A REVIEW OF THE USE OF SUGARCANE BAGASSE ASH WITH A HIGH LOI CONTENT TO PRODUCE SUSTAINABLE CEMENT COMPOSITES

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Abstract

In recent years, agricultural wastes have been employed as supplementary cementitious materials to produce sustainable cement composites. One of these wastes is the sugarcane bagasse ash (SCBA). The SCBA is available in large quantities in developing countries such as Brazil, India and Mexico, and its disposal is causing different environmental issues. The SCBA has high amounts of silicon, aluminum and iron oxides as major components. Several researchers report that the high amount of these oxides leads to the improvement of the mechanical and microstructural properties of cementing composites containing the SCBA. On the other hand, a high amount of unburned carbon, commonly expressed by the loss on ignition (LOI), could be also present in the SCBA due the inefficient burning process of the bagasse in the boiler in sugar mills. It has been reported that this high LOI content in the SCBA change the water requirement and the rheological properties of cement binders. This might adversely affect the mechanical, microstructural and durability properties of hardened cement composites prepared with this material as well. In order to decrease the LOI content of the SCBA the combination of sieving, grinding and recalcination have been proposed; however, these methods are highly demanding in energy and generate additional contaminants. Sieving is the less energy demanding procedure and appears to be an interesting approach to post-treat the existing SCBA in open damps. Based on the above, this paper presents a review on the effects of the use of SCBA with a high LOI content to manufacture cement composites.

Keywords:
Recalcination, cement composites, grinding, sieving, post-treatment

1 INTRODUCTION

Portland cement is used in cement composites (concrete, mortars and other cementitious materials) and is considered one of the most produced and significant building material for society´s infrastructures around the world [Hendriks 2004, CIF 2011]. Currently, concrete is produced in large quantities, between 2 and 2.8 billion of tons annually [Schneider 2011, Shi 2011], to satisfy the housing demand of the population and industrial activities. A demand scenario indicates that the Portland cement production could reach 3.69 to 4.40 billion of tons by 2050 [IEA 2009]. However, the cement production is a high energy-intensive process yielding an enormous negative effect on the environment. In this context, it is reported that the production of each ton of Portland cement emits approximately 0.8 to 1.0 tons of anthropogenic CO_2 into the atmosphere [Aprianti 2015, Habert 2013]. This represents between 3 and 5% of current global emissions [IEA 2009].

For this reason, several studies have been focused in the use of alternative materials, such as wastes generated from the industry and agriculture, which are used as supplementary cementitious materials of Portland cement composites [Aprianti 2015]. The disposal of these wastes is another serious problem worldwide. Waste materials form the industry such as fly ash, ground granulated blast furnace slag and silica fume have been successfully used in cement composites for many years [Madurwar 2013, Shafigh 2014, Demis 2014].

Agricultural waste materials have been employed in cement composites recently. The utilization of these wastes as a partial Portland cement replacement can provide the break-through needed to make a more environment friendly and sustainable construction industry [Madurwar 2013, Demis 2014, Aprianti 2015]. It has been reported that the agricultural wastes in large quantities are sugarcane bagasse ash, rice husk ash, palm oil fuel ash, wood waste ash, corn cob ash and bamboo leaf ash. This review focuses on the use of sugarcane bagasse ash (SCBA) as cement replacement in cement composites.

The SCBA is a by-product generated from the combustion process of sugarcane bagasse in sugar mills. The production of SCBA is approximately 15 millions of tons annually and is causing serious disposal problems and environmental issues worldwide [Frías 2013]. The SCBA is mostly composed by silicon, aluminum and iron oxides. Several researches confirm that a high amount of these oxides in the chemical composition of the SCBA leads to the improvement of the mechanical and microstructural properties of cementing composites (when the SCBA replaces up to 30% of Portland cement). They also suggest the improvement of some durability properties of Portland cement based composites added with this material [Ganesan 2007, Cordeiro 2009a, Cordeiro 2009b, Morales 2009, Chusilp 2009a, Chusilp 2009b, Frías 2011, Bahurudeen 2015].

However, it is reported that a high amount of unburned carbon particles, generally presented in the form of cellular particles and commonly expressed by the loss on ignition (LOI), could be present in the SCBA [Chusilp 2009a, Somma 2012, Maldonado 2012, Bahurudeen 2015, Asrif 2016]. The high LOI content in the SCBA can be attributed to termo-mechanical conditions during the burning process of the bagasse in the boilers of sugar mills as well as the nature of the parent biomass [Batra 2008]. A high LOI content can be an obstacle for the use of the SCBA in cement composites due to the reduction of the fluidity during the mixing process [Jímenez 2013], and due to a slight effect in the compressive strength development of these composites as well [Chusilp 2009a].

Several researchers have focused on the implementation of some post-treatments to the SCBA in order to reduce the LOI content, such as sieving, grinding, recalcination or the combination of them. They suggest that these methods can increase the pozzolanic activity when the SCBA is subjected to specific conditions of grinding or recalcination [Cordeiro 2009a, Chusilp 2009, Somma 2012, Buhurudeen 2015]. Unfortunately, these methods are highly demanding in energy making necessary to use them as “practically as received” from sugar mills, i.e. a SCBA processed with a minimum energy demand post-treatment such as only sieving.

Based on the afore mentioned dilemma, a discussion about the effects of the use of SCBA with a high LOI content in cement composites is presented on this paper.

2 NATURE AND PYROLYSIS PROCESS OF THE SUGARCANE BAGASSE

The sugarcane bagasse is a fibrous residue obtained after the crushing and milling process of the sugarcane stalks to squeeze the juice out. It is reported that the sugarcane bagasse is made up of water, fiber bundles (which consist of cellulose, hemicelluloses, lignin, pectin, waxes and pentosane), vesels, parenchyma, epidermal cells and small amounts of soluble solids. Each of the mentioned compounds varies according with the soil type, harvesting methods, variety and maturity of the sugarcane. It has been reported that cellulose is a hydrophilic compound while hemicelluloses and lignin have hygroscopic and hydrophilic properties, respectively [Sanjuán 2001, Chiparus 2004, Verma 2012]. The nature of the cellulose and hemicellulose could elucidate the rheological performance of the SCBA when is used as cement replacement.

Some studies suggest that the pyrolysis of the sugarcane bagasse is divided in two steps. In the first step, a rapid mass loss occurs due the volatilization of the cellulose obtaining bio-oil. In the second step, a slower mass loss rate occurs due the lignin decomposition obtaining products with properties of char and bio-oil [Gani 2007, Varma 2016].

3 CHEMICAL COMPOSITION AND MORPHOLOGY OF THE SUGARCANE BAGASSE AFTER BURNING

After the burning process of the sugarcane bagasse, the residual ash is composed by approximately 85% of silicon, aluminum and iron oxides (Tab. 1). It also contains other compounds such as calcium, potassium, sodium and magnesium oxides as well as unburned carbon particles. From Tab.1, it can be seen that the SCBA may have different LOI contents, ranging from 0.40 to 24.15%. The different chemical compositions of the SCBA depend on the variety, maturity and harvesting methods of the sugarcane; likewise depend on the bagasse combustion environment and bagasse ash collection [Arif 2016].

Several researchers have shown that the SCBA has a morphology consisting in particles with a large variety of shapes and sizes [Batra 2008, Cordeiro 2009a, Chusilp 2009a, Maldonado 2012, Buhurudeen 2015]. This morphology is attributed to the variations of the temperature and air flow during the burning process of the bagasse. In general, the SCBA has prismatic, agglomerated, spherical and fibrous particles (unburned matter) (Fig. 1).

Researchers reported that the SCBA has a potential use as a beneficial cement replacement in cement composites; however, the physical and chemical variations limitates its use as cementing material [Frías 2011, Demis 2014]. In view of this, it is suggested that individual sources of SCBA should be evaluated in terms of physical and chemical characteristics in order to determinate its most effective utilization [Arif 2016].

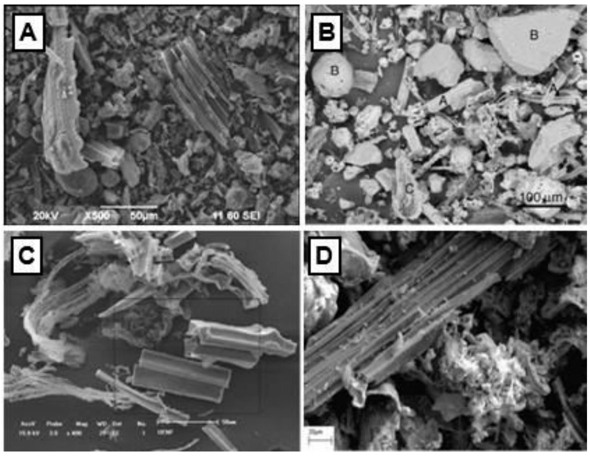

Fig. 1: Morphology of the SCBA. SEM images obtained from A) Maldonado 2012, B) Batra. 2008, C) Cordeiro 2009a and D) Chusilp 2009a.

*Tab. 1: Summary of chemical compositions and LOI content of SCBAs from varied sources (%, in mass). S = sieving, G = grinding, R = recalcination, * = Selected chemical compositions from the mentioned paper.*

Reference	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	LOI	Post-treatment
Martirena 1998	72.74	5.26	3.92	7.99	2.78	0.13	3.47	0.84	1.56	**0.77**	R
Ganesan 2007	64.15	9.05	5.52	8.14	2.85	---	1.35	0.92	---	**4.90**	R + G
Cordeiro 2008	78.34	8.55	3.61	2.15	---	---	3.46	0.12	---	**0.42**	G
Cordeiro 2009a, *	60.96	0.09	0.09	5.97	8.65	---	9.02	0.70	8.34	**5.70**	R
Chusilp 2009a	54.10	5.69	3.54	15.37	1.41	0.03	---	---	---	**19.36**	G
Morales 2009, *	58.61	7.32	9.45	12.56	2.04	0.53	3.22	0.92	2.09	**2.73**	G + S
Noor-ul 2011	87.40	3.60	4.90	2.56	0.69	0.11	0.47	0.15		**8.25**	R + G
Hernández 2010	51.66	9.92	2.32	2.59	1.44	---	2.10	1.23	0.90	**24.15**	S
Somma 2012	55.00	5.10	4.10	11.00	0.90	2.20	1.20	0.20	---	**19.60**	G
Maldonado 2012	56.37	14.61	5.04	2.36	1.43	---	3.29	1.57	0.85	**10.53**	S
Valencia 2012	70.05	8.50	3.10	2.80	0.50	---	---	---	---	**8.50**	---
Frías 2013	58.61	7.32	9.45	12.56	2.04	0.53	3.22	0.92	2.09	**2.73**	---
Montakartiwong 2013, *	67.10	5.70	2.50	2.90	0.50	---	---	---	---	**20.4**	G
Buhurudeen 2015, *	72.95	1.68	1.89	7.77	1.98	4.45	9.28	---	---	**21.00**	S, S + G
Rerkpiboon 2015	55.04	5.14	4.06	11.03	0.91	---	1.22	0.24	---	**19.60**	G
Arif 2016	78.49	7.27	3.48	1.28	1.28	1.55	1.14	0.69	---	**7.15**	---
Cordeiro 2016	80.80	5.10	1.60	3.10	---	1.50	6.30	---	0.80	**0.40**	G
Soares 2016	72.30	5.52	10.80	1.57	1.13	---	---	---	1.11	**1.52**	---

4 EFFECT OF THE CALCINATION ON THE PERFORMANCE OF SCBA IN CEMENT COMPOSITES

Some authors suggest that a proper calcination of the sugarcane bagasse is enough to obtain ashes with good quality to be used as replacement in cement composites. In general, it is recommended that the sugarcane bagasse must to be calcined at temperatures between 600 and 800ºC considering a heating rate of 10ºC/min [Morales 2009, Cordeiro 2010, Ribeiro 2014]. For example, [Cordeiro 2009a] evaluated the pozzolanic behavior of SCBA obtained under controlled calcination conditions. Sugarcane bagasse samples were burnt in an aired electric oven at 350ºC with a heating rate of 10ºC for 3 hours, and then at temperatures between 400 and 800ºC for another 3 hours. They found that the LOI content of the SCBA decreased with increasing the temperature of calcination. The authors found that the SCBA produced with air calcination at 600ºC for 3 hours with a rate of heating of 10ºC/minute present amorphous silica, low carbon content (5.70% by mass represented by the LOI content according with Tab. 1) and hence a good pozzolanic activity.

[Morales 2009] evaluated the microstructural features of SCBA obtained under controlled calcination conditions. For this purpose, the sugarcane bagasse was calcined at temperatures of 800 and 1000ºC (±5ºC) in an electric furnace for 20 minutes. The ashes were ground and sieved to <90μm after the calcination process. The authors concluded that the textures and morphologies of the SCBA calcined at both temperatures change in dependence of the Ca and Si content. They also concluded that the calcination process not only influence the mineralogical composition of the SCBA but also change the morphology and composition of their individual particles in dependence of the Ca and Si contents. Finally, the authors suggest that the SCBA, obtained from both calcination temperatures, have properties which indicate a high pozzolanic activity.

[Cordeiro 2010] evaluated the influence of ultrafine SCBA in the properties of high performance concretes. The SCBA was obtained by controlled burning and ultrafine grinding process. The burning process was in two steps. In the first step the bagasse was calcined at 350ºC and, in the second step the bagasse was calcined at temperatures between 400 and 800ºC considering a heating rate of 10ºC/min and a resident time of 3 hours. The authors suggest that a burning process at 600ºC in a muffle oven produce an amorphous SCBA with high specific surface area and with low LOI content; while the ultrafine grinding process during 120 minutes leads the production of a SCBA with pozzolanic activity of 100%. The results indicate that the SCBA used in this research improved the durability properties of the high-performance concretes without any change on the rheological and mechanical properties.

[Ribeiro 2014] evaluated the pozzolanic activity of the SCBA obtained under controlled calcination conditions when is used as a partial Portland cement replacement in mortars. The sugarcane bagasse was calcined at 500, 600 and 700ºC in an oven considering a heating rate of 10ºC/min. The authors concluded that the particle size of the SCBA is higher as the calcination temperature increase; they also found that the specific gravity decrease due to the loss of the organic matter. The authors reported that the SCBA calcined at 600ºC has a higher amorphous matter than the SCBA calcined at 500 and 700ºC. Mortars prepared with 10% of SCBA as partial Portland cement replacement showed better mechanical properties compared with a control mortar for all temperatures examined.

5 INFLUENCE OF THE LOI CONTENT AND DIFFERENT POST-TREATMENTS ON THE POZZOLANICITY OF THE SCBA IN CEMENT COMPOSITES

Several post-treatments are used to reduce the high LOI content of the SCBA and in consequence to improve its pozzolanic activity in cement composites. It has been suggested that a minimum processing method must to be employed for these purposes, because the as received SCBA from sugar mills contains large quantities of unburned carbon particles which is the result of uncontrolled calcination procedures in the boilers [Cordeiro 2009b, Chusilp 2009a, Hernández 2010, Somma 2012, Buhurudeen 2015]. The outcome of the research indicate that the most common post-treatments used for the SCBA improvement are sieving, grinding, recalcination and the combination of them.

5.1 Sieving

Sieving is the main process used to remove coarse and fine fibrous particles in the SCBA received from sugar mills [Buhurudeen 2015]. Researchers conclude that a sieving process is sufficient to exceed the minimum strength activity index (75% of the control at 7 and 28 days) required in the ASTM C618 standard.

[Hernández 2010] evaluated the replacement of 10 and 20% of Portland cement by sieved SCBA (sieved through the 75μm ASTM mesh for five minutes) on the mechanical and durability properties of mortars with different curing times. The SCBA used in this research has the highest LOI content showed in the Tab. 1 (24.15%). The results show that a poor curing time had a negative effect on the compression strength of the mortars; however, the replacement of 10 and 20% of cement by sieved SCBA decreases in about 50% the chloride diffusion coefficients.

[Maldonado 2012] evaluated the compressive strength and microstructural properties of mortars (at long ages) containing 10 and 20% of SCBA with a LOI content of 10.53 (obtained at temperatures between 550 and 700ºC in the boiler from a sugar mill). The SCBA used on this research was sieved for only 5 minutes through the 75μm ASTM mesh (this post-treatment was selected in accordance with the reported by [Hernández 2010]). The results show that the compressive strength was higher at 28, 90 and 450 days in comparison with the control mortar; likewise, the microstructure of the mortars was denser due to the consumption of the calcium hydroxide during the pozzolanic reactivity of the SCBA. The author suggests that the durability of the mortars containing SCBA with a high LOI content could be increased. This is based on the microstructure refinement observed in the mortars which reduce the chloride diffusion coefficients of the mortars. This statement is also based on the analysis of electrochemical test results obtained in an ongoing long-term study of the durability of reinforced mortars (containing SCBA with a high LOI content of 24.15%) exposed to wetting and drying cycles in a NaCl solution of 3% during 1000 days which was started by [Hernández 2010].

[Torres 2014] evaluated the pozzolanic activity of two sieved SCBAs obtained from the bottom of the multicyclone and precipitator of a boiler which were acquired at temperatures between 600 and 900ºC. The sieving process through the 106, 90 and 75μm meshes was applied to reduce the LOI content of the both ashes to 3.7 and 11%, respectively. The authors concluded that the pozzolanic activity indexes of the ashes were higher than the minimum from the required by the ASTM C618. However, according with the results from the Frattini test, an additional grinding process to the ashes is suggested.

[Buhurudeen 2015] suggest that the coarse particles and fine fibrous carbon particles in the SCBA could be completely removed by sieving. They found that the ash passing through the 300μm ASTM mesh is enough to have fine burnt particles rich in silica content. The authors found that a simple sieving process by the 300μm ASTM mesh increased the pozzolanic activity of the SCBA above the minimum requirement by the ASTM. However, the pozzolanic activity of the sieved ash could be improved by a grinding process reducing the particle size of the ash to the cement fineness (300m^2/kg).

[Arenas 2016] analyzed the influence of SCBA "practically as received" on the mechanical and durability properties of mortars mixtures. The used SCBA was only sieved thought the 75μm ASTM mesh during five minutes. They found that the addition of 10 and 20% of sieved SCBA decrease the compressive strengths of the mortars at early ages but after 90 days were similar or higher than the mortars without SCBA or fly ash additions. It was found that the electrical resistivity increased generally for all the mortars except for the mortar containing 10% of SCBA which surpassed the reference at 180 days. Finally, it was also found that the level of permeability decreased in all the mortars but it was especially observed in the mortar containing 20% of SCBA. The authors hypothesize that the unburned matter from the SCBA could bond chlorides.

[Maldonado 2016] evaluated the carbonation of reinforced mortars containing 10 and 20% of SCBA with a high LOI content. The SCBA used on this research was obtained by [Hernández 2010] and the reinforced mortars were exposed for 2000 days to wetting and drying cycles following the methodology described by [Maldonado 2012]. The results, obtained by the phenolphthalein method and by pH measurements of the alkaline reserve of the mortars, suggest that the high LOI content of the SCBA decrease the alkalinity of the mortars; however, the pH value remains above 10 which is the minimum value considered to activate the corrosion mechanism of the steel embedded in cement composites.

5.2 Grinding

Grinding is the main post-treatment used to control the particle size distribution and decrease the negative effect of the crystalline compounds on the pozzolanic reactivity of the SCBA [Cordeiro 2009b, Chusilp 2009b]. Several researchers suggest that grinding is the most useful post-treatment to obtain a higher pozzolanic reactivity for the SCBA in comparison with sieving methods.

[Cordeiro 2008] found that the ground SCBA produced in a vibratory mill considering grinding times from 8 to 240 minutes increase the compressive strength of mortars due to an increase in the pozzolanic behavior of the sugarcane ash and to the improvement of the packing density in the mortars. The authors concluded that the pozzolanic activity of mortars containing ground SCBA increase significantly with longer grinding times.

[Chusilp 2009a] affirm that the grinding process reduce the particle size of the SCBA making the particles more dense. In that research SCBA with a high LOI content (Tab. 1) was used to study the development of the compressive strength and the sulfate resistance of mortars. The obtained SCBA was ground in a ball mill (until the particles retained by a 45µm mesh were less than 5% by weight), and subsequently the ground ash was put in an oven at 550°C for about 45 minutes to reduce the LOI content down to 5%. They made different mortar mixtures using SCBAs with 5, 10, 15, and 20% of LOI content. The authors concluded that the high LOI content of the SCBA is attributed to the carbon content of the unignited bagasse but this LOI had no adverse effects on the properties of mortars. Nonetheless, ground SCBA with a LOI content less than 10% was proved to be an excellent pozzolanic material.

[Somma 2012] studied the utilization of ground SCBA with a high LOI content to improve the mechanical properties and durability of recycled aggregated concrete. The SCBA was ground to improve its reactivity because the original collected ash showed a lower strength activity index than the suggested by the standards. After grinding, the SCBA had higher fineness and lower porosity in comparison with the original ash and the strength activity indexes at 7 and 28 days were higher than those required by the ASTM C 618. The results of the experiments indicate that the mechanical properties and durability of these concretes were improved when Portland cement was replaced by up to 20% of ground SCBA with a high LOI content.

[Montakarntiwong 2013] evaluated two different SCBAs with low and high LOI contents, respectively. The SCBAs were ground in a ball mill until the particles retained by a 45µm mesh were less than 5% by weight. They replaced the ordinary Portland cement with 20, 30 and 40% of SCBA by weight of the binder. The results indicate that the cement replacement by ground SCBA with low and high LOI content at 20 and 30% by weigh of binder, respectively, resulted in a compressive strength higher than the control mixture. However the concrete mixed with SCBA with a low LOI content had a slightly higher compressive strength than the concrete mixed with SCBA with a high LOI. The authors also found that most of the original SCBA (before the grinding process) with low and high LOI had the same particle shapes showing tubular shaped particles with highly irregular shapes and porous structure. These irregularities in shape remained even after the grinding process.

[Rerkpiboon 2015] evaluated the replacement of 10, 20, 30, 40 and 50% of Portland cement by ground SCBA with a LOI content of 19.60 (Tab.1) on the mechanical and durability properties of concretes. The SCBA was ground using a ball mill until the particles retained by a 45µm mesh were only 0.42%. The results show that the cement replacement of 50% by ground SCBA did not have any effect on the modulus of elasticity of the concrete. It was also found that the replacement of 10 to 50% by ground SCBA increased the chloride resistance of the concrete. However the replacement of 20% of Portland cement by ground SCBA contributed to obtain the highest compressive strength.

[Cordeiro 2016] explored a selective grinding process to reduce the content of quartz in the SCBA. The proposed strategy was capable to remove the quartz and hence to increase the homogeneity and the pozzolanic activity of the SCBA. The authors suggest that selective grinding could result in a less costly ultrafine grinding due the quartz particles were about over fifteen times the strength of the cellular-based SCBA particles.

5.3 Recalcination

Recalcination is a process which helps to decrease the coarse unburnt particles in as received SCBA from sugar mills to increase its pozzolanic reactivity [Bahurudeen 2015].

[Martirena 1998] evaluated the SCBA as probable pozzolanic material. The SCBA was burned to remove undesirable substances such as carbon particles. The authors conclude that the main factors that affect the reactivity of the SCBA are the degree of the crystallinity of the silica and the presence of impurities such as carbon and unburned matter. The carbon and unburned matter could limit the reaction between the reactive silica with the calcium hydroxide to form stable compounds. These impurities take place due to high temperatures and incomplete combustion of the sugarcane bagasse in the boilers of sugar mills.

[Bahurudeen 2015] evaluated the effect of the burning process in the pozzolanic activity of the SCBA. They burnt bagasse ash samples, collected from a sugar mill, at temperatures of 600, 700, 800 and 900°C. The authors found that the pozzolanic activity indexes of burnt samples were higher than the obtained with the as received ash because the burning of the fibrous particles. However, an increase of the burning temperature beyond 700°C reduces the index value due the crystallization of the crystoballite.

5.4 Combination of different post-treatments

More research suggests that the combination of different post-treatments help to decrease the LOI content and improve the pozzolanic activity of the SCBA. For example, as a mentioned earlier, [Bahurudeen 2015] concluded that a sieving process through the 300µm ASTM mesh is enough to decrease LOI content of the SCBA; however, a grinding process could improve it as well. The most common combinations used are burning plus grinding and sieving plus grinding.

[Ganesan 2007] studied the effects of SCBA as a partial Portland cement replacement on physical and mechanical properties of hardened concrete. The SCBA was burnt under controlled temperature at 650°C for one hour and ground to 5.4µm mean grain size (after collecting from a sugar mill). The results indicate that the SCBA (with a LOI content of 4.90%, Tab.1) is an effective mineral admixture, and can replace up to 20% of Portland cement because of the resulting improvement of its pozzolanicity.

[Noor-ul 2011] also reported the impact of the use of SCBA as a partial Portland cement replacement on the physical and mechanical properties of hardened concrete. The SCBA was burned at 650ºC for one hour and ground before being used. The burning process reduced the carbon content of the ash as the LOI content decreased from 8.28 to 4.5%. The processed SCBA was used in seven different proportions (ranging from 5 to 30%) in concrete mixtures. The results indicate that the SCBA is an effective mineral admixture and pozzolan, with an optimal replacement ratio of 20% cement, which reduces the chloride diffusion of the concrete by 50% without any adverse effects on the mechanical properties of concretes. This behavior is mainly attributed to the fines particles which have a large surface area to react and filling the micro and macropores and developing a discontinuous and tortuous pore structure in the concrete matrix.

[Buhurudeen 2015] studied the influence of different post-treatments such as sieving, grinding, burning and combination of these methods on the pozzolanic performance of the SCBA. They suggest that a minimum processing energy is needed to obtain a good pozzolanic activity and a low value of LOI for the SCBA. The authors obtained a pozzolanic activity index of 108% and 106% at 7 and 28 days for the SCBA subjected to sieving (material passing thought the 300μm mesh) and grinding. However, they obtained a pozzolanic activity index of 79% when the SCBA was only sieved, which is higher than the minimum required pozzolanic index value required by the ASTM C311 standard. The authors recommend a combination of sieving through the 300μm mesh to remove coarse and fine fibrous particles and grinding to cement fineness (300m^2/kg).

6 POZZOLANIC BEHAVIOUR OF THE AS RECEIVED SCBA IN CEMENT COMPOSITES

There are only few studies addressing the use of as received SCBA from sugar mills for Portland cement replacement. One of these studies [Valencia 2012] reported that the replacement of 10% of as received SCBA increased the compressive strength of mortars; however, its effects on the durability are not clear. These uncertainties can be attributed to the physical properties of the ash.

[Frías 2011] showed that the as received SCBA from sugar mills did not show a properly pozzolanic activity in comparison with the ash obtained under controlled laboratory conditions (obtained in an electrical furnace under two burning temperatures; 400ºC during 20 minutes followed by 800ºC during 60 minutes, with heating rate of 10ºC/min). From this research a proper management for the sugarcane bagasse before their use as combustibles removing all the contaminant materials is suggested; moreover, the authors suggest a controlling calcination of the bagasse at temperatures around 800ºC in order to obtain a SCBA with a similar pozzolanic behavior to that showed by the SCBA obtained in the laboratory.

[Arit 2016] reported the effects of the used of as received SCBA obtained with a high-efficiency co-generation boiler in a sugar mill. The authors concluded that this sugarcane ash does not contain significant amorphous silica which substantially reduces the pozzolanic reactivity of the ash in cement composites. Only pastes with addition of 5% of as received SCBA showed a proper pozzolanic reactivity. Results also indicate that up to 15% SCBA replacements achieve a pozzolanic activity index above to 75%. The authors suggest that this performance could be attributed more likely to a filler effect rather than true pozzolanic activity.

[Soares 2016] evaluated the pozzolanic behaviour of the SCBA by comparing it to amorphous and crystalline silica. Cement pastes with partial cement replacement by 20% of as received SCBA, 20% of quartz, and 0, 5, 10, 15 and 20% of silica fume were cast for this purpose. The results show that the as received SCBA has a low pozzolanic activity which is closer to crystalline SiO_2 (observed at the x-ray diffraction patterns between SCBA-pastes and quartz-pastes). Based on this finding, the authors suggest that the as received SCBA evaluated on this research should be used as an inert supplementary material.

7 DISCUSSION

In general, researchers suggest that a post-treatment such as sieving, grinding, recalcination or combination of them significantly influence the pozzolanic activity of the as received SCBA from the sugar mills. In some cases, the LOI content is reduced to less than 10% leading to beneficial effects when the ash is used as cement replacement in cement composites. [Chusilp 2009a] suggested that a SCBA with a LOI content lower than 10% by mass is a good pozzolanic material to partially replace, up to 20%, the Portland cement in concrete mixtures; they also reported that a high LOI content (more than 10% by mass) in the bagasse ash slightly affect the 28 and 90 days compressive strength of mortars. Another research [Somma et al. 2012] reported that the use of SCBA with a high LOI content (19.6%) is suitable to improve the mechanical properties and durability of recycled aggregate concrete; however in both studies the used SCBA was physically improved by a grinding process.

Additional research suggests that a sieving process is enough to remove some unburned carbon particles and unburned matter from the SCBA. In this case sieving contributes to enhance the pozzolanic activity of the as received SCBA from sugar mills when is used as partial cement replacement in cement composites even if the ash has a LOI content larger than 10% [Hernández 2010, Maldonado 2012, Bahurudeen 2015, Arenas 2016, Arif 2016]. As a summary, it can be stated that the sieving process is the lower energy demanding post-treatment in comparison with the grinding and recalcination processes and it appears to be a good environment friendly alternative for the use of the SCBA which is actually available in open damps.

On the other hand, some studies suggest that the unburned fibrous carbon particles of the SCBA are amorphous. This is because some carbon fibers are covered with a layer of Si and O and have a cell structure, with intercellular channels, containing pits in the cell walls [Batra 2008, Bahurudeen 2015]. Therefore, the potential use of as received SCBA as cement replacement could be a more environment friendly for a usual practice. However, research suggests that a low LOI content (less than 10%) does not assure an appropriate pozzolanic performance of the SCBA since the SiO_2 (the main compound in the SCBA) could be quite crystalline. For example [Soares 2016] used 20% of SCBA (as received from a sugar mill) with a low LOI content (1.52%) as partial cement replacement in cement pastes; however, they found that the pozzolanic activity of the SCBA was similar to the pozzolanic activity obtained in cement pastes added with 20% of quartz. Another example is showed by [Arift 2016]. They found that the SCBA as received from a high-efficiency co-generation boiler (which has a LOI content of 7.15%, Tab. 1) does not show a proper pozzolanic activity in cement composites. This is because the ash has low amorphous silica content.

8 CONCLUSIONS

SCBA with a high LOI content must be subjected to a post-treatment in order to obtain an acceptable pozzolanic activity (more than the required by the strength activity index in the ASTM C618) and be used as a partial Portland cement replacement. Sieving appears to be a more environment friendly post-treatment process when compared to grinding and recalcination; however, long-term durability tests of composites prepared with this ash are needed to allow its use in large quantities.

The existing SCBA in open damps could have a high amount of unburned carbon due the poor controlled burning process of the bagasse in the boilers of sugar mills. Nonetheless, some unburned carbon particles could be amorphous increasing the reactivity of the ash. A detailed study about the amorphous phase of the unburned carbon particles of the SCBA is suggested.

It has been observed that the SCBA with high LOI content decrease the chloride diffusion coefficient of cement composites. There are a number of possible explanations about the interactions between the LOI content of the SCBA and chlorides. First, the unburned carbon could bond chlorides; second, the unburned carbon works only as a physical barrier for chlorides; and three, the unburned carbon particles are amorphous, as mentioned earlier, increasing the reactivity of the SCBA and hence improving the microstructure of the composites.

The use of SCBA with a high LOI content decreases the pH value of the alkaline reserve of cement composites. However, this value is higher than the critical pH value suggested in the literature to promote active corrosion of the steel embedded in the composites. A detailed study about the $Ca(OH)_2$ consumption during the pozzolanic reactions of the SCBA and its interaction with the high LOI content of the ash could be evaluated in further research.

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