

Properties of MSWI Fly Ash Slag-blended Cement Concrete

Chieh-Jen Chang¹, Tzen-Chin Lee¹⁺, Kuo-Kang Lin¹, and Yi-Xiang Wu¹

Abstract: Municipal solid waste incinerator (MSWI) fly ash was melted into slag and then pulverized to generate particle sizes of less than 38 μm in diameter (sieve #400) for experimental studies. Several slag-blended cement concrete (SBCC) specimens 10 cm in diameter and 20 cm in height were molded using 20% cement replacement with slag powder. Then, three water/cementitious (w/c) ratios, namely 0.36, 0.52 and 0.68, were selected to test the specimens for slump, setting time, compressive strength and durability. The compressive strengths of specimens of various ages were compared with those of ordinary Portland cement concrete (OPCC) specimens. The results reveal that the compressive strengths of the SBCC specimens were lower than those of the OPCC specimens at an early stage and became similar to those of the OPCC specimens at the age of 28 days. Moreover, the compressive strengths of the SBCC specimens are 100-113% and 105-118% those of the OPCC specimens after 56 and 90 days, respectively. The slumps (i.e. workability) and setting times for both the SBCC and OPCC specimens were similar. Our test results show that MSWI slag-blended cement concrete is usable for practical applications and can be applied to the concrete pavement.

Key words: Cement concrete; Compressive strength; MSWI fly ash; Pozzolanic reaction.

Introduction

This paper focuses on how best to recycle fly ash produced from municipal solid waste incinerators (MSWI). In Taiwan, fly ash often contains many types of toxic heavy metals and is usually solidified into blocks by adding about 20 wt.% cement and a chelating agent before being disposed of in sanitary landfill sites. However, as a long-term measure, toxic heavy metals might still leach out from stabilized blocks after deposition in landfill sites [1-2]. Besides, a shortage of landfill area is a serious problem in densely populated countries such as Taiwan. Recycling fly ash could help address this problem.

Studies on fly ash and bottom ash recycling have reported limited success. Fly ash and bottom ash can be used as a roadbed material in road construction contexts [3-5] and can be formed into permeable blocks and pavement bricks [6, 7] and ceramic tiles for the construction industry [8]. The possibility of using MSWI fly ash and bottom ash in concrete is of particular interest [9-15]. However, direct recycling of fly ash as a resource can be hazardous to the environment, because it contains many types of heavy metals [16-19]. To tackle the problem of heavy metals leaching from fly ash, it is first melted into glassy slag before reuse. During the melting process, heavy metals are immobilized in the Si-O matrix within the thermally treated slag, which prevents them from leaching out of the slag and harming the environment [16, 20, 21]. The reuse of MSWI fly ash slag as a cement substitute in cement paste and mortar seems very promising. Lin [22] studied the effects of mixing Type I, Type II and Belite cements with MSWI fly ash slag-blended cement paste. Experimental results suggest that the slag-blended cement paste exhibited slower compressive strength development in the early stages with obvious acceleration during

later stages. Furthermore, Lin et al. [20] investigated the reuse of MSWI fly ash slag as a cement substitute in mortar. Their Toxicity Characteristic Leaching Procedures (TCLP) analysis proved that MSWI fly ash slag was non-hazardous. Mortar with 10% substitution exhibited a strength that was 1-2 MPa higher than that of un-substituted mortar after curing for either 60 or 90 days. To improve the early strength of the slag-blended cement mortar, Lin et al. [23] and Lee et al. [24] added aluminum oxide (Al_2O_3) and Calcium Carbonate (CaCO_3) to MSWI fly ash for melting, respectively, then water-quenched the resulting mixtures to produce a modified slag. This modified slag was used as a cement additive, with which various slag-blended cement paste (and mortar) cubic specimens for experimental study were molded. Their results reveal that the early strengths of all specimens were enhanced, and the heavy metal leaching concentrations were relatively low. All specimens met relevant regulatory thresholds. However, to our knowledge, there are no reports of MSWI fly ash slag being used in concrete for practical construction engineering projects.

The aim of this study is to investigate the use of MSWI fly ash slag to replace 20 wt.% cement in concrete. Slag powder with particle sizes of less than 38 μm (sieve #400) was used to create concrete cylinder specimens 10 cm in diameter and 20-cm height for compressive strength and related testing. The results were analyzed and evaluated in terms of the feasibility of partial cement replacement with MSWI fly ash slag in concrete.

Material and Methods

Materials

Hsinchu MSWI, Taiwan, supplied MSWI fly ash with a specific gravity (S.G.) of 2.91. The fly ash was held in an aluminum oxide crucible, which was then placed into an electrical furnace, heated gradually to 1,400°C and maintained at that temperature for half an hour. The resulting material was then air-cooled, and fly ash slag was obtained. The ignition loss was 26.4%. This black-brown vitrified solid slag was ground into particle sizes of less than 38 μm

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Table 1. The Proportioning of Plain Cement Concrete and Slag-blended Cement Concrete (Proportion Weights per 0.60 m³).

Specimen Name	Cement (kg)	Slag (kg)	Water (kg)	Sand (kg)	Aggregate ^a (kg)
OPCC (0.36) ^b	32.16	-	11.58	31.38	63.72
SBCC (0.36)	25.73	6.43	11.58	31.38	63.72
OPCC (0.52)	22.26	-	11.58	40.20	63.72
SBCC (0.52)	17.81	4.45	11.58	40.20	63.72
OPCC (0.68)	17.04	-	11.58	44.88	63.72
SBCC (0.68)	13.63	3.41	11.58	44.88	63.72

^a Coarse aggregate with a nominal maximum size of 25 mm

^b The number in parentheses denotes the water-to-cementitious ratio

(sieve #400) with S.G. = 2.78.

The cement used was Type I ordinary Portland cement (OPC) obtained from Taiwan Cement Company. The OPC exhibited a specific gravity of 3.14 and a specific surface of 0.352 m²/g, while its physical and chemical properties met the ASTM C150 specifications [25].

Fine aggregate (sand) was obtained from the middle region of the Ta-an River in Miao-Li, Taiwan. The fineness modulus was 2.83.

Coarse aggregate was also obtained from the middle region of the Ta-an River. Large stones were crushed, and those with sizes of 10 mm and 20 mm were mixed according to a certain ratio and then used as coarse aggregate. The fineness modulus was 6.72.

Los Angeles Abrasion Test for the Coarse Aggregate

All tests were performed according to ASTM C131 [26]. Aggregates of crushed stones were impacted and abraded with steel balls in a Los Angeles, CA, testing machine to determine the weight loss associated with the coarse aggregates.

XRD Analysis of Ash-mix and Slag Powder

Powder X-ray diffraction (XRD) analysis was carried out using an X-ray diffractometer (Rigaku, D/Max-2200, Japan) with Cu K_{α1} radiation and 2θ scanning that ranged between 5° and 85°. The XRD scans operated in 0.05° increments, at one increment per second.

SEM/EDS Analysis of Fly Ash and Slag Powder

Samples of fly ash and slag powder were oven-dried at 100°C for 24 hours and cooled in a desiccator. After being coated with platinum, the samples were analyzed with a scanning electron microscope (SEM, JEOL, JSM-5600, Japan). Elemental analysis was conducted with energy dispersive X-ray spectrometry (EDS, Oxford, 6587, UK), which was performed in conjunction with SEM in order to analyze the chemical composition of the above-mentioned materials.

TCLP Analysis of Fly Ash and Fly Ash Slag

Leaching rates for the fly ash and slag were analyzed by TCLP testing according to “Toxicity Characteristic Leaching Procedures

(TCLP): SW 846-1311 (USA).” Heavy metal concentrations were then measured based on SW-846-7131A for Cd, SW 846-7421 for Pb, SW 846-7951 for Zn, SW 846-7211 for Cu and SW 846-7191 for Cr.

Molding and Testing of Concrete Cylinder Specimens

Concrete cylinder specimens 10 cm in diameter and 20 cm in height were molded according to ASTM C39/C39M-03 [27]. The target water-to-cementitious ratios were 0.36, 0.52 and 0.68; the slump metric was 12.5 cm. The largest of the aggregates measured 25 mm, and the design proportions of both plain and slag-blended cement concrete specimens are listed in Table 1. Fresh concrete was used for slump, chloride content, air content and both the initial and final setting times test. All of the specimens were cured in saturated calcium hydroxide (Ca(OH)₂) solution at a temperature of 23 ± 1.7°C. The chamber was programmed to a certain temperature for 1 to 90 days. The resulting cylindrical concrete specimens were subjected to compressive strength testing and stress-strain analyses.

Fresh Concrete Tests

Slump tests were performed according to ASTM 143 [28] to measure slump data for both the SBCC and OPCC (reference) groups.

The measurement of air content in fresh concrete was performed according to ASTM C231 [29]. The volume variation of concrete due to pressure changes was measured with a pressure-type air content meter (Fornay, USA).

The unit weight of fresh concrete was measured as specified in ASTM C138 [30].

Chloride content was measured according to Taiwan National Standard CNS 3090. A chloride content meter (CL-1B, Rikin, Japan) was used for this test.

Setting time was measured according to ASTM C403 [31]. A concrete penetration meter (H-4133, Humboldt Mfg. Co.) was used for these tests.

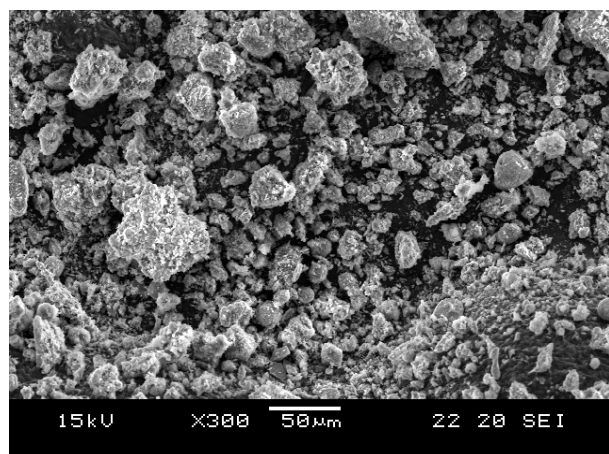
Hardened Concrete Tests

The OPCC and SBCC concrete-cylinder specimens were prepared according to ASTM C39 and were cured for 1 to 90 days. At each curing assessment stage, three cylinder specimens were tested for compressive strength.

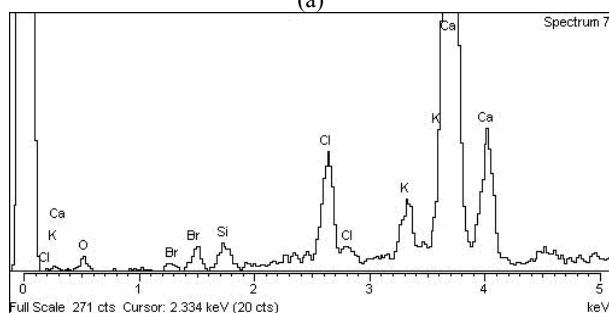
Stress-strain curves were obtained when the concrete specimens were under compressive loading. Data from the linear variable differential transformer (LVDT) apparatus and from strain gauges on the specimens were captured by a computer from which appropriate stress-strain curves could be plotted.

The relationship between stress and strain in concrete is not always linear. According to ACI-318 codes [32], the elastic modulus is defined as the slope of the line drawn from a stress of zero to a compressive stress of 0.45 f_c' (f_c' is the compressive strength of specimens cured for 28 days). Thus, the secant modulus obtained from the straight line connecting the point of 0.45 f_c' to the original point on the stress-strain curve was used as the elastic modulus.

Durability tests were performed according to Taiwan National

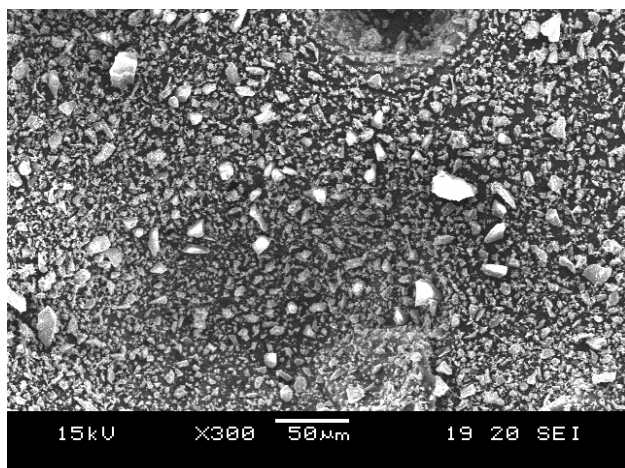


(a)

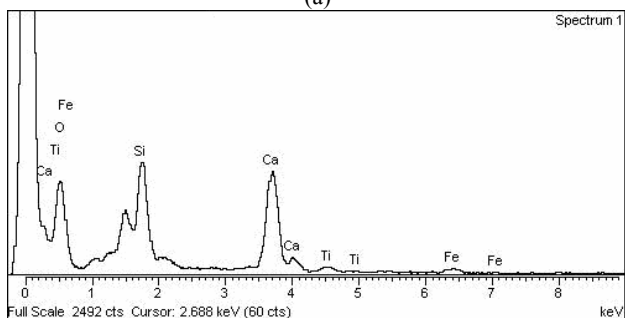


(b)

Fig. 1. SEM/EDS Analyses of MSWI Fly Ash: (a) SEM Micrograph; (b) EDS Spectrum.



(a)



(b)

Fig. 2. SEM/EDS Analyses of MSWI Fly Ash Slag Powder: (a) SEM Micrograph; (b) EDS Spectrum.

Table 2. Chemical Compositions of Cement, MSWI Fly Ash and Fly Ash Slag.

Chemical Constituents (wt.%)	Cement	MSWI Fly Ash	MSWI Fly Ash Slag
Na ₂ O	—	1.90	1.32
K ₂ O	—	2.00	0.21
CaO	62.12	48.91	36.07
ZnO	—	1.27	1.87
SO ₃	—	12.98	—
MgO	2.79	2.26	2.51
SiO ₂	22.31	12.64	37.32
Al ₂ O ₃	5.74	5.25	10.73
Fe ₂ O ₃	3.36	2.28	3.92
Cl ⁻	—	4.17	—
P ₂ O ₅	—	2.36	—
TiO ₂	—	2.60	—
CuO	—	0.40	—

Standard CNS 1167 (refer to ASTM C88-05 [33]). The concrete specimens were attacked chemically by saturated sodium sulfate solution (Na₂SO₄). The specimens were immersed in this solution for 18 hours before being heated and dried for 6 hours. The process of alternate immersion and drying was repeated for five cycles, after which the specimens were tested for compressive strength to measure any relevant losses.

Results and Discussion

SEM/EDS Analyses

Fig. 1(a) and Fig. 2(a) show SEM micrographs of the fly ash and fly ash slag, respectively. Fly ash particles look like agglomerates, and fly ash slag particles seem to be aggregates of particle size less than 38 µm. The constituents were identified through EDS analyses. The totality of the micrographs is shown in Fig. 1(b) and 2(b). As seen from the SEM/EDS analysis, the Cl peak is pronounced on the fly ash sample. However, there is no Cl peak on the slag sample. It may be deduced that Cl probably combined with Pb, Cu and Cd to form chlorides, which are evaporated below 1000°C [34]. As for Zn, which has a low boiling point, some of it was most certainly lost due to evaporation. Na, K and SO₃ evaporated as well (see Table 2). Table 2 shows that the fly ash slag contains non-calcium oxides of SiO₂ and Al₂O₃, totaling 51.97 wt.%. The CaO content reaches 36.07%, which meets the requirements for C grade fly ash content according to ASTM C618. Non-calcium oxides are key substances that are involved in the Pozzolanic reaction. The compositions with greater calcium oxide content might be better in terms of favorable development of early compressive strength.

XRD Analysis of Fly Ash and Slag

Fig. 3 depicts the X-ray diffractograms for the fly ash and slag. The identified phases of fly ash were, with decreasing intensity, Portlandite (Ca(OH)₂), Quartz (SiO₂), Anhydrite (CaSO₄), Hydrophilite (CaCl₂), Sylvite (KCl), and Halite (NaCl). The X-ray diffraction pattern for the slag seems amorphous (glassy), which is

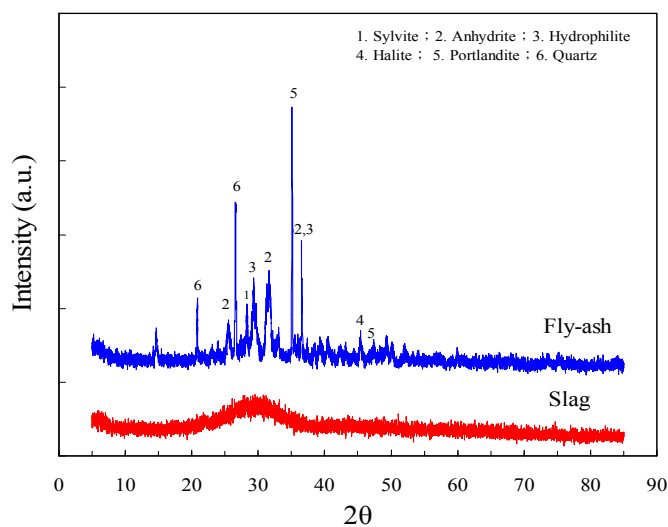


Fig. 3. X-ray Diffractograms of the MSWI Fly Ash and Slag.

Table 3. Heavy Metals and TCLP Leaching Concentrations from Fly-ash, Fly Ash Slag, OPCC and SBCC Specimens.

	Zn	Cr	Cu	Pb	Cd
Total Metal (mg/kg)					
Fly Ash	13700	891	940	2413	165
Fly Ash Slag	353	57	52	39	ND ¹
TCLP(mg/L)					
Fly Ash	23.1	5.8	6.3	15.7	1.8
Slag	3.6	ND	2.1	0.2	ND
OPCC Specimens	ND	ND	ND	ND	ND
SBCC Specimens	0.02	ND	ND	ND	ND
Regulatory Limits	—	5	15	5	1

ND: denote not detected

¹ The limit of detection for Zn ≤ 20 ppb; Cr ≤ 10 ppb; Cu ≤ 10 ppb; Pb ≤ 2 ppb; Cd ≤ 10 ppb

Table 4. Air Content, Chloride Content and Unit Weights for Fresh Concrete.

Notation	Plain Concrete			Slag-blended Concrete		
W/C ratio	0.68	0.52	0.36	0.68	0.52	0.36
Air Content (%)	0.81	0.99	0.85	0.80	0.95	0.82
Chloride Content (kg/m ³)	0.059	0.056	0.051	0.050	0.044	0.037
Unit Weight (kg/m ³)	2.418	2.426	2.437	2.411	2.419	2.428

apparent from the characteristic broadened peak typical of the random packing of atoms and molecules. The figure shows that the slag contains large amounts of glass, as indicated by the broad diffuse bands between 24° and 37° (2θ), and without any peak. The material rich in amorphous SiO₂ is a characteristic of Pozzolanic material.

Test of Los Angeles Abrasion

The abrasive loss of coarse aggregate used in this study was 16.39%, which meets ASTM C131 (requiring that this metric be no more than 40%).

Tests of Toxicity Characteristic Leaching Procedure (TCLP)

Table 3 lists the results of TCLP tests. The leaching concentrations of Cr, Pb and Cd from the original fly ash exceed the regulatory threshold values, while the leaching concentrations of Zn, Cr, Cu, Pb and Cd from the fly ash slag are far below the regulatory threshold values. We failed to detect any leaching of these heavy metals from the OPCC and SBCC specimens. The reason may be that heavy metals in the original fly ash are immobilized in the glassy matrix of the Si-O network. Thus, the original fly ash is converted into dense, acid- and basic-resistant, low leaching slag after melting [16, 17, 21]. Hence, the TCLP results for all the slag, OPCC and SBCC specimens meet the current regulatory thresholds as specified by the EPA (see Table 3). This may imply that the reduction in leaching concentrations may be due to the evaporation of the chlorides of Pb, Cu and Cd. However, these gaseous elements can be captured by a simple scrubbing system and recycled to be a useful resource such as ZnO. Obviously, it is much safer than the direct discharge of this dissolution hazard of heavy metals exposed to the underground water, such as the case with the land-fill of MSWI fly ash (a current disposal method).

Test Results for Fresh Concrete

The slumps associated with the OPCC specimens with water/cementitious ratios of 0.36, 0.52 and 0.68 were 13.5 cm, 11.9 cm and 12.5 cm, respectively. The slumps of the SBCC specimens with those same water/cementitious ratios were 13.0 cm, 11.5 cm and 13.0 cm, respectively. The average slump was 12.5 cm. Slumps of both groups were close to the target slump of 12.5 cm, but the slumps of the SBCC specimens were somewhat lower than those of the OPCC specimens.

Suitable air content can increase the workability and uniformity of concrete and may decrease the amount of bleeding water in a concrete specimen. However, excessively high air content can decrease the compressive strength and durability of concrete. Table 4 shows the air content metrics for our fresh concrete. The average air contents of the OPCC and SBCC are 0.88% and 0.86%, respectively. These metrics meet relevant ACI design proportion limits (< 1.5%).

Elevated chloride content in concrete can cause the rusting of steel. Rusted steel swells and exerts pressure on the concrete, causing the concrete to crack and be crushed. Taiwan National Standard CNS regulations limit the chloride content of pre-stress concrete to 0.15 kg/m³ and that of reinforced concrete to 0.3 kg/m³. Table 4 shows the chloride content readings of our fresh concrete samples. The average contents of OPCC and SBCC are 0.051-0.059 kg/m³ and 0.037-0.050 kg/m³, respectively. Both are far below the threshold values.

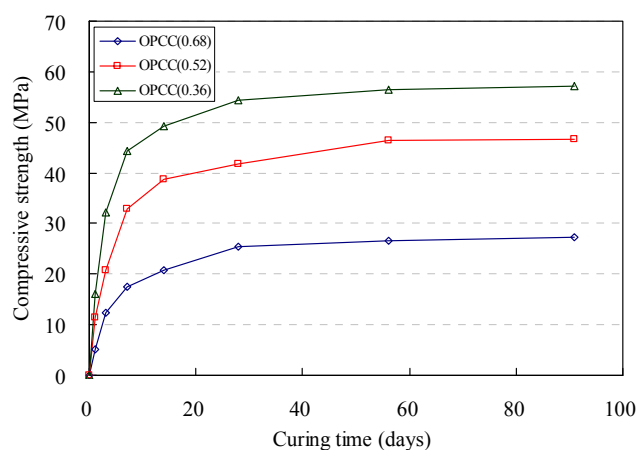
Table 5 lists unit weights for both fresh and hardened concrete. The unit weight of fresh concrete increases with a decreased water to cementitious (W/C) ratio. This is because the concrete with a

Table 5. The Unit Weights of Fresh and Hardened Concrete.

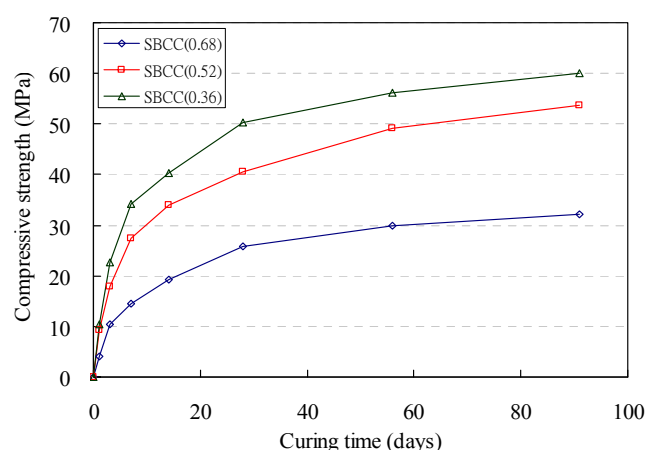
(Water/ Cementitious Ratio)	Plain Cement Concrete		Slag-blended Concrete	
	Fresh	Hardened	Fresh	Hardened
0.36	2.437	2.391	2.428	2.372
0.52	2.426	2.366	2.419	2.355
0.68	2.418	2.340	2.411	2.331

Table 6. The Setting Times of Reference Cement Concrete and Slag-blended Cement Concrete (Hours: Minutes).

Water/Cementitious ratio	Plain concrete		Slag concrete	
	Initial time	Final time	Initial time	Final time
0.36	04:38	06:40	04:46	07:12
0.52	04:49	06:56	05:09	07:25
0.68	05:03	07:40	05:29	07:56



(a)



(b)

Fig. 4. Evolution of Compressive Strength in (a) Ordinary Portland Cement Concrete and (b) Slag-blended Cement Concrete.

W/C ratio of 0.36 contains more cement per unit volume than those with W/C ratios of 0.52 and 0.68. The unit weights for hardened concrete samples are listed in Table 5. The unit weights for the OPCC and SBCC specimens are in the ranges of 2,340–2391 kg/m³ and 2331–2372 kg/m³, respectively. The weights of the SBCC specimens were slightly lower than those of the OPCC specimens,

because the unit weight of the slag with S.G.=2.78 was smaller than that of the cement with S.G.= 3.14. In general, the lower the water to cementitious ratio, the higher the unit weight. The average OPCC unit weight is 2.366 t/m³ and that of SBCC is 2.353 t/m³, which is somewhat lower than that of OPCC.

Table 6 shows the initial and final setting times of the concrete with three water/cementitious ratios. The initial OPCC setting time is in the range of 4.63 to 5.05 hours, and the final setting time is in the range of 6.67 to 7.67 hours. The initial SBCC setting time is in the range of 4.77 to 5.48 hours, and the final setting time is in the range of 7.20 to 7.93 hours. The initial and final setting times of SBCC are longer than those of OPCC. For example, at a water to cementitious ratio of 0.68, the initial setting time and the final setting time for SBCC are 26 min and 16 min, respectively, which is somewhat longer than for OPCC. These small differences in setting times will only minimally impact possible real-world construction applications.

Compressive Strength Tests for Plain and Slag Concrete Cylinder Specimens

The compressive strength test results for the three water/cementitious (w/c) ratios of concrete cylinder specimen are as follows:

(1) W/C = 0.36

For the specimens aged less than 28 days, the compressive strengths of the SBCC group were lower than those of the OPCC group (reference group). The strength of 1 day SBCC specimen was 64% that of OPCC specimen, and the strength of 28-day SBCC was 93% that of OPCC specimen. However, the compressive strengths of SBCC specimens with ages of 56 days and 90 days were equal to or higher than that of the reference group (OPCC specimens) by 100% and 105%, respectively. Fig. 4 shows relevant strength evolutions.

(2) W/C = 0.52

For specimens aged less than 28 days, the compressive strengths of the SBCC group were below those of the OPCC group. The strength of the SBCC group after 1 day was 83% that of the reference group (OPCC). After 28 days, the SBCC group reached 97%; after 56 days, 106%; and after 90 days, 115%. The resulting strength evolutions are shown in Fig. 4.

(3) W/C = 0.68

The tendency of the strength evolution at w/c = 0.68 was similar to the above two cases. The compressive strengths for the 1-, 28-, 56- and 90-day SBCC specimens were 77%, 102%, 113% and 118%, respectively, that of the OPCC specimens. The associated strength evolutions are shown in Fig. 4.

These results suggest that the compressive strengths of the SBCC specimens at early curing stages are lower than those of the OPCC groups, but because of the Pozzolanic reaction in slag concrete, their strengths surpassed those of the reference group at later stages.

Figs. 4(a) and 4(b) show the curves of three water to cementitious ratios for the OPCC and SBCC groups. It is clear that the strength evolution tendencies are approximately parallel. The curves of the lower water to cementitious ratio specimens contained larger cement and exhibited higher compressive strengths, consistent with the mechanical theory of concrete. Fig. 5 shows that the strength

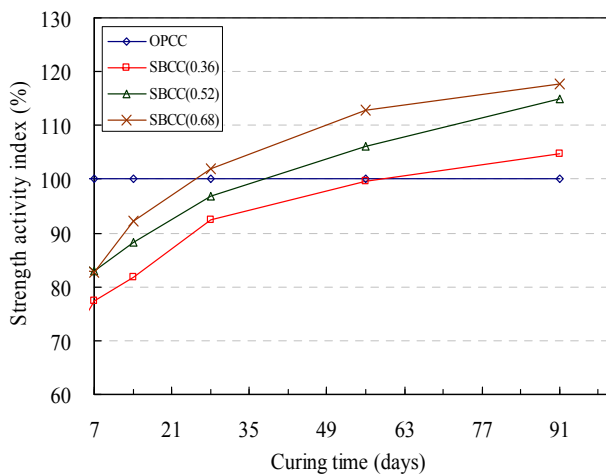


Fig. 5. Relationship between the Strength Activity Index of Slag-cement Concrete and Curing Age.

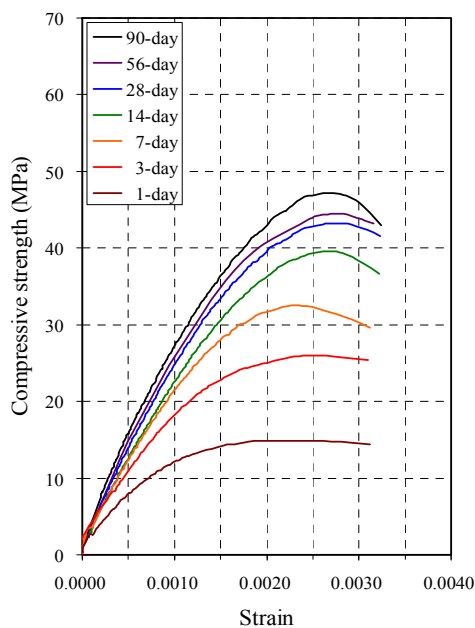
activity index of the SBCC specimens relative to the OPCC specimens increases with curing age. The strength activity indices of SBCC (0.36), SBCC (0.52) and SBCC (0.68) specimens after 7, 28, 56 and 90 days were 77–83%, 93–102%, 100–113% and 105–118%, respectively, that of the OPCC specimens. This result may suggest that the strength activity indices of the SBCC specimens are weaker than those of the OPCC specimens at the early stages (1 to 14 days). These SBCC specimens are then similar to the OPCC specimens at 28 days and eventually exceed those of the OPCC specimens after 56 and 90 days. The greater the water to cementitious ratio, the higher the strength activity index of the SBCC specimens is due to a stronger Pozzolanic reaction. Relevant variations are shown in Fig. 5.

Fig. 6 shows the longitudinal stress/strain curves for the OPCC

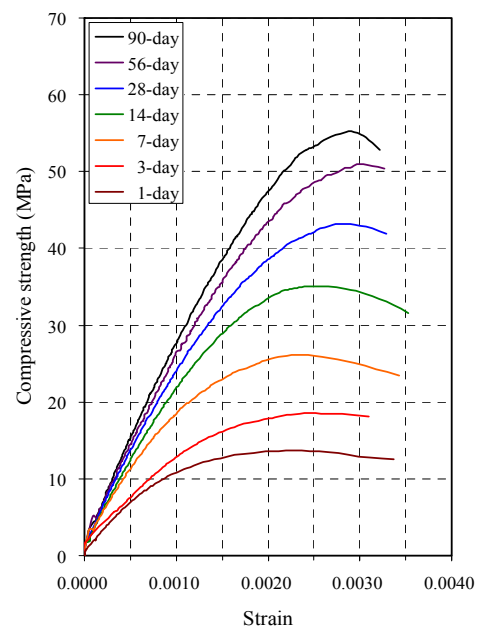
and SBCC specimens with $w/c = 0.52$ for curing periods of 1, 3, 7, 14, 28, 56 and 90 days. The longitudinal strains are not significantly different between the two groups. The intervals from the stress-strain curves at ages of 28, 56 and 90 days for the SBCC specimens are substantially greater than those for the OPCC specimens of the same ages. The increased rate of compressive strength evolution of the SBCC specimens during the same curing period was greater than that of OPCC specimens. The greater interval of the stress-strain curves and the greater increased rate of strength improvement during these curing periods may be linked with the Pozzolanic reaction in slag concrete. This tendency is similar to the evolution of the compressive strength of the OPCC specimens and the SBCC specimens, as shown in Figs. 4 and 5. Fig. 6 suggests that failure strains for the 1- and 3-day specimens are not apparent, and the stress-strain curves are flat. Failure strains for the 14-, 28-, 56- and 90-day specimens are clear and quite similar to the failure strains of those between 0.0025 and 0.003 measured for both groups.

Elastic Modulus Analysis

The strain ϵ_c obtained from the stress-strain curve at $0.45 f_c'$ was used to calculate the elastic modulus E_c using the equation $E_c = 0.45 f_c' / \epsilon_c$. The average values of the elastic modulus E_c for all specimens are listed in Table 7. According to ACI-318 codes, given the predicted elastic modulus equation, we plotted E_c vs. $\sqrt{f_c'}$ for both OPCC and SBCC groups (see Fig. 7(a)). The elastic modulus shown in the regression equation is comparable with that of ACI-318 code [32]. The two linear regression coefficients are as follows:



(a) OPCC(0.52)



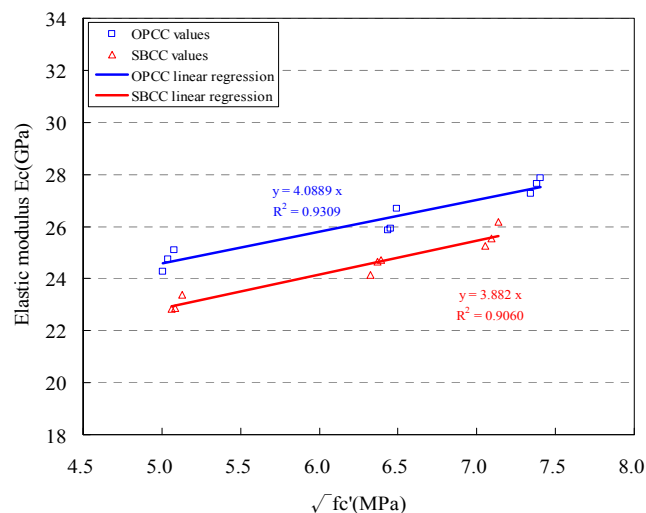
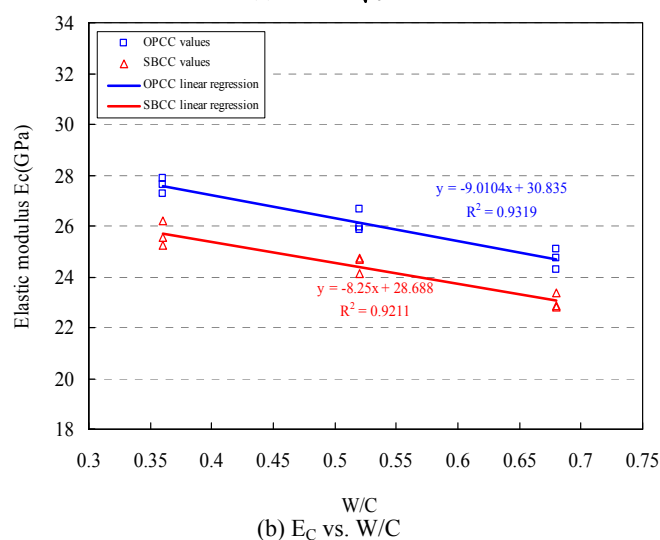
(b) SBCC(0.52)

Fig. 6. The Longitudinal Stress-strain Curves of the (a) OPCC (0.52) and (b) SBCC (0.52) Specimens.

Table 7. Elastic Moduli of Cured 28-day-old Concrete Specimens.

Notation	OPCC Specimens			SBCC Specimens		
W/C ratio	0.68	0.52	0.36	0.68	0.52	0.36
E_c (GPa) ^a	24.71	26.15	27.59	23.03	24.50	25.67

^a The E_c value was averaged across three test specimens

(a) E_c vs. $\sqrt{f_{c'}}$ (b) E_c vs. W/C**Fig. 7.** The Elastic Modulus, E_c , of the OPCC and SBCC Specimens and Its Correlation with the W/C and $\sqrt{f_{c'}}$ Metrics.**Table 8.** Compressive Strength Losses for OPCC and SBCC Cylinder Specimens Under Durability Testing.

Water/Cementitious Ratio	Strength Losses (%)	
	OPCC Specimens	SBCC Specimens
0.36	7.0	4.0
0.52	10.6	6.2
0.68	14.1	7.5

OPCC concrete:

$$E_c \text{ (GPa)} = 4.089 \sqrt{f_{c'}} \quad (R^2 = 0.931) \quad (1)$$

SBCC concrete:

$$E_c \text{ (GPa)} = 3.882 \sqrt{f_{c'}} \quad (R^2 = 0.906) \quad (2)$$

Our plots of E_c vs. W/C are shown in Fig. 7(b). The regression equations are:

OPCC concrete:

$$E_c \text{ (GPa)} = -9.010 \times (W/C) + 30.835 \quad (R^2 = 0.932) \quad (3)$$

SBCC concrete:

$$E_c \text{ (GPa)} = -8.250 \times (W/C) + 28.688 \quad (R^2 = 0.921) \quad (4)$$

The above four regression equations imply that the effects of the compressive strength ($\sqrt{f_{c'}}$) and the water to cementitious ratio (W/C) on the elastic modulus of both concrete groups are quite significant. The four regression equations with correlation coefficients of above 90% should yield suitable predictions for the elastic moduli of both the concrete groups studied.

Durability Test

Table 8 shows the reduction in compressive strength of the concrete-cylinder specimens after being cured for 28 days and then immersed in saturated sodium sulfate solution (Na_2SO_4) and hot dried over five cycles. The higher the W/C ratios, the greater the reduction in compressive strength. The reduction for the OPCC and SBCC specimens were 7.0-14.1% and 4.0-7.5%, respectively. The specimens with higher W/C had the greater pore volume within the interior of concrete, which resulted in weaker resistance in the penetration of Na_2SO_4 solution. The loss of compressive strengths in SBCC specimens is about 3.0-6.6% less compared to those of the OPCC specimens. This is because the formation of CSH colloids transfer from $\text{Ca}(\text{OH})_2$ during the Pozzolanic reaction in the slag-blended cement concrete greatly decreases the leachable lime content [35] and may similarly increase the durability of the concrete.

Conclusions

In this study, 20 wt.% cement replacement with MSWI fly ash slag powder was used to prepare slag-blended cement concrete (SBCC) specimens, which were then compared with ordinary Portland cement concrete (OPCC) specimens. The compressive strengths and related characteristics of the slag concrete were tested to evaluate the feasibility of recycling MSWI fly ash slag for partial cement replacement in concrete. Our conclusions are as follows:

- (1) Comparisons of the compressive strength between the specimens of SBCC and OPCC show that the compressive strengths of the SBCC specimens aged 7, 28, 56 and 90 days were 77-83%, 93-102%, 100-113% and 105-118%, respectively, that of the OPCC group (reference group).
- (2) The greater the water to cementitious ratio, the higher the strength activity index of the SBCC specimens because of the stronger Pozzolanic reaction.

- (3) The elastic moduli of the SBCC specimens were similar to those of the OPCC specimens. The variations between the stress-strain curve intervals for various ages of specimens and the trends in compressive strength evolution were similar across both groups.
- (4) The values of air content, unit weight and chloride content for the SBCC specimens were very close to those of the OPCC specimens.
- (5) The slumps of both groups were similar, and the differences in initial and final setting times between the two groups were similar. The differences observed should exert negligible impact on practical construction applications.
- (6) Results of durability testing show that the strength losses of the SBCC specimens were less pronounced than those of the OPCC specimens. The SBCC samples exhibited better corrosion resistance.

In this study, our test results from the SBCC specimens suggest the feasibility of recycling MSWI fly ash slag for partial cement replacement in concrete. Recycling toxic MSWI fly ash for use in concrete pavement construction can be environmentally safe and may address the need for sustainable development practices.

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