ABNT (Technical Standards Brazilian Association), Rio de Janeiro, Brazil; 1982.

[11] De Larrard F. Concrete mixture proportioning: a scientific approach. London: E. & F.N. Spon; 1999.

[12] ABNT NBR 5751, Pozzolans – Pozzolanic activity – Determination of pozzolanic activity index with lime, ABNT (Technical Standards Brazilian Association), Rio de Janeiro, Brazil; 1992.

[13] ASTM C 109-05, Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens); 2005.

[14] ABNT NBR 5752, Pozzolans – Pozzolanic activity – Determination of pozzolanic activity index with Portland cement, ABNT (Technical Standards Brazilian Association), Rio de Janeiro, Brazil; 1992.

[15] Montgomery DC. Design and analysis of experiments. New York: Wiley; 1997.

[16] Palaniandy S, Azizli KAM, Hussin H, Hashim SS. Study on mechanochemical effect of silica for short grinding period. Int J Miner Process 2006. doi: 10.1016/j.minpro.2006.10.008.

[17] ABNT NBR 12653, Pozzolanic materials, ABNT (Technical Standards Brazilian Association), Rio de Janeiro, Brazil; 1992.

[18] ASTM C 618-05, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, 2005.

[19] Lawrence P, Cyr M, Ringot R. Mineral admixtures in mortars – effect of inert materials on short-term hydration. Cement Concrete Compos 2003;33(12):1939–47.

[20] Ryou J. Examination of grinding techniques for the reuse of by-products of cement production. Mater Lett 2004;58(3–4):425–7.

[21] Kanno Y. Properties of SiC, Si_3 N_4 and SiO_2 ceramic powders produced by vibration ball milling. Powder Technol 1985;44(1):93–7.

[22] Kitamura M, Sahara T, Senna M. Effects of milling $Al(OH)_3$ prior to mix with $Ca(OH)_2$ for a rapid cement hardener. Powder Technol 2001;118(3):203–8.

[23] Benezet JC, Benhassaine A. The influence of particle size on the pozzolanic reactivity of quartz powder. Powder Technol 1999;1036(1):26–9.

[24] Diamond S. The utilization of flyash. Cement Concrete Res 1984;14(4):455–62.