Properties of Cement Mortar Produced from Mixed Waste Materials with Pozzolanic Characteristics

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Abstract

Waste materials with pozzolanic characteristics, such as sewage sludge ash (SSA), coal combustion fly ash (FA), and granulated blast furnace slag (GBS), were reused as partial cement replacements for making cement mortar in this study. Experimental results revealed that with dual replacement of cement by SSA and GBS and triple replacement by SSA, FA, and GBS at 50% of total cement replacement, the compressive strength (Sc) of the blended cement mortars at 56 days was 93.7% and 92.9% of the control cement mortar, respectively. GBS had the highest strength activity index value and could produce large amounts of CaO to enhance the pozzolanic activity of SSA/FA and form calcium silicate hydrate gels to fill the capillary pores of the cement mortar. Consequently, the Sc development of cement mortar with GBS replacement was better than that without GBS, and the total pore volume of blended cement mortars with GBS/SSA replacement was less than that with FA/SSA replacement. In the cement mortar with modified SSA and GBS at 70% of total cement replacement, the Sc at 56 days was 92.4% of the control mortar. Modifying the content of calcium in SSA also increased its pozzolanic reaction. $CaCl_2$ accelerated the pozzolanic activity of SSA better than lime did. Moreover, blending cement mortars with GBS/SSA replacement could generate more monosulfoaluminate to fill capillary pores.

Key words: cement mortar; coal combustion fly ash; compressive strength; granulated blast furnace slag; hydration reaction; pozzolanic reaction; sewage sludge ash

Introduction

THE DISPOSAL OF SEWAGE SLUDGE is a challenging issue in Taiwan because of the continuous upgrading of the service rate of the urban sewerage system and increasingly stringent environmental regulations. Taiwan produces nearly 180,000 tons of sewage sludge annually from 22 sewage treatment plants (Lin and Lin, 2005). Most of this sludge is disposed of through land filling, spreading on reclaimed land, or incineration (Helena Lopes *et al.*, 2005; Lin *et al.*, 2005; Pawłowska and Siepak, 2006). Although incineration results in optimum volume reduction and stabilization for sewage sludge, the sewage sludge ash (SSA) obtained should still be disposed of in landfills. Different methods of SSA disposal have different degrees of environmental impact and cost effectiveness. Therefore, there is an urgent need to develop alternative methods of SSA disposal.

Recently, a number of studies have been carried out to investigate the use of SSA as a construction material. The reuse

of SSA as a construction material not only alleviates disposal problems but also has economic, ecological, and energy-saving advantages. For example, SSA has been used as a filler in asphalt concrete applications (Al Sayed *et al.*, 1995), for manufacturing bricks and tiles (Okuno and Takahashi, 1997; Jordán *et al.*, 2005; Chen and Lin, 2009), and as a lightweight aggregate (Cheeseman and Viridi, 2005; Wang *et al.*, 2005). Moreover, SSA contains primarily SiO_2 and Al_2O_3 , and it is suitable as a pozzolan because of its high silicon content. Since its pozzolanic reactions could increase the mechanical strength and durability of cement, SSA has been considered to partially replace the use of cement (Monzó *et al.*, 1996; Pan and Tseng, 2001; Valls *et al.*, 2004).

Unfortunately, due to the slow hydration rate of SSA, cement mixed with high volumes of SSA has lower strength development and lower durability than ordinary Portland cement. Previous research on using SSA to replace cement showed that most mixtures of greater than 20% replacement had poor early mechanical strength. When the replacement ratio reached 50%, the compressive strength (Sc) was only 14% of that of the control cement mortar after a curing period of 28 days (Pan *et al.*, 2002). These results indicated that the incorporation of other activators to accelerate the hydration of SSA should be studied further.

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Li and Zhao (2003) found that mixing coal combustion fly ash (FA) and ground granulated blast furnace slag (GBS) to replace cement achieved better Sc than FA alone after a curing period of 28 days. Combining FA and GBS as binders in concrete achieved higher strength levels at all ages compared with conventional concrete (Papayianni and Anastasiou, 2010). This shows that GBS can accelerate the hydration rate of FA when incorporated with FA as a binder in cement mortar. Therefore, the present study examined the possibility of blending cement with increasing replacement ratios of SSA, GBS, and/or FA to reuse these waste materials and to accelerate the hydration and pozzolanic reactions of SSA in cement mortar.

Moreover, Isaia *et al.* (2003) found that adding calcium to pozzolan, which has a low calcium/silicon ratio, enhanced the hydration reaction for the formation of calcium silicate hydrate (CSH) gels and further improved the mechanical strength of high-performance concrete. Consequently, the present study also attempted to modify the properties of SSA through the addition of calcium. The effect of calcium on the pozzolanic reaction of the modified SSA was evaluated. In addition, the hydration characteristics of the cement mortars prepared by blending cement with SSA or modified SSA, GBS, and/or FA were examined at different curing ages.

Materials and Methods

Materials

The dewatered sewage sludge cake produced from a belt filter press was collected from Taipei Pa-Li Wastewater Treatment Plant. The sampled dewatered sludge cake was incinerated at 700°C for 3 h in a modular incinerator and then air cooled down to room temperature; and the coarse SSA collected from the incinerator was then finely ground in a ball mill. The GBS was obtained from CHC Resources Corporation, Kaohsiung City, Taiwan. It is the by-product of the iron-making process and is produced by water quenching of molten blast furnace slag from the China Steel Company, Kaohsiung City. Low-calcium FA equivalent to ASTM Class F was obtained from the Lin-Ko Power Plant, Taiwan Power Company. Ordinary Portland cement equivalent to ASTM Type I, supplied by the Taiwan Cement Company in Yilan County, was used as a control cement for comparison.

The chemical compositions of these materials were analyzed by microwave-assisted digestion (Eaton *et al.*, 2005) followed by inductively coupled plasma atomic emission spectrometry (ICAP-9000; Jarrell-Ash). Table 1 presents the analytical results for SSA, GBS, and FA.

Table 1 indicates that the SSA and FA were composed mainly of silica and alumina oxide. It can be seen that SSA could be used as a pozzolan such as FA. Further, due to its high calcium oxide content, GBS could supply the calcium for the pozzolanic and hydration reaction.

Preparation of blended cement mortar

The preparation and curing of the blended cement mortar followed ASTM C109 (2002) and ASTM C311 (2000) test methods. The cement mortars were prepared with 1,375 g graded sand as aggregate, a water/binder ratio of 0.61, and 500 g binder mixtures. Table 2 shows the binder combination for each batch of mortar, which was categorized into three types: (1) 50% dual replacement of cement by SSA and FA (D-I

TABLE 1. CHEMICAL COMPOSITIONS OF SEWAGE SLUDGE ASH, GRANULATED BLAST FURNACE SLAG, AND FLY ASH

Compositions (wt.%)	SSA	GBS	FA
SiO ₂	48.0	31.3	41.8
Al ₂ O ₃	13.7	1.7	17.0
Fe ₂ O ₃	6.2	0.1	5.3
CaO	3.6	34.2	5.9
MgO	1.9	0.5	1.6
Na ₂ O	1.0	ND	0.2
K ₂ O	2.1	0.1	0.6
SO ₃	1.7	1.8	0.7

FA, fly ash; GBS, granulated blast furnace slag; ND, not detected (<0.1%); SSA, sewage sludge ash.

and D-II) or SSA and GBS (D-III and D-IV); (2) 50% triple replacement of cement by all three materials (T-I and T-II); and (3) 70% replacement of cement by modified SSA and FA (M-I and M-II) and modified SSA and GBS (M-III and M-IV). It should be noted that the modified SSA was prepared in two ways: (1) the dewatered sewage sludge cake was coincinerated with 30% (w/w) industrial lime at 700°C for 3 h in a modular incinerator and then finely ground to obtain SSA-CaO (M-I and M-III); (2) M-II and M-IV were added, along with 3% (w/w) chemical grade CaCl₂, directly into the blended cement mortars. In addition, the binder combinations for the dual and triple replacement of cement were designed based on the different weight ratios of each pozzolan (*i.e.*, SSA, FA, and GBS) to compare the effect of other activators on enhancing the pozzolanic reaction of SSA.

Six 5-cm cube specimens were made from each batch of the blended cement mortar and cured in a container with 98% relative humidity at 23°C. The Sc of the mortar specimens curing in a saturated Ca(OH)_{2(aq)} was measured at 7, 28, 35, 42, and 56 days. The microstructure and hydration characteristics of the blended cement mortars were evaluated and compared with those of control mortars produced with Portland cement. Specimens were observed by scanning electron microscopy (SEM) at 28 and 56 days. Thermogravimetry analysis (TGA) was conducted on specimens

TABLE 2. MIXTURES OF THE BLENDED CEMENT MORTARS

Binder combination	Binder (g)				Total cement replacement ratio (%)
	Cement	SSA	FA	GBS	
Control	500	0	0	0	0
D-I	250	125	125	0	50
D-II	250	62.5	187.5	0	50
D-III	250	125	0	125	50
D-IV	250	62.5	0	187.5	50
T-I	250	62.5	125	62.5	50
T-II	250	62.5	62.5	125	50
M-I	150	175 ^a	175	0	70
M-II ^b	150	175	175	0	70
M-III	150	175 ^a	0	175	70
M-IV ^b	150	175	0	175	70

^aSSA replaced by SSA-CaO.

^bAn addition of 3% CaCl₂ in blended cement mortars.

D, dual-replacement; T, triple replacement; M, modified SSA by adding calcium.

cured for 7, 28, and 56 days (Mangialardi *et al.*, 1998; Payá *et al.*, 1998), and a mercury intrusion porosimetry (MIP) test was conducted on specimens cured for 28 days (Gallé, 2001).

Analytical methods

The crystalline constituents of FA, GBS, and SSA were analyzed by X-ray diffractometry (FTS-40; Siemens); and crystalline phases were identified from the International Center for Diffraction Data database (Shih *et al.*, 2005). The strength activity index (SAI) following the ASTM C311 (2000) test method was used to evaluate the pozzolanic activity of SSA, FA, GBS, and SSA-CaO. The SAI was the ratio of the Sc of standard mortar bars prepared with 80% reference cement plus 20% SSA, FA, GBS, and SSA-CaO by mass to the Sc of standard mortar bars prepared with reference cement alone, when tested at the same age (Donatello *et al.*, 2010). The reactivity of pozzolan depends on the crystalline/amorphous silica ratio, which is an important controlling component in the use of cement and building materials. The amorphousness of silica (also called soluble silica) was estimated from the silica activity index (Katz, 1998; Payá *et al.*, 2001), which was determined by subtracting from the total silicon dioxide content the fraction contained in the residue that was insoluble in 4 mol/L NaOH at 75°C after a 24-h extraction period.

The Sc of each hardened cement mortar was measured in triplicate at different ages after ASTM C109 (2002). The microstructure and hydration characteristics were analyzed via SEM (S-800; Hitachi, Japan), MIP (AutoPore 9520; Micromeritics), and TGA techniques for pulverized and sieved (#300) samples whose hydration was terminated at the tested age with acetone under a vacuum for 24 h. The TGA of the samples was obtained by a thermal analyzer (TGA7; Perkin-Elmer, USA) with a heating rate of 10°C/min from 50°C to 900°C.

Results and Discussion

Characterization of the materials blended in the cement

Figure 1 shows the X-ray diffraction pattern of the materials blended in the cement. The predominant crystalline constituents of SSA were quartz and moganite, both of which are crystalline silicon oxides. Even though the amount of quartz and moganite in SSA-CaO was less than that in SSA, some peaks of calcite were found. In addition, the predominant crystalline constituents of FA and GBS were quartz/mullite and calcite/ferrite, respectively.

Although the analytical results of the chemical compositions in Table 1 indicate that SSA and FA had a similar proportion of total silicon oxide, Fig. 1 reveals that the intensity of quartz and the content of crystalline silicon oxides in SSA were higher than in FA. Therefore, the amount of amorphous silicon oxides in FA might be greater than that in SSA. In general, it is well known that pozzolanic activity is proportional to the amount of amorphous silicon oxide (Payá *et al.*, 2001). Consequently, the pozzolanic activity of SSA would be lower than that of FA.

Table 3 shows the pozzolanic activity, that is, SAI values and the soluble silica content (%), of the materials used for the replacement of cement. The FA had a better pozzolanic activity than SSA: the SAI values at 28 days were 83.7% and 82.2%, and the soluble silica contents were 18.3% and 12.7%

FIG. 1. X-ray diffraction pattern of the materials blended in cement.

for FA and SSA, respectively. Moreover, the SAI values of GBS were 106.8% and 123.0% at 7 days and 28 days, respectively. The pozzolanic activity of GBS was higher than that of FA and SSA. The primary reason for this is that GBS had large amounts of CaO (34.2%, as shown in Table 1), which could have enhanced its pozzolanic activity. Although the percentage of soluble silica in SSA-CaO was less than that in FA and SSA, the SAI value of SSA-CaO was higher. This confirms that modifying the calcium content of SSA also increased its pozzolanic reaction.

TABLE 3. POZZOLANIC ACTIVITY OF SEWAGE SLUDGE ASH, FLY ASH, GRANULATED BLAST FURNACE SLAG, AND SEWAGE SLUDGE ASH-CAO

Sample	SAI (%)		Soluble silica content (%)
	7 days	28 days	
SSA	80.2	82.2	12.7
FA	78.7	83.7	18.3
GBS	106.8	123.0	^a
SSA-CaO	89.2	86.4	7.9

^aGBS and NaOH resulted in the hydration reaction, thus this measurement method did not apply.

SAI, strength activity index.

Sc development of the mortars

According to the results of a previous study, when SSA alone was used to replace cement at replacement ratios of 25% and 50%, the Sc was 52% and 14%, respectively, than that of the control mortar at 28 days (Pan *et al.*, 2002). These results imply that a lack of Ca(OH)_2 , which is generated during cement hydration, impeded the pozzolanic reaction and decreased the Sc. However, in this study, dual and triple substitution of cement by SSA and FA and/or GBS at 50% of total cement replacement significantly enhanced Sc development compared with the previous study (Fig. 2A, B).

Figure 2A reveals that the Sc development of dual replacement by SSA and GBS (D-III/D-IV) was much better than that of dual replacement by SSA and FA (D-I/D-II). The Sc of D-III/D-IV mortar at 28 and 56 days was 88.9%–93.1% and 91.1%–93.7% of that of the control mortar, respectively. In addition, Fig. 2B also shows that the Sc development of T-II mortar was better than that of T-I mortar. Thus, the more GBS was used in the replacement (D-IV, T-II, and D-III), the higher the Sc. As previously mentioned, GBS had the highest SAI value and could produce large amounts of CaO to enhance its pozzolanic activity. Consequently, the Sc development of the cement mortar with GBS replacement was better than that of the mortar without GBS (Ahmed and Buenfeld, 1997).

FIG. 2. Compressive strength (Sc) development for cement mortars with (A) dual replacement, (B) triple replacement, and (C) modified sewage sludge ash (SSA) replacement.

In addition, the Sc of T-II mortar was higher than that of D-III mortar and approached that of D-IV mortar (Fig. 2A, B). A possible explanation for this is that GBS produced a large number of calcium ions to decrease the latency of cement and accelerate the pozzolanic reaction. Thus, GBS can simultaneously accelerate the pozzolanic reaction of SSA and FA.

Figure 2C shows the results of Sc development for the cement mortars with modified SSA and FA or GBS at 70% of total cement replacement. The Sc development of M-III/M-IV mortars was better than that of M-I/M-II mortars. These results indicate that enough Ca(OH)_2 was generated in the cement mortars to enhance the pozzolanic reaction when modified SSA and GBS (M-III/M-IV) were used to replace cement, even at as high as 70% of total cement replacement. Moreover, modified SSA with the addition of CaCl_2 could foster the Sc of M-IV mortar up to 92.4% of that of the control mortar at 56 days; meanwhile, the Sc of M-III mortar (SSA-CaO and GBS) was 76.5% of that of the control mortar. This finding reveals that CaCl_2 enhanced the pozzolanic activity of SSA better than lime did, because CaCl_2 was easily hydrolyzed in the pore solution to release large amounts of calcium ions to promote cement hydration and form adequate Ca(OH)_2 . In addition, the existence of chloride ions can accelerate the decomposition of calcium silicate for cement hydration and the formation of high-density CSH gels (El-Didamony *et al.*, 1996).

Porosity distribution in the blended cement mortars

It is well known that pore size and distribution affect the pore structure property of cement mortar. The Sc depends on the pore structure and degree of hydration of the cementitious material (Ozturk and Baradan, 2008; Lin *et al.*, 2009). Therefore, MIP tests were carried out to determine the pore size distribution and the total porosity of all types of blended cement mortar used in this study. The test results for some selected cement mortars are shown in Fig. 3.

Generally speaking, the pore size of the cementitious material could be approximately classified into gel pore ($<0.01 \mu\text{m}$) and capillary pore ($>0.01 \mu\text{m}$) levels (Mindess *et al.*, 2003). The major pore size of D-II mortars was between $0.01 \mu\text{m}$ and $0.3 \mu\text{m}$; and the major pore size of D-IV, T-II, M-

FIG. 3. Pore size distribution of the hardened cement mortars. (A) control one; (B) dual and triple replacement; and (C) modified SSA replacement.

III, and M-IV mortars was $<0.01\ \mu\text{m}$ (Fig. 3). The change in these pore size distributions was likely to be the consequence of capillary pores filled with CSH gels, which contained finer gel pores and formed via latent hydraulic reactions. This hypothesis was reinforced by the fact that the enhancement of later strength coincided with the shift in pore size.

In addition, the pore volume of all types of blended cement mortar was larger than that of the control mortar (14.8%). Therefore, the S_c of the blended cement mortars was less than that of the control mortar. Further, at 50% of total cement replacement, the pore volume and capillary pore volume of D-II cement mortar were greater than those of D-IV and T-II mortars, as shown in Fig. 3B. The cumulative total porosity of D-IV (15.3%) and T-II (16.0%) mortars was lower than that of D-II mortar (20.6%). This proved that GBS could accelerate the pozzolanic reaction of SSA/FA and form CSH gels to fill the capillaries. Consequently, the pore volume of blended cement mortars with GBS/SSA replacement was less than with FA/SSA replacement.

Moreover, even at as high as 70% of total cement replacement, the porosity of M-IV mortar (19.5%) was lower than that of M-III mortar (20.6%; Fig. 3C). This was primarily because the CaCl_2 added to SSA could promote cement hydration and form adequate $\text{Ca}(\text{OH})_2$ easier than lime, as previously mentioned. All in all, the porosity results of the blended cement mortars were consistent with the S_c development.

Microstructure studies

SEM photos of the surface morphologies of hydration products in selected specimens appear in Fig. 4. When SSA and FA

were used as dual cement replacement, there were numerous un-hydrated FA particles with clear edges, and the surface was partially covered with CSH gels (Fig. 4A). A comparison of Fig. 4A and B shows a higher degree of hydration in D-IV mortar (dual replacement by SSA and GBS) than D-II mortar (dual replacement by SSA and FA). In addition, Fig. 4B demonstrates that many hydration products, such as monosulfoaluminate, $\text{Ca}(\text{OH})_2$, and CSH gels, were formed, and the structure of the cementitious materials was strengthened.

In the case of triple replacement of cement by SSA, FA, and GBS, the greater the GBS to FA ratio (T-II mortar > T-I mortar), the higher the degree of hydration obtained. This was confirmed by results shown in Fig. 4C and D. Generally speaking, both the OH^- ions and alkalis produced by GBS could react with SiO_2 and break down the glass phase of SSA/FA. Thus, the glass structure of SSA/FA was easily broken down in the higher alkalinity condition, and then their activation and hydration processes were accelerated (Li *et al.*, 2002). The result for T-I cement mortar in Fig. 4C indicates that the surface of the FA particle was covered with hydration products and had a large degree of particle erosion. However, SEM observation of T-II cement mortar in Fig. 4D shows that the microstructure was greatly changed with the incorporation of more GBS, and no FA particles were observed. Consequently, when SSA was mixed with FA and GBS to replace cement, GBS could activate the pozzolanic reaction of SSA/FA at the same time.

It can be seen from Fig. 4F that there was a great deal of cotton-shaped CSH gels in the M-IV cement mortar, but the meshed structure of monosulfoaluminate was observed in Fig. 4E. According to the hydration products at 28 days of curing age shown in Fig. 4E and F, the rate of hydration of

FIG. 4. Scanning electron microscopy photos of selected cement mortar specimens. (A) D-II cured for 56 days; (B) D-IV cured for 56 days; (C) T-I cured for 56 days; (D) T-II cured for 56 days; (E) M-III cured for 28 days; and (F) M-IV cured for 28 days. CSH, calcium silicate hydrate; FA, fly ash; AFm, monosulfoaluminate; CH, calcium hydroxide.

M-IV cement mortar was faster than that of M-III. Thus, the greater and faster formation of CSH gels improved the strength and other properties of M-IV cement mortar compared with M-III cement mortar.

TGA of the blended cement mortars

Further quantification of the hydration products of the cement mortars was performed based on the derivative thermogravimetric (DTG) curve obtained from TGA results. Figure 5 shows the DTG results for selected cement mortars cured for 7, 28, and 56 days. There are seven peaks on each curve indicating the major hydration products (Wang and Scrivener, 1995; El-Didamony *et al.*, 1996; Martinez-Aguilar *et al.*, 2010). Also, the results demonstrate the mass loss of CSH during the DTG analysis of the mortars; as the reaction proceeded up to 56 days, the amount of CSH gel increased. Consequently, the Sc and the degree of densification increased with the increase in curing age of the cement mortars. In ad-

FIG. 5. Derivative thermogravimetric results for the hardened cement mortars.

dition, the pozzolans used in this study could convert the dense $\text{Ca}(\text{OH})_2$ into CSH gels through the pozzolanic reaction; thus, the $\text{Ca}(\text{OH})_2$ peak of each type of blended cement mortar in Fig. 5 was basically lower than that of the control cement mortar.

Moreover, there were more CSH gels in D-IV mortar than in the control mortar, as shown in Fig. 5. Therefore, the pozzolanic reaction rate of D-IV cement mortars should have increased greatly and then improved Sc development. Consequently, the Sc of D-IV mortar should have theoretically extended beyond that of the control mortar; however, Fig. 2A shows that the Sc of D-IV mortar was slightly less than that of the control. This might imply that some large capillaries in the blended mortar were never filled or eliminated, and these might be the instinct pores in SSA particles.

Figure 5 also shows that the amounts of CSH gels, monosulfoaluminate, and ettringite formed in the D-IV and T-II mortars were greater than those in D-II and T-I, respectively. This is primarily because of the higher amount of GBS used as cement replacement in D-IV and T-II than in D-II and T-I. An explanation for this might be that the more GBS (with high $\text{CaO} + \text{MgO}$ content) participated in the hydration process and reacted with $\text{Ca}(\text{OH})_2$, the hydration product of Portland cement, the more CSH gels were formed. The mechanism behind this reaction was the ability of GBS to produce more nucleating sites and make OH^- ions as well as alkalis easily dissolve into the pore fluid (Li and Zhao, 2003). At the same time, the cement hydration reaction generated homogeneous hydration products such as ettringite and $\text{Ca}(\text{OH})_2$, which had larger specific surface areas, than un-hydrated Portland cement. Then, the CSH gels, ettringite, and $\text{Ca}(\text{OH})_2$ acted as nucleating sites, precipitated around SSA/FA particles, and led to the increase in the hydration rate of SSA/FA. Moreover, ettringite was formed at the surface of C_3A ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$) grains at the beginning of hydration. Once the hydration of sulfate was complete, ettringite became unstable and dissolved into the pore fluid to supply the sulfates, and C_3A hydration continued to result in the formation of monosulfoaluminate (Mehta and Monteiro, 1993). Consequently, mixing SSA with GBS to replace cement could generate a large amount of monosulfoaluminate.

In addition, the $\text{Ca}(\text{OH})_2$ peaks in Fig. 5 are quite low for M-III/M-IV cement mortars. There are two major reasons for this: First, M-III/M-IV cement mortars with 70% total cement replacement resulted in less cement for the formation of $\text{Ca}(\text{OH})_2$; and second, additional Ca-salt accelerated the rate of hydration, and a low Ca/Si ratio hydration product formed at an early age (Kakali *et al.*, 2000). Meanwhile, the CSH gel peaks of M-III/M-IV mortars shifted to the left, as shown in Fig. 5. These findings are in line with those of Sakai *et al.* (2005), who found that when Ca-salt increases, sufficient calcium ions in the solution help the nucleation effect of $\text{Ca}(\text{OH})_2$ and reduce latency to promote the hydration reaction of blended cement.

Conclusions

Using SSA, FA, and GBS as cement replacements for making cement mortar and blending modified SSA with GBS to substitute cement are found to be feasible. This study demonstrates that the SAI values of FA, SSA, and GBS at 28 days were 83.7%, 82.2%, and 123.0%, respectively. It confirms

that these pozzolans can partially replace cement in making cement mortars. In addition, modifying the content of calcium in SSA by adding CaO to sewage sludge and then co-incinerating or adding CaCl₂ directly to SSA can also increase the pozzolanic characteristics of the modified SSA.

This study also found that with dual replacement of cement by SSA and GBS and triple replacement by SSA, FA, and GBS at 50% of total cement replacement, the Sc of the blended cement mortars was 93.7% and 92.9% of that of the control cement mortar, respectively. These results reveal that GBS which contains large amounts of CaO (34.2%) can simultaneously accelerate the pozzolanic reaction of SSA/FA and achieve better performance as cement replacement than SSA alone. Blending modified SSA (by adding CaCl₂) with GBS to substitute for cement at as high as 70% of total cement replacement results in the Sc up to 92.4% of that of control mortar.

In addition, the porosity results of the blended cement mortars found in this study were consistent with the Sc development. The GBS that contains high levels of CaO (34.2%) and MgO (0.5%) can produce a large number of OH⁻, thus destroying the glass phase of SSA/FA and reacting with SiO₂ to form CSH gels. It also produces a large number of calcium ions to decrease the latency of cement and to accelerate the cement hydration. Moreover, mixing SSA with GBS to replace cement generated a large amount of monosulfaluminate. The most interesting finding is that the overall pozzolanic reactions were complementary among the combination of pozzolans (*i.e.*, SSA, FA, and GBS) that were used to replace cement.

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Author Disclosure Statement

No competing financial interests exist.

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