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Effects of sugar cane bagasse ash as a cement replacement on properties of mortars

Abstract: Sugar cane bagasse ash (SCBA), a by-product of sugar and alcohol production, is one of the potential pozzolanic material that can be blended with Portland cement. In this study, SCBA with particle sizes <45 µm was used to replace type I ordinary Portland cement with various dosages (10%, 20%, and 30%) by weight of binder. The water/cementitious material (w/cm) and sand/binder ratios were kept at constants of 0.55 and 2.75, respectively. Composites were mixed, and effects of SCBA on properties were investigated by conducting flow test, water absorption test, initial surface absorption test, drying shrinkage test, compressive strength test, rapid chloride penetration test (RCPT), thermal gravimetric analysis (TGA), and scanning electron microscopy (SEM). Experimental results show that the flow spread of fresh mortars would decrease with an increase of SCBA replacement. The specimens with 10% SCBA have the superior performance on compressive strength, drying shrinkage, water absorption, initial surface absorption, and chloride ion penetration, TGA, and SEM at the age of 56 days. It indicates that 10% cement replacement of SCBA may be considered as the optimum limit.

Keywords: properties; rapid chloride penetration test (RCPT); scanning electron microscopy (SEM); sugar cane bagasse ash; thermal gravimetric analysis (TGA).

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1 Introduction

Bagasse is a by-product of the sugar cane industry. The application of sugar cane bagasse ash (SCBA), one of the main by-products from the bagasse combustion, in concrete production provides an acceptable solution to some of the environmental concerns [1]. Meanwhile, SCBA can be used as a mineral admixture in mortar and concrete because it presents proper chemical composition for application as a pozzolan, mainly in regard to its high content in silica. Several studies have been conducted to investigate the chemical effect or pozzolanic activity of SCBA and concluded that SCBA is a pozzolan, which improves the performance when mixed to cement [2–7].

SCBA is a pozzolan that can partially replace clinker in cement production, and its use improves the behavior of the cementitious material [1]. The main products from the reaction between calcium hydroxide and SCBA are calcium silicate hydrates (C-S-H) gel [2]. Singh et al. [3] found that in the presence of SCBA, a large amount of C-S-H was formed in the paste, and the compressive strength increased. In addition, Ganesan et al. [5] showed that SCBA used as a partial replacement for Portland cement could increase the mechanical properties and durability. A high content in silica makes the SCBA to be a pozzolan, but the presence of unburned material and carbon may reduce its reactivity as concluded by Hernández et al. [2]. Cordeiro et al. [6] indicated that SCBA would be classified as a pozzolanic material, and its reactivity depended mainly on the maximum particle size and fineness. The production of pozzolanic ash from SCBA requires the use of ultrafine grinding to transform this industrial residue in a mineral admixture, and coarser SCBA may be used as an inert filler in the cementitious mixtures [6, 8]. The effects of fineness and loss on ignition (L.O.I.) of SCBA on compressive strength and the kinetics of the pozzolanic reaction were reported by previous researchers [9–12]. However, SCBA advantages and optimum dosages resulting from chemical or physical effect are not yet clarified, and its application is limited. Further testing results are required.

In this study, cementitious composites use SCBA as a partial replacement for Portland cement in mortars. Composites were mixed, and the effects of SCBA with various amounts of cement replacement on properties were investigated by conducting flow test, water absorption test, initial surface absorption test, drying shrinkage test, compressive strength test, rapid chloride penetration test (RCPT), thermal gravimetric analysis (TGA), and scanning electron microscopy (SEM).

2 Experimental program

2.1 Materials

The cement used was type I ordinary Portland cement (OPC) conforming to the American Society for Testing and Materials (ASTM) standard C150-05 [13]. SCBA used was collected at Huwei sugar cane factory in the Yunlin county of Taiwan. The bagasse is ignited in boilers at temperatures varying from 900°C to 1100°C. After cooling, the SCBA was dried and ground into a fine powder with a particle size passing the no. 325 sieve before it was used as a cement replacement material. SEM micrographs of SCBA are shown in Figure 1. SCBA particles were of irregular shape with rough surfaces and highly porous textures. The chemical composition, loss on ignition, and specific gravity of OPC and SCBA are listed in Table 1. It can be seen that SCBA has about three times higher silica content than OPC and contains a considerable amount of CaO and Al_2O_3. Meanwhile, it is noteworthy that SCBA showed the loss on ignition value of 9.4%. Figure 2 shows the XRD pattern of SCBA, where the quartz (SiO_2) is evident and consistent with its high SiO_2 contents of 54.4% as shown in Table 1. The fine aggregate used was river sand with a fineness modulus of 2.40. The absorption value is 1.61%, and its relative density at the saturated surface dry (SSD) condition is 2.64.

2.2 Mixture and specimen preparation

SCBA-blended cements were used to replace OPC with different amounts of SCBA (0%, 10%, 20%, and 30%) by weight of cement in dry condition. The mixes were completely homogenized and kept in polythene bottles before use. The water/cementitious material (w/cm) and sand/binder ratios were kept at a constant of 0.55 and 2.75, respectively. These mixes were designated as BA0 for control mix, BA10 for SCBA mix with cement replacement of 10%, BA20 for SCBA mix with cement replacement of 20%, and BA30 for SCBA mix with cement replacement of 30%. The mix proportions are summarized in Table 2. The cubic specimens (50×50×50 mm) and cylindrical specimens (ψ100×200 mm) were cast and kept in steel molds for 24 h, and then, the specimens were demolded and tested in triplicate sets for each mix until the time of testing.

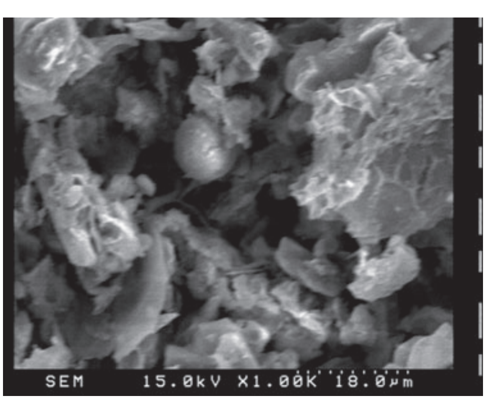

Figure 1 SEM micrograph of SCBA (×1K).

Chemical composition (%)	OPC	SCBA
Calcium oxide, CaO	63.9	12.4
Silicon dioxide, SiO_2	20.7	54.4
Aluminum oxide, Al_2O_3	5.4	9.1
Ferric oxide, Fe_2O_3	3.2	5.5
Sulfur trioxide, SO_3	4.0	4.1
Sodium oxide, Na_2O	0.2	0.9
Potassium oxide, K_2O	1.1	1.3
Magnesium oxide, MgO	2.0	2.9
L.O.I.	1.0	9.4
Specific gravity	3.14	1.94

Table 1 Chemical composition, loss on ignition, and specific gravity of OPC and SCBA.

2.3 Methods

2.3.1 Flow test

Flow was determined by ASTM C1437-07 [14]. A cone-shaped mold was filled with fresh mix in two lifts and placed at the center of a flow table. When the mold was removed, the vibrating table was dropped 25 times in 15 s. Diameters (mm) of the mixes were measured along four lines.

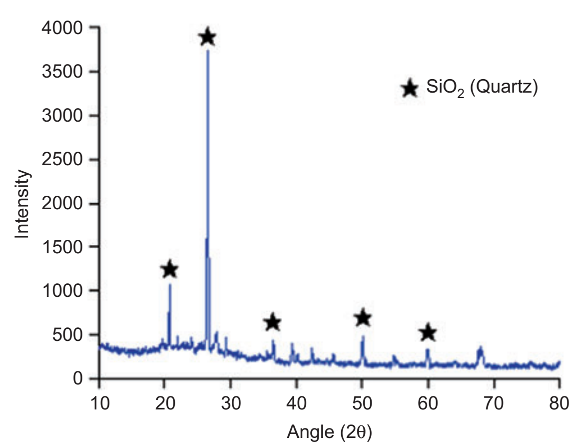

Figure 2 XRD pattern of SCBA.

Mix no.	w/cm	Water (kg/m³)	Cement (kg/m³)	SCBA (kg/m³)	Fine aggregate (kg/m³)
BA0	0.55	288.1	523.8	0	1440.4
BA10	0.55	264.3	480.6	53.4	1468.6
BA20	0.55	239.7	435.7	108.9	1497.9
BA30	0.55	214.0	389.0	166.7	1528.3

Table 2 Mix proportions of SCBA-blended mortars.

2.3.2 Water absorption (WA)

Water absorption was obtained in accordance with ASTM C642-06 [15]. Specimens were prepared and tested for each mix at the age of 56 days. After the required curing period, the cubic specimens (50 mm) were oven dried at temperature of 105±5°C for 24 h and weighed and then immersed in water for 24 h and weighed again. Water absorption was calculated as follows.

$$\text{Water absorption: WA}(\%) = \frac{w_s - w_d}{w_d} \times 100 \quad (1)$$

where w_d is the weight of the dried specimens before the test, w_s is the weight of the dried specimens immersed in water for 24 h.

2.3.3 Initial surface absorption test (ISAT)

The initial surface absorption test was performed on a cylinder (ψ100×50 mm) to measure the absorptive characteristics of the surface in accordance with BS 1881-201 [16]. After the specimens were cured for 28 days, the specimens were oven dried at a temperature of 105±5°C to constant weight prior to the test. Water absorption was measured at 10, 30, 60 and 120 min after testing begins. Initial surface absorption rate is expressed in milliliters per square meter per second ($ml/m^2\,s^{-1}$).

2.3.4 Drying shrinkage measurement

The drying shrinkage was carried out following the ASTM C596-01 [17]. Prismatic specimens with 25×25×285 mm dimensions were prepared from bagasse mortar mixes and cured for 23.5±0.5 h. After demolding, the specimens were soaked in water for another 48 h and then kept in an environmental control room at a temperature of 23±1°C and related humidity of 50% R.H., and then the initial length (Li) of the shrinkage specimens was measured. The length (L_x) of the shrinkage specimens was measured at the ages of 4, 11, 18, and 25 days, respectively. The length change was then calculated by the following formula:

$$\text{Length change: LC}(\%) = \frac{L_i - L_x}{G} \times 100 \quad (2)$$

where G is the nominal effective length.

2.3.5 Compressive strength test

The compressive strength tests of the specimens were conducted according to ASTM C109-08 [18]. Three 50-mm cubic specimens were prepared and tested for each mix at the ages of 7, 14, 28, and 56 days, respectively.

2.3.6 Rapid chloride penetration test (RCPT)

The RCPT was performed in accordance with ASTM C1202-05 [19] for each mix. Two specimens of 100 mm in diameter and 50 mm in thickness at the age of 56 days, which had been conditioned according to the standard were subjected to a 60±0.1 V potential for 6 h. The total charge passed through the specimens was determined and used to evaluate the chloride permeability of each concrete mixture. ASTM C1202 recommends the qualitative criterion "chloride ion penetrability" according to the range of the total charge passed as shown Table 3.

2.3.7 Thermal gravimetric analysis (TGA)

Thermal analysis has been defined by the International Confederation of thermal analysis (ICTA) as a general term, which covers a variety of techniques that record the physicochemical changes occurring in a substance as a function of temperature [20]. Specimens at the ages of 28 and 56 days were prepared to evaluate the hydration activity by TGA. Thermal analysis was performed using the model TGA/SDTA851[e] thermal gravimetric analyzer manufactured by Mettler Teledo Inc. (Switzerland).

Charge passed	Chloride ion penetrability
>4000	High
2000~4000	Moderate
1000~2000	Low
100~1000	Very low
<100	Negligible

Table 3 Chloride ion penetrability based on charge passed recommended in ASTM C 1202 [19].

The specimen was ground into powder passing the no. 50 sieve and subjected to TGA, by gradually raising the temperature from 25°C to 1000°C at the rate of 10°C/min.

2.3.8 Scanning electron microscopy (SEM)

The specimens with a dimension of 10×10×3 mm were obtained from 10 mm cube. Representative samples were air dried first and then followed by resin impregnation. The impregnated specimens were ground and softly polished with decreasing grades down to 0.25 µm. SEM was performed using a HITACHI S-4800 microscope equipped with an energy dispersive spectroscopy (EDS).

3 Results and discussions

3.1 Flow spread

The flow spread of the mixes containing SCBA is given in Table 4. It shows that the flow spread decreased with an increasing amount of SCBA. The control mix (BA0) has a flow spread of 207 mm. The flow spreads of mixes BA10, BA20, and BA30 show a decrease of 164, 139, and 137 mm, respectively. It was reported that SCBA is hygroscopic in nature, and it needs more water for proper consistency due to the irregular shape with rough surfaces and highly porous textures of SCBA compared to that of cement [5]. The higher porous texture of SCBA increases the water demand and consequently decreases the flow value, thus resulting in a reducing workability. The flow value of BA30 reduced to 37% due to its higher amount of cement replacement and smaller particle size. The smaller particle size of SCBA increases the specific surface area, and water cannot be totally reached in each pore, thus decreasing the flow value.

3.2 Water absorption

The water absorption of the mixes containing SCBA is given in Table 4. With the exception of the mix containing 10% BA (BA10), there exists a slight increase in water absorption with an increasing amount of BA. Mixes BA10 have a slightly lower water absorption observed than the control mix (BA0). However, the mixes containing 20% SCBA (BA20) show a slight increase of 1.52% on water absorption compared to the control mix (BA0). When the cement replacement of SCBA increases to 30%, the water absorption increases evidently. The high water absorption of the mixes containing SCBA was due to the porous nature and rough surface of the SCBA particles. The percentage of water absorption is a measure of pore volume or porosity in hardened concrete, which is occupied by water in saturated conditions. Thus, 10% cement replacement of SCBA may be considered as the optimum limit.

Mix No.	Flow value (mm)	Water absorption (%)	Total charge passed (Coulomb)
BA0	207	10.44	7270
BA10	164	9.91	3454
BA20	139	11.96	6527
BA30	137	16.73	7930

Table 4 Flow value, water absorption, and total charge passed of cement-based composites.

3.3 Initial surface absorption test

The variations of initial surface absorption with respect to testing time except the mixes containing 30% SCBA (more than 3.6 ml/m^2 s) are plotted in Figure 3. The initial surface absorption values of the mixes decrease with testing time. Lower initial surface absorption values have been obtained in mixes containing SCBA than the comparable control mix (BA0). Meanwhile, initial surface absorption values of mixes BA20 are higher than those of mixes BA10 within testing time. The mixes containing SCBA can effectively reduce the initial surface absorption due to pozzolanic reaction between calcium hydroxide and reactive silica in SCBA. Thus, the addition of SCBA leads to a reduction of the permeable voids, and 10% cement

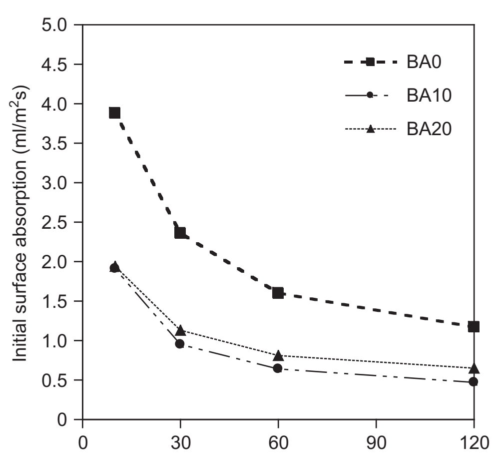

Figure 3 Initial surface absorption vs. testing time.

replacement of SCBA seems to be the optimal limit based on the initial surface absorption test results.

3.4 Drying shrinkage measurement

Drying shrinkage is an important technical parameter influencing structural properties and durability of the material. The drying shrinkage results calculated for the SCBA blended mixes at the ages of 4, 11, 18, and 25 days are presented in Figure 4. The drying shrinkage value of the mixes with SCBA is lower than that of the control mix (BA0) at all ages. It may be due to the filler effects or due to the pozzolanic reactions of SCBA. The drying shrinkage of the mixes is BA20<BA10<BA30<BA0 at the ages of 4, 11, and 18 days. However, at the age of 25 days, the drying shrinkage of BA20 is higher than those of BA10 and BA30. The proportion of drying shrinkage on BA10, BA20, and BA30 are 8%, 5%, and 7% as low as that of the control mix (BA0) at the age of 25 days. Though the drying shrinkage of BA10 is higher than that of BA20 at the age of 18 days, however, with prolonged ages from the drying shrinkage point of view, 10% of SCBA is still the optimal limit.

3.5 Compressive strength

The compressive strength developments of SCBA-blended cement mortars are shown in Figure 5. The compressive strength decreases with an increase in the dosages of SCBA. The compressive strengths of mixes containing SCBA are lower than that of the control mix (BA0) at the ages of 7, 14, and 28 days. The control mix

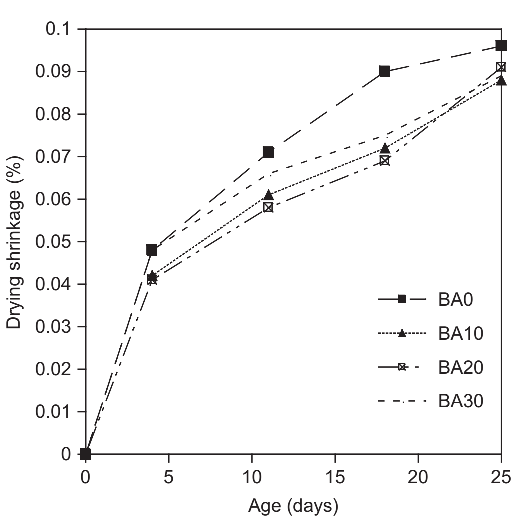

Figure 4 Drying shrinkage vs. age.

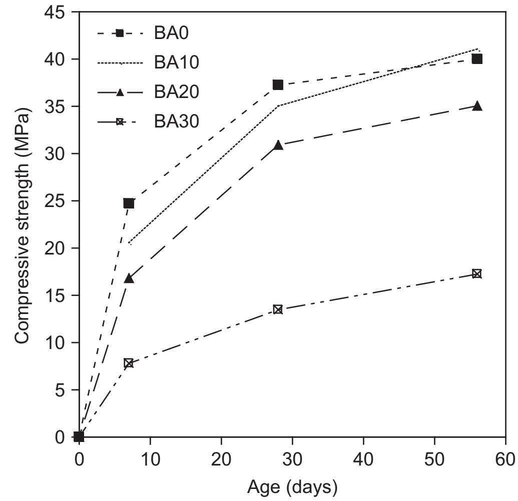

Figure 5 Compressive strength vs. age.

had a compressive strength of 37.2 MPa at the age of 28 days, which increased to 40.0 MPa at the age of 56 days. Mixes containing 10% SCBA (BA10) had compressive strengths of 35.0 and 41.1 MPa at the ages of 28 and 56 days, respectively. Normally, SCBA can be classified as a pozzolanic material, and its small particles can fill the voids in the concrete structure and thus increases compressive strength [21]. But in this study, the addition of SCBA decreases compressive strength. Particularly, BA30 showed a very low compressive strength of 17.3 Mpa at the age of 56 days. It may be due to the high replacement of cement and low pozzolanic reaction of SCBA. Based on the test results mentioned above, 10% of the SCBA replacement to cement is the optimal limit. At 30% SCBA replacement to cement, it could be that only 10% SCBA acted as pozzolanic materials, and 20% SCBA acted as fillers. In addition, the SCBA presents physicochemical properties appropriate for its use as mineral admixture, and its reactivity depended mainly on the maximum particle size and fineness. SCBA particles used in this study were of irregular shape with rough surfaces and highly porous textures and lower specific gravity and higher L.O.I. compared to that of cement. Thus, the replacement of cement by SCBA indicates the lower compressive strengths.

3.6 Rapid chloride penetration test (RCPT)

RCPT is a convenient test to evaluate concrete permeability. The test results of the mixes containing SCBA are given in Table 4. The total charge passed of BA10 and BA20 showed a decrease that ranged from 7270 to 3454 and 6527 Coulombs compared to BA0, respectively. But the total charge passed of BA30 is higher than that of BA0. It indicates that chloride permeability is reduced by <20% replacement of cement with SCBA. Thus, the replacement of cement with SCBA is limited, and 10% cement replacement of SCBA is considered as the optimal limit based on the results of RCPT.

3.7 Thermal gravimetric analysis (TGA)

Thermal analysis encompasses many classical techniques such as differential thermal analysis (DTA) and TGA. DTA locates the ranges corresponding to thermal decompositions of different phases in paste, while TGA simultaneously measures the weight loss due to the decompositions. The calcium silicate hydrate (C-S-H) endothermal peak can be identified at a temperature range of 115~225°C, ettringite at 120~130°C, calcium hydroxide (CH) in the range of 430~550°C, and calcium carbonate ($CaCO_3$) at 750~850°C [22]. The weight loss of SCBA-blended cement mortars at the ages of 28 and 56 days are listed in Table 5. To evaluate the hydration reactivity, this study aimed to discuss the ettringite and CH decomposition at the temperatures that ranged from 115°C to 550°C. The weight loss of mixes containing SCBA decreases with an increase in dosages of SCBA and is lower than that of the control mix (BA0) at the age of 28 days. The control mix BA0 had a weight loss of 4.2% at the age of 28 days, which decreased to 3.14% at the age of 56 days. Mixes containing 10% SCBA (BA10) had a weight loss of 3.98% and 3.5% at the ages of 28 and 56 days, respectively. At the age of 28 days, BA10 showed less loss in C-S-H and CH compared to BA0. However, the weight loss due to the decomposition of hydration products was significant at the age of 56 days. It was shown that the early hydration of BA10 was lower, but it accelerated at a later stage compared with that of BA0. Thus, 10% cement replacement of SCBA is considered as the optimal limit based on the results of TGA.

Temperature	Age (days)	Weight loss (%)			
		BA0	BA10	BA20	BA30
105~440°C	28	4.20	3.98	2.30	2.13
	56	3.14	3.50	3.05	1.88
440~580°C	28	1.14	0.69	0.50	0.36
	56	0.87	0.82	0.81	0.35
580~995°C	28	4.80	4.69	4.10	2.16
	56	2.84	2.67	2.50	2.85

Table 5 Weight loss of cement-based composites.

3.8 Scanning electron microscopy (SEM)

SEM images were used to explore the microstructure of the corresponding specimens. SEM images of the specimens with and without SCBA at the age of 56 days were investigated by means of SEM methods. Figure 6 shows the SEM photograph of BA0. It can be seen that a lot of hydration products – like C-S-H gel, Aft crystals, and several pores were formed on the surface of BA0. Figure 7 shows the SEM images obtained for the specimen of BA10. Observations revealed that the rough surface of the mixture of BA10 showed to contain C-S-H gel, Aft crystals, and also narrow pores. However, the differences in the microstructural features between the specimens without and with bagasse ash are not obvious. With the addition of 10% SCBA to the mixture, there takes place the reaction of the portlandite produced by the hydration of the calcium silicates in the cement with the silica and alumina reactivates in the pozzolanic material. This reaction produces C-S-H gel, which grows into the capillary spaces. Hence, the paste structure tissue became dense. The observations are consistent with those of water absorption, initial surface absorption, compressive strength, and RCPT results.

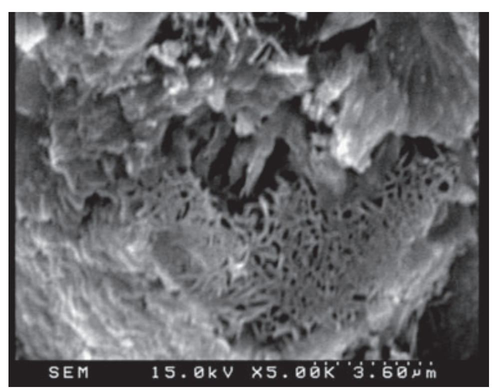

Figure 6 SEM image of specimen without bagasse ash BA0 (×5K).

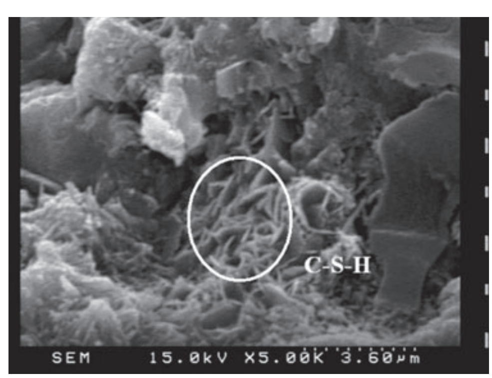

Figure 7 SEM image of specimen with 10% bagasse ash (×5K).

4 Conclusions

In the past, sugar cane bagasse wastes were burned as a means of solid waste disposal, but during the last decade these residuals were burned to produce steam and electricity in a cogeneration plant at the ethanol factory. Meanwhile, SCBA produced in boilers of the sugar industry can be classified as a probable pozzolanic material. At present, the cost of SCBA is zero or even negative because it is a residual material and should be disposed by the sugarcane plant or ethanol factory. Akram et al. [23] indicated that the cost of ingredients of specific self-compacting concrete (SCC) containing bagasse ash is 35.63% less than the concrete without the addition of SCBA. Pippo et al. [24] reported the economic and environmental advantages of using bagasse wastes. However, like other residual pozzolans such as fly ash or slag, the cost of the raw material may tend to increase with the increasing demand of the market.

SCBA is an effective mineral admixture, and 10% of SCBA replacement to cement may be considered as the optimal limit on properties of cement-based composites. Based on the testing results, the principal conclusions are summarized as follows:

1. The flow spread of fresh mortars would decrease with the increase of bagasse ash replacement. The specimens with 10% bagasse ash as a Portland cement replacement have the superior performance on compressive strength, drying shrinkage, water absorption, initial surface absorption, and chloride ion penetration at the age of 56 days.
2. TGA showed that more amounts of $Ca(OH)_2$ loss were obtained in the specimens with 10% SCBA than the comparable control mix at the age of 56 days. Meanwhile, SEM revealed that the microstructural properties of BA10 are denser than that of BA0.

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