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PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT-BASED COMPOSITES WITH BAGASSE ASH

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Key words: bagasse ash (BA), properties, particle size, scanning electron microscopy (SEM).

ABSTRACT

Bagasse ash (BA), a byproduct of sugar and alcohol production, is among the potential pozzolanic materials that can be blended with Portland cement. The purpose of this study was to investigate the properties of cement-based composites that have various particle sizes of BA and cement replacement percentages. Three particle size distributions—passing the No. 100, No. 200, and No. 325 sieves— and replacement of cement at 10%, 20%, and 30% by weight of binder, were designed to cast nine BA composites. The performance of the BA specimens was compared with reference mortars produced using ordinary Portland cement (OPC). The experimental results showed that when the replacement of BA increased, the flow spread of fresh mortars decreased. The increase in the replacement of cement with BA also reduced the compressive strength of the BA specimens. Overall, the 56-day-old specimen with 10% BA passing the No. 325 sieve demonstrated the highest performance regarding the compressive strength, drying shrinkage, water absorption, initial surface absorption, and chloride ion penetration. Moreover, this specimen showed denser microstructural properties—determined using a scanning electron microscope—compared with those of OPC. Based on these results, 10% BA passing the No. 325 sieve was considered the optimal dosage and particle size.

I. INTRODUCTION

Bagasse ash (BA), a byproduct of sugar and alcohol production, is among the potential pozzolanic materials that can be blended with Portland cement. Applying BA in concrete production positively affects the environment because it reduces the problems associated with their disposal. Because of its high silica content, BA can be used as a mineral admixture in mortar and concrete (Hernández, 1998; Singh, 2000). Several studies have been conducted to investigate the chemical effect or pozzolanic activity of BA, and those studies concluded that BA is a pozzolan that improves the performance of cement.

Cordeiro et al. (2008) reported that BA can be classified as a pozzolanic material, and that its reactivity depends mainly on the maximum particle size and fineness. Fairbairn et al. (2010) verified that BA is a pozzolan that can partially replace clinkers in cement production and its use improves the behavior of the cementitious material. Singh et al. (2000) reported that in the presence of BA, large amounts of C-S-H were formed in a paste and the compressive strength of the composite was increased. In addition, Ganesan et al. (2007) showed that using BA as a partial replacement of Portland cement could increase the mechanical properties and durability of materials. The high silica content of BA renders it a pozzolan; however, Hernández et al. (1998) concluded that the presence of unburned materials and carbon may reduce its reactivity of BA. Almir and Sofia (2010) reported that coarser BA may be used as inert fillers in cementitious mixtures. Previous studies have reported the effects of fineness and loss on ignition (L.O.I.) of BA on the compressive strength and kinetics of the pozzolanic reaction (Villar-Cociña, 2003; Frías, 2005; Chusilp, 2009; Chi, 2010; Rukzon, 2012). However, the advantages and optimal dosages of BA resulting from chemical or physical effects are not clearly understood; in addition, its application is limited. Therefore, further experimental studies are required.

In this study, cement-based composites involving BA as a partial replacement of Portland cement were mixed. Their physical and mechanical properties of the composites were subsequently investigated by conducting flow test, water absorption (WA) test, initial surface absorption test (ISAT), drying shrinkage test, compressive strength test, rapid chloride penetration test (RCPT), and scanning electron microscopy (SEM). The effects of various particle sizes of BA and cement replacement percentages on physical and mechanical properties of the composites were explored and discussed.

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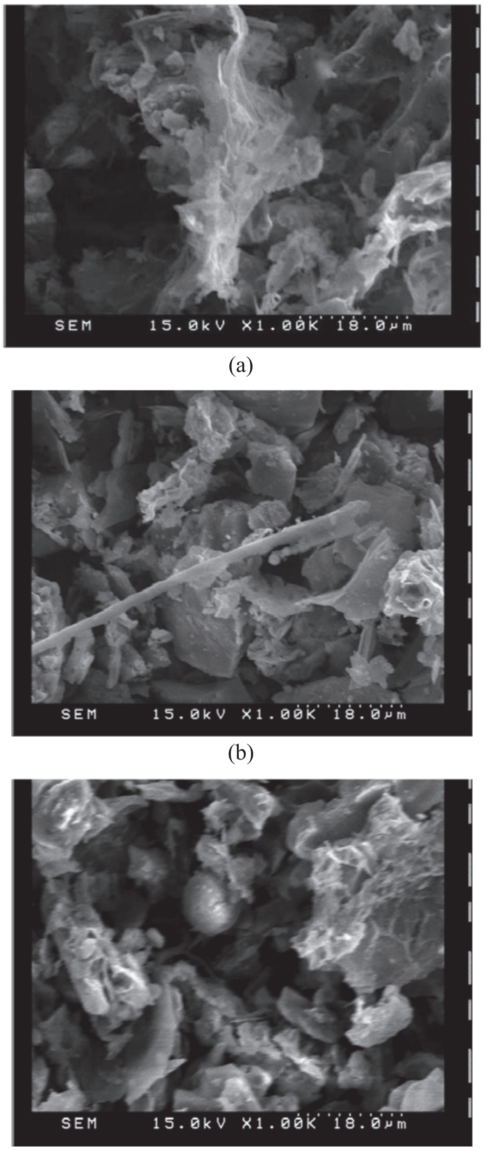


(a)

(b)

(c)

Fig. 1. (a) SEM micrograph of BA passing No. 100 sieve (× 1K), (b) SEM micrograph of BA passing No. 200 sieve (× 1K), and (c) SEM micrograph of BA passing No. 325 sieve (× 1K).

II. EXPERIMENTAL PROGRAM

1. Materials

This study used type I ordinary Portland cement (OPC) that conforms to the American Society for Testing and Materials (ASTM) C150-05 standard (ASTM C150, 2005). The used BA was collected from a Huwei sugarcane factory in Yunlin County, Taiwan. The bagasse was ignited in boilers at temperatures ranging from 900 to 1100°C. After cooling, the BA was dried and crushed into fine powder with particle sizes passing the No. 100, No. 200, and No. 325 sieves, respectively.

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

Chemical composition (%)	OPC	BA
Calcium oxide, CaO	63.9	12.4
Silicon dioxide, SiO_2	20.7	54.4
Aluminium 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
Loss on Ignition, L.O.I.	1.0	9.4
Specific gravity	3.14	1.94

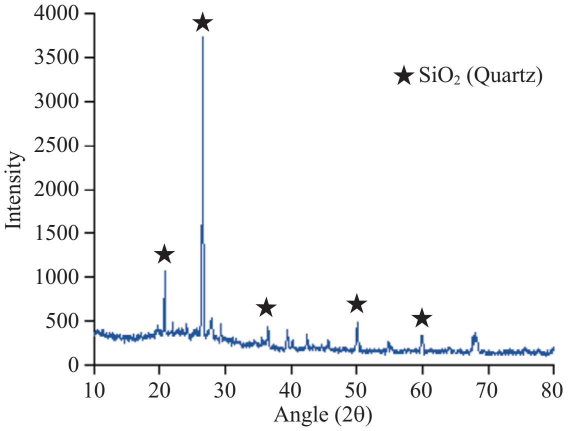


Fig. 2. XRD pattern of BA

Figs. 1(a)-(c) show SEM micrographs of BA with various particle sizes, indicating that BA particles have irregular shapes with rough surfaces and highly porous textures. Table 1 lists the chemical composition, L.O.I, and specific gravity of OPC and BA, indicating that BA has nearly 3 times higher silica content than that of OPC and contains a considerable amount of CaO and Al_2O_3. In addition, BA showed an L.O.I value of 9.4%. Fig. 2 shows the XRD pattern of BA, clearly indicating the quartz (SiO_2), which is consistent with the high SiO_2 content (54.4%), as shown in Table 1. River sand, with a fineness modulus of 2.40, was used as the fine aggregate. The absorption value of river sand was 1.61% and its relative density at the saturated surface dry condition was 2.64.

2. Mixture and specimen preparation

BA, comprising three particle size distributions, and blended cement were used to replace OPC with different amounts of BA (0%, 10%, 20%, and 30%) by weight of dry cement. The mixtures were completely homogenized and kept in polythene bottles before use. Ten different proportions of mixtures (BA with three particle size distributions and three dosages), including one control mix, were prepared. The water-to- cementitious material (w/cm) and sand-to-binder ratios were maintained at 0.55 and 2.75, respectively. These mixtures were denoted as BA0 for the control mix, BA11 for the BA mix with the particle size passing the No. 100 sieve and

Table 2. Mix proportions of BA blended mortars.

Mix No.	w/cm	Water (kg/m^3)	Cement (kg/m^3)	BA (kg/m^3)	Sand (kg/m^3)
BA0	0.55	288.1	523.8	0	1440.4
BA11	0.55	264.3	480.6	53.4	1468.6
BA12	0.55	239.7	435.7	108.9	1497.9
BA13	0.55	214.0	389.0	166.7	1528.3
BA21	0.55	264.3	480.6	53.4	1468.6
BA22	0.55	239.7	435.7	108.9	1497.9
BA23	0.55	214.0	389.0	166.7	1528.3
BA31	0.55	264.3	480.6	53.4	1468.6
BA32	0.55	239.7	435.7	108.9	1497.9
BA33	0.55	214.0	389.0	166.7	1528.3

cement replacement of 10%, BA22 for the BA mix with the particle size passing the No. 200 sieve and cement replacement of 20%, and BA33 for the BA mix with the particle size passing the No. 325 sieve and cement replacement of 30%. Table 2 shows a summary of the mix proportions. The cubic specimens (50 × 50 × 50 mm) and cylindrical specimens (ψ100 × 200 mm) were cast and kept in steel molds for 24 h; the specimens were then demolded and tested in triplicate sets for each of the different types of curing until the time of testing.

3. Methods

1) Flow Test

The flow was determined according to ASTM C1437-07 standard test method (ASTM C1437, 2007). A cone-shaped mold was filled with a fresh mixture 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. The diameters (mm) of the mixtures were measured along four lines.

2) Water Absorption

The WA was obtained according to the ASTM C642-06 standard test method (ASTM C642, 2006). Specimens at the age of 56 days were prepared and tested for each mix. After the required curing period, cubic specimens (50 mm) were oven-dried at a temperature of 105 ± 5°C for 24 h. The dried specimens were weighed and then immersed in water for 24 h and weighed again. The WA was calculated as follows:

$$Water\ Absorption: WA(\%) = \frac{w_s - w_d}{w_d} \times 100 \qquad (1)$$

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

3) Initial Surface Absorption Test

The ISAT was performed on a cylinder (ψ100 × 50 mm) to measure the absorptive characteristics of the surface according to BS 1881-201 (BS 1881-201, 1986). After curing the specimens for 28 days, they were oven dried at a temperature of 105 ± 5°C to a constant weight prior to the test. WA was measured at intervals of 10, 30, 60, and 120 min after the test was initiated. The initial surface absorption rate was expressed in milliliters per square meter per second ($mL/m^2 \cdot s$).

4) Drying Shrinkage Measurement

The drying shrinkage was conducted following the ASTM C596-09 (ASTM C596, 2009). Prismatic specimens (25 × 25 × 285 mm) were prepared from bagasse mortar mixtures 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 temperatures of 23 ± 1°C and relative humidity (R.H.) of 50%; the initial length (L_i) of the shrinkage specimens was measured. The length (L_x) of the shrinkage specimens was measured at 4, 11, 18, and 25 days, respectively. The change in length was then calculated using the following formula:

$$Length\ Change: LC(\%) = \frac{L_i - L_x}{G} \times 100 \qquad (2)$$

where G is the nominal effective length.

5) Compressive Strength Test

The compressive strength tests of the specimens were conducted according to ASTM C109-08 standard test method (ASTM C109, 2008). Three 50-mm cubic specimens were prepared and tested for each mix at 7, 14, 28, and 56 days, respectively.

6) Rapid Chloride Penetration Test

The RCPT was performed for each mix in accordance with the ASTM C1202-05 standard test method (ASTM C1202, 2005). Two 100-mm diameter and 50-mm thickness specimens at the age of 56 days and conditioned according to the standard were subjected to a potential voltage of 60 ± 0.1 V for 6 h. The total charge that passed through the specimens was determined and used to evaluate the chloride permeability of each concrete mixture. ASTM C1202-05 (ASTM C1202, 2005) recommends the qualitative criterion "chloride ion penetrability" according to the range of the total charge passed (Table 3).

7) Scanning Electron Microscopy

Specimens (10 × 10 × 3 mm) were obtained from a 10-mm cube. Representative samples were first air-dried and then impregnated with resin. The impregnated specimens were crushed and softly polished with decreasing grades down to 0.25 μm. The SEM observation was performed using a HITACHI S-4800 microscope equipped with an energy dispersive spectroscope.

III. RESULTS AND DISCUSSION

1. Flow Value

Table 4 shows the flow values of the mixtures containing

Table 3. Chloride-ion penetrability based on charge passed recommended in ASTM C 1202-05.

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

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

Mix No.	Flow value (%)	Water Absorption (%)	Total charge passed (coulomb)
BA0	107	10.44	7270
BA11	63	10.22	3696
BA12	55	10.51	4774
BA13	78	14.07	7470
BA21	67	10.01	3586
BA22	46	10.87	5516
BA23	87	15.35	7744
BA31	64	9.91	3454
BA32	39	11.96	6527
BA33	37	16.73	7930

BA, indicating that BA0 has a flow value of 107%. The flow values of the mixtures containing 10% BA (BA11, BA21, and BA31) were decreased by 63%-67%; however, no significant difference between the flow values of the mixtures with different particle sizes was observed. When the amount of cement replacing BA was increased, the flow values of mixtures containing 20% BA (BA12, BA22, and BA32) decreased from 39% to 55%; the flow values decreased with the particle sizes of BA. A previous study reported that BA is hygroscopic in nature and it requires more water for proper consistency because of its irregular shape, rough surfaces, and highly porous textures compared with cement. The highly porous texture of BA increases the water demand and consequently decreases the flow value, thus resulting in decreased workability. However, in this study, when the amount of cement replacement of BA increased to 30%, the flow values of BA13 and BA23 were higher than those of BA11, BA21, BA12, and BA22, despite no significant flow states being observed for BA13 and BA23. In addition, the flow value of BA33 decreased to 37% because of its high amount of cement replacement and small particle size. The small particle size of BA increased the specific surface area, and water could not completely flow into each pore, thus decreasing the flow value.

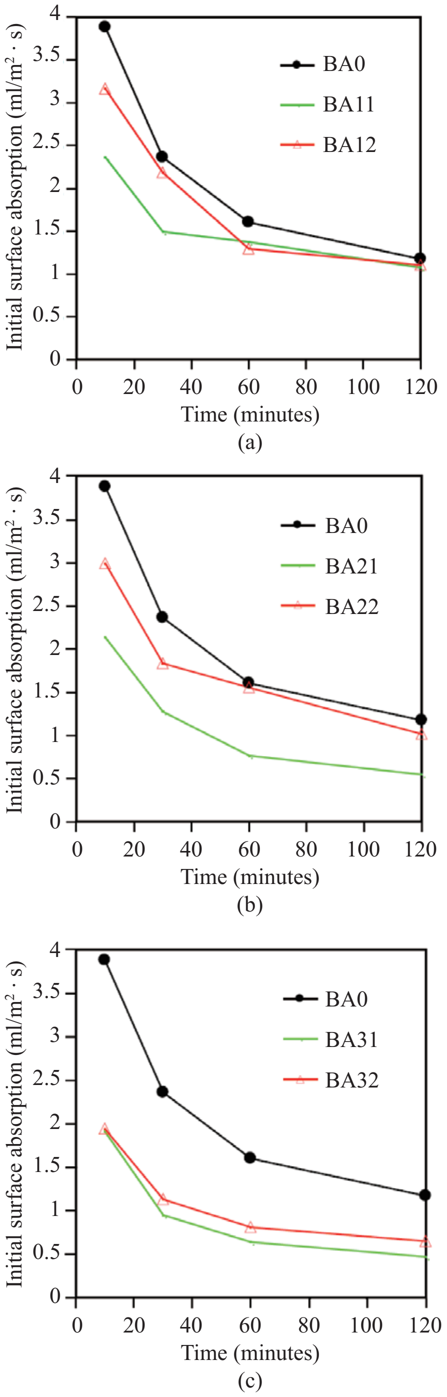


Fig. 3. (a) Initial surface absorption *vs*. Time (BA passing No. 100 sieve), (b) Initial surface absorption *vs*. Time (BA passing No. 200 sieve), and 3(c) Initial surface absorption *vs*. Time(BA passing No. 325 sieve).

2. Water Absorption

Table 4 shows the WA of the mixtures containing BA. The WA increased with the increasing cement replacement percentage by BA. For mixtures containing 10% BA, The WA of BA11, BA21, and BA31 was a slightly lower than that of BA0. However, the WA of BA12, BA22, and BA32 showed a slight increase ranging from 0.07% to 1.52% compared with the WA of BA0. When the amount of cement that replaced BA increased to 30%, the WA of BA13, BA23, and BA33 mixtures achieved 14.07, 15.35, and 16.73% after 56 days, respectively, demonstrating higher WA gain compared with the others. The high WA of the mixtures containing BA was due to the porous nature and rough surface of the BA particles. In addition, the WA decreased with the particle size of BA because of the particle filling effect of BA. The percentage of WA is a measure of pore volume or porosity in hardened concrete, which is occupied by water in saturated conditions. Thus, a 10% cement replacement of BA with the particle size passing the No. 325 sieve may be considered the optimal limit.

3. Initial Surface Absorption Test

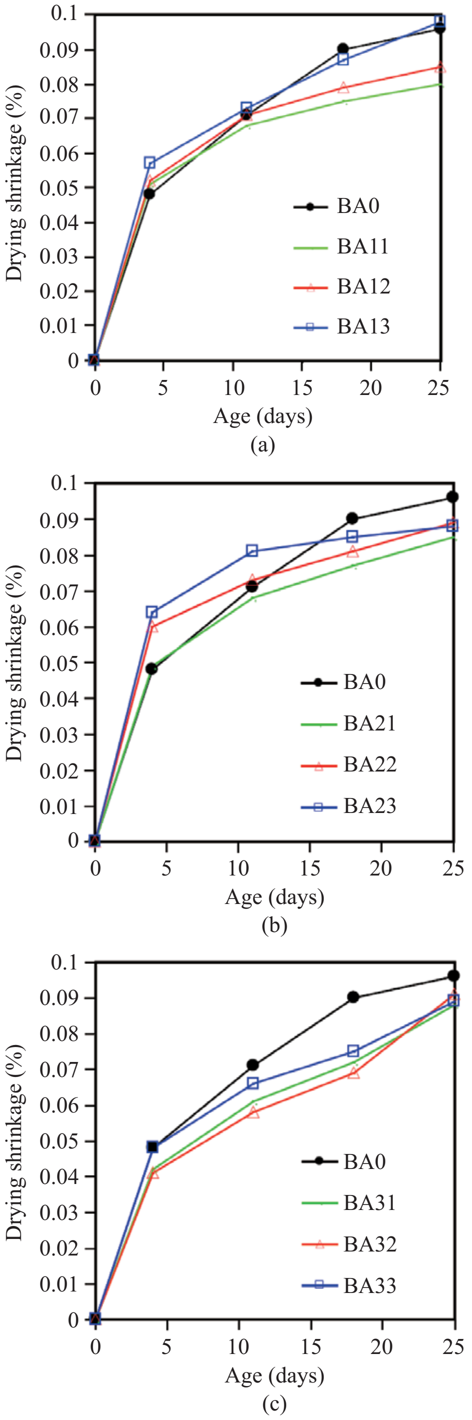
Figs. 3(a)-(c) illustrate the variations of the initial surface absorption with respect to the test time, except the mixtures containing 30% BA (more than 3.6 mL/m^{2}s). The initial surface absorption values of the mixtures decreased with the test time. The initial surface absorption values obtained in the mixtures containing BA were lower compared with those of BA0. In addition, within the test time, the values of the initial surface absorption of mixtures with 20% BA were higher than those with 10% BA. Regarding the effects of particle sizes, the mixtures containing BA passing the No. 100, No. 200, and No. 325 sieves respectively registered initial surface absorption values of 2.36-3.16, 2.13-2.99, and 1.91-1.94 mL/m^{2}s at 10 min. Furthermore, the initial surface absorption values of the mixtures containing BA passing the No. 100, No. 200, and No. 325 sieves respectively decreased to 1.07-1.10, 0.54-1.01, and 0.47-0.65 mL/m^{2}s at 120 min. The initial surface absorption values of the mixtures decreased with the particle sizes of BA.

Mixtures containing BA can effectively reduce the initial surface absorption because of the pozzolanic reaction between calcium hydroxide and reactive silica in BA. Thus, adding BA reduces permeable voids. According to the ISAT results, a cement replacement of 10% by weight of BA with the particle size passing the No. 325 sieve may be the optimal limit.

4. Drying Shrinkage Measurement

Drying shrinkage is a crucial technical parameter that affects the structural properties and durability of cement-based composites. Figs. 4(a)-(c) show the drying shrinkage results for the BA-blended mixtures at the ages of 4, 11, 18 and 25 days. After 18 days, the values of the drying shrinkage of the mixtures containing BA were lower than that of BA0. This may be due to the filler effects or pozzolanic reactions of BA. At 25 days, the drying shrinkage value of the mixtures containing 10% BA was lower than those of the other mixtures.

The proportions of drying shrinkage in BA11, BA21, and BA31 were 16%, 11%, and 8% as high as that of BA0 at 25 days. At 18 days, the drying shrinkage of BA31 was higher than that of BA32; however, with prolonged ages from drying shrinkage, mixtures containing 10% BA showed the relatively lower drying shrinkage than the other mixtures. The BA11 mixture with a cement replacement of 10% by weight of BA passing the No. 100 sieve demonstrated the lowest drying shrinkage at 25 days. The amount of BA blended in cement has still an influence on the drying shrinkage of cement-based composites.



(a)

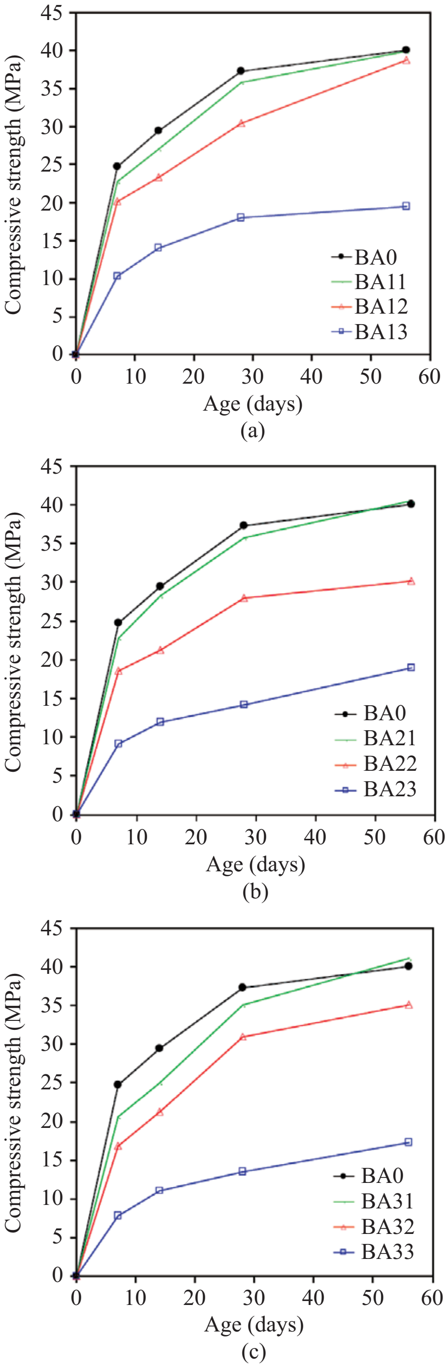
(b)

(c)

Fig. 4. (a) Drying shrinkage *vs.* Age (BA passing No. 100 sieve), (b) Drying shrinkage *vs.* Age (BA passing No. 200 sieve), and (c) Drying shrinkage *vs.* Age (BA passing No. 325 sieve).

5. Compressive Strength

Figs. 5(a)-(c) show the compressive strength developments of the BA-blended cement mortars. The compressive strength was decreased when the amount of BA was increased. At 7, 14, and 28 days, the compressive strengths of the mixtures



(a)

(b)

(c)

Fig. 5. (a) Compressive strength *vs.* Age (BA passing No. 100 sieve), (b) Compressive strength *vs.* Age (BA passing No. 200 sieve), and (c) Compressive strength *vs.* Age (BA passing No. 325 sieve).

containing BA were lower than that of BA0. BA0 had a compressive strength of 37.2 MPa at 28 days, and its strength increased to 40.0 MPa at 56 days. Mixtures containing 10% BA passing the No. 100, No. 200, and No. 325 sieves (BA11, BA21, and BA31) had compressive strengths of 35.8, 35.3, and 35.0 MPa at 28 days, and 39.9, 40.5, and 41.1 MPa at 56 days, respectively. At 56 days, the compressive strengths of BA21 and BA31 were 1% and 3% higher than that of BA0. Generally, BA can be classified as a pozzolanic material and its small particles can fill the voids in the concrete structure, thus increasing the compressive strength (Chusilp et al., 2009). However, in this study, adding BA decreased the compressive strength of the composites. BA13, BA23, and BA33, in particular, showed low compressive strengths of 19.5, 18.9, and 17.3 MPa at 56 days, respectively. These low compressive strengths may be due to the high amount of cement replacement and low pozzolanic reaction of BA. Based on the aforementioned test results, replacing cement with 10% BA is the optimal limit. When 30% of BA replaced cement, only 10% and 20% of BA possibly acted as pozzolanic materials and fillers, respectively.

BA also demonstrated physicochemical properties appropriate for its use as a mineral admixture; furthermore, its reactivity depended mainly on the maximum particle size and fineness. The BA particles used in this study had irregular shapes, rough surfaces, highly porous textures, lower specific gravity, and higher L.O.I. compared with cement. Thus, replacing cement with BA resulted in lower compressive strengths.

6. Rapid Chloride Penetration Test

RCPT is a convenient test for evaluating concrete permeability. Table 4 shows the test results of the mixtures containing BA. The mixtures containing 10% BA with various particle sizes (BA11, BA21, and BA31) demonstrated a decrease in total charge passed of approximately 50% compared with BA0. In addition, the total charge passed of the mixtures containing 20% of BA (BA12, BA22, and BA32) showed a decrease ranged from 7270 to 4774, 5516, and 6527 C, respectively, compared with BA0. However, the total charge passed of mixtures containing 30% of BA (BA13, BA23, and BA33) was higher than that of BA0. This indicates that replacing cement with less than 20% of BA reduced the chloride permeability. Furthermore, the total charge passed of the mixtures containing 10% BA decreases with the particle size of BA. Thus, the replacement of cement with BA is limited and based on the RCPT results; replacing cement with 10% BA was considered the optimal limit.

7. Scanning Electron Microscopy

SEM images were used to explore the microstructure of the corresponding specimens. SEM images of the specimens with and without BA at 56 days were captured using a HITACHI S-4800 microscope. Fig. 6 shows the SEM photograph of BA0, indicating that numerous hydration products—such as C-S-H gels, AFt crystals, and several pores—were formed on the surface of BA0. Fig. 7 shows the SEM image of BA31, indicating that the rough surface of BA31 contained C-S-H gels, AFt crystals, and narrow pores.

The differences in the microstructural features between the specimens without and with BA were not obvious. When 10% BA was added to the mix, the portlandite produced by the

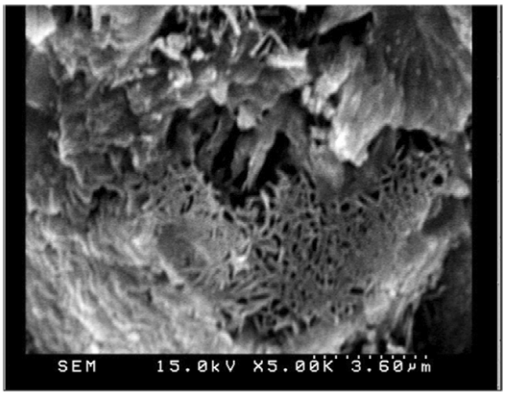


Fig. 6. SEM image of specimen without bagasse ash BA0 (× 5K).

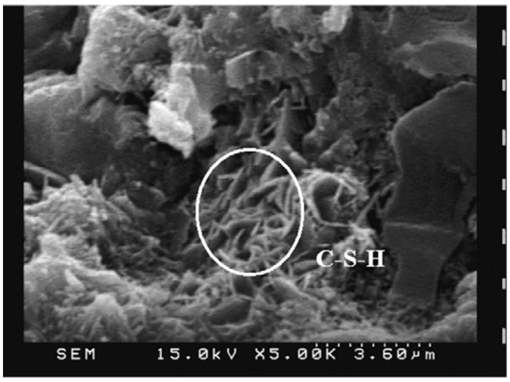


Fig. 7. SEM image of specimen with 10% bagasse ash (× 5K).

hydration of the calcium silicates in the cement reacted with the silica and alumina reactivates in the pozzolanic material. This reaction produced C–S–H gels, which grew into the capillary spaces. Hence, the tissue of the paste structure became dense. These observations are consistent with those of the WA, initial surface absorption, compressive strength, and RCPT results.

IV. CONCLUSIONS

This study investigated the effects of BA with different particle sizes and various dosages of cement replacement on the physical and mechanical properties of cement-based composites. Seven tests were performed: the flow test, WA test, ISAT, drying shrinkage test, compressive strength test, RCPT, and SEM. The results show that both the replacement of cement and the particle size of BA significantly influence the properties of cement-based composites. In the fresh mixtures, the flow value of the mixtures decreased when the amount of BA replacement increased. In the hardened specimens, the specimens with 10% BA demonstrated superior performance in compressive strength, drying shrinkage, WA, initial surface absorption, and chloride ion penetration at 56 days. In addition, these specimens showed denser microstructural properties—determined using SEM—than those of OPC. This result indicates that replacing cement with 10% BA passing the No. 325 sieve may be considered the optimal dosage and the particle size.

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