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Performance of Self-compacting Concrete with Stainless Steel Slag Versus Fly Ash as Fillers: A Comparative Study

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Abstract
Recently, stainless steel slag -a byproduct of manufacturing stainless steel is accepted as a cementitious material, the chemical characteristics of which are highly variant. This study reuses two types of stainless steel reducing slag with specific surface area of 1766 cm^2/g (S1) and 7970 cm^2/g (S2) in developing self-compacting concrete (SCC). Particularly, two S2-blended SCCs incorporating with S1 and fly ash as fillers (calling as S-mix and F-mix) were prepared for a comparative investigation. In both SCCs, ordinary Portland cement was replaced by S2 with various ratios (from 0 % to 50 %, increment 10 %). Testing results show that in fresh state, the F-mix exhibits higher workability and longer initial setting time than those of S-mix. In hardened state, 10 % compressive strength loss was realized as increasing S2 content up to 30 % in the both SCCs; the strength of F-mix is up to 1.9 times of S-mix at the same rate of S2 replacement. Water absorption of the F-mix was below 3 %, suggested as a "good" quality concrete; whilst the S-mix could be longs to an "average" one. Resistivity and sulfate resistance of F-mix are considerably higher than those of S-mix. Moreover, based on the obtained data, compressive strength and electrical resistivity are correlated well with a logarithmic form.

Keywords
stainless steel reducing slag, filler, self-compacting concrete, workability, compressive strength, durability

1 Introduction

Self-Compacting Concrete (SCC) was first developed in Japan in 1980s to obtain good quality concrete without needs of vibrated equipment or skilled labor [1]. In recent years, there has been widespread applications of SCC as in the cases of the ready-mixed concrete or typical precast concrete due to excellent capability of the self-filling/self-compacting under its own weight through densely congested reinforcements or framework corners. This special concrete could be obtained by increasing the amount of fine materials (known as filler, passing the 0.125-sieve) without changing the water content in mixture proportion in comparing to normal concrete. So, maintaining high workability with low water-cement ratio is a key ensuring success for SCC mix design. Finely crushed limestone is commonly used in SCC mixtures to improve rheological properties and durability. In spite of this, this material is seldom expensive and unavailable for some regions. It is reported in the literature that industrial by-products or wastes (inert or active) like fly ash, blast furnace slag, silica fume, ceramic powder would be potential alternative fillers [2].

Stainless steel slag is a byproduct of manufacturing stainless steel from scrap iron in electric furnace arcs. Approximately, producing one ton of stainless steel would generate about 1/4–1/3 ton of slag wastes, including oxidizing slag and reducing slag associated with the preprocessing (steel making) and post processing (steel refining) stages, respectively [3, 4]. The former slag is a byproduct of aggregate, and the latter is formed as dust with mean particle size of around 3 µm. In 2018, world production of stainless steel exceeded 50.7 million tones [5], accounted for 12.67–16.90 million tons of steelmaking slags were produced. These slags with a considerable amount are generally treated as wastes and dumped in landfills which

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creates seriously environmental issues [4, 6]. In different with ground blast furnace slag (BFS), widely used as a mineral admixture for blended cement, application scope of the steel slag is limited to make aggregates for concrete production or to make roadbed material after undergoing stabilization treatments [7]. Therefore, enhancement of utilization of the steel slag in construction sector for sustainability has attracted great attention of many researchers.

Chemical components of the steelmaking slag are quite similar to those of blast furnace slag or Portland cement, such as high CaO, Al_2O_3, MgO, and low SiO_2. However, high variation of the oxides composition is basically observed for the steel slags [8, 9]. Few scholars have studied on cementitious performance of stainless steel slags and concluded that these slags are possibly used as a supplementary cementitious material and the main hydration product of which is C-S-H gels [9, 10]. According to these research, hydraulic reactivity of stainless steel slags highly depends on their chemical composition and mineralogical characteristics. It agreed that extremely poor pozzolanic activity causing by the slow cooling and relatively high content of inert phases of steel slag in comparing to Portland cement would be remarkable issues. Kriskova et al. [9] stated that if used stainless steel slag solely as a binder, the compressive strength after 90 days is about 20 % of the corresponding OPC. However, prolonged milling stainless steel slag caused the increase of surface area by more than 10 times; and this mechanical activation effectively increased the hydraulic activity of the slag. A similar trend could be found on the experimental work by Saly et al. [10]. They established a comparative investigation on basic oxygen-furnace carbon slag (BOF-C) and electric-arc-furnace stainless steel slag (EAF-S) regarding the cementitious performance. Their results indicated BOF-C had higher strength activity index (SAI); and EAF-S tends to extend the setting time of blended cement even at low replacing ratio. This means that stainless steel slag was not as good as carbon steel slag in providing mechanical strength of blended cement. Rosales et al. [11] revealed that replacing 10 % cement with stainless steel slag in mortar blends could improve the compressive and flexural strength; enhancement of these strengths could be further obtained if the slag was crushed. Nevertheless, beyond this replacing level the mechanical strength of blended cement gradually decreased; while, the shrinkage increased excessively. A study of our group [8] presented the replacing OPC by stainless steel reducing slag (SSRS) with Blaine's fineness of 4400 cm^2/g up to 30 % by weight resulted in higher compressive strength comparing of cement mortar, specified by ASTM C150 [12]. In addition, the SAI value of this SSRS was comparable to that of blast furnace slag Grade 80.

Volume instability (swelling) due to presence of free lime (*f*-CaO) and magnesia (*f*-MgO) in steel slag would be a serious issue when producing construction materials [11]. Therefore, the steel slag must be stabilized/ solidified before its applications to avoid undesirable expansion. In practice, there are several methods of slag treatment such as: weathering (leaving in outdoor environment at least six months), steam aging, autoclave technique. In addition, combined use with inert materials or ternary blends with siliceous material and cement/ or hydrated lime would be appropriate to eliminate the soundness phenomenon [13]. On the other hand, due to addition of ferrochrome and nickel during processing, SSRS contains toxic ingredients (i.e., chromium, lead, nickel, cadmium, …). These heavy-metal ions such as Cr^{6+} leaching from landfilled slag threat to both human health and environment. Therefore, making the slag to be non-hazardous prior its applications or landfills is mandatory [4].

In this study, a comparative study on characteristics of two types of stainless steel slag-blended SCCs (denoted as S-mix and F-mix) incorporated with different fillers (steel slag and fly ash) was made aiming to access the feasible use of stainless steel slag as both of cement replacement and filler, increasing the sustainability. For this target, two kinds of stainless reducing slags; S1 (Blaine's fineness of 1766 cm^2/g) and S2 (Blaine's fineness of 7970 cm^2/g) were employed as filler and cementitious substitution, respectively. In order to deeply understanding effect of the stainless steel slags, fresh and hardened properties of the SCCs were examined.

2 Materials and methods

2.1 Materials used and mix proportions

(1) *Cement*. A Portland cement Type I/42.5R with a specific surface area of 3800 cm^2/g (Blaine's fineness) and a specific gravity of 3.15, conforming to the ASTM C150 Type I Portland cement.

(2) *Mineral admixtures*. Two kinds of water-quenched stainless steel reducing slag with Blaine's fineness of 1776 cm^2/g (denoted as S1, passing the 75 μm sieve) and 7970 cm^2/g (denoted as S2, passing the 25 μm sieve) were used as the filler and cement substitute, respectively. The relative specific density of S1 is 2.85 and respective value for S2 is 2.83. These slags are completely met

the environmental acceptance based on the Toxicity Characteristic Leaching Procedure (TCLP test) [14], as seen in Table 1. In addition, common fly ash (FA) Type F was used as filler being alternative to S1. The photos of cement and mineral admixtures used in this study were shown in Fig. 1; and their chemical and physical properties were reported in Table 2.

(3) *Aggregates*. Coarse aggregate (C/A) are made from crushed stone and has the fineness modulus of 6.96 and the specific gravity of 2.63. Meanwhile, fine aggregate (F/A) is river sand with fineness modulus of 2.68 and the specific gravity of 2.62. The particle sizes of coarse and fine aggregates are fully satisfied the ASTM C33 [15] for making concrete.

(4) *Addictive*. The polycarboxylate-based supper plasticizer (SP) conforming to the ASTM C494 [16] Type F was used as a high-range water-reducing admixture (HWRA).

(5) *Water*. The tap water from the laboratory was used for mixing.

In regards to mix proportion, the DMDA (densified mixture design algorithm) [17] was applied to design SCC mixtures. The DMDA concept is based on assumption that the best characteristics of concrete would be achieved as its density is high; and for this idea, a fine particle component (calling as filler) is added to fill the voids between aggregate system as much as possible. Two SCC mix groups incorporated with the same amount of FA and S1 (fineness of 1766 cm^2/g) as fillers (coding as F-mix and S-mix) were separately developed for the investigation. The water/powder ratio (w/p) was chosen at 0.32 after several trials and the total mass of powder were fixed at 577 kg/m^3. Moreover, in

Table 1 Result of TCLP test for SSRS used in this study

Items	Toxicity Characteristic Leaching Procedure (mg/L)						
	Cr	Cu	Cd	Pb	As	Hg	Cr^{+6}
This slag	0.18	<0.05	< 0.01	0.31	0.0012	< 0.0005	< 0.5
Standard	5.0	-	1.0	5.0	5	0.2	2.5

(a) OPC (b) S1 (c) S2 (d) Fly ash

Fig. 1 Photos of powder materials used in this study

Table 2 Oxide components and properties of OPC, SSRS and fly ash used in this study

Analysis results	OPC, Type I	SSRS	Fly ash
1. *Chemical analysis* (%)			
Silicon dioxide, SiO_2	20.87	22.97	63.73
Aluminum oxide, Al_2O_3	4.56	4.0	22.98
Ferric oxide, FeO/Fe_2O_3	3.44	0.08	4.72
Calcium oxide, CaO	63.14	51.26	1.79
Magnesium oxide, MgO	2.82	8.10	0.71
Sulfur trioxide, SO_3	2.06	-	0.57
Titanium oxide, TiO_2	-	0.09	-
Loss on ignition, L.O.I	2.30	-	-
Basicity ratio, $CaO/(Al_2O_3+SiO_2)$	2.40	1.90	0.02
2. *Physical properties*			
- Fineness (cm^2/g)	3851	1766 (S1); 7970 (S2)	3480
- Specific gravity	3.15	2.85 (S1); 2.83 (S2)	2.28

Table 3 Mix proportion for $1m^3$ SCC mixtures used in this study and the slump flows

Mix ID	w/p	S2 (%)	OPC (%)	Fly ash (kg)	S1 (kg)	Powder (kg)	C/A (kg)	F/A (kg)	SP (kg)	Slump flow (mm)
F00	0.32	0	100	108	-	577	829	791	6.63	633
F10		10	90	108	-	577	829	791	6.60	698
F20		20	80	108	-	577	829	791	6.57	663
F30		30	70	108	-	577	829	791	6.55	628
F40		40	60	108	-	577	829	791	6.52	613
F50		50	50	108	-	577	829	791	6.49	568
S00		00	100	-	108	577	829	791	6.63	523
S10		10	90	-	108	577	829	791	6.60	533
S20		20	80	-	108	577	829	791	6.57	548
S30		30	70	-	108	577	829	791	6.55	608
S40		40	60	-	108	577	829	791	6.52	638
S50		50	50	-	108	577	829	791	6.49	653

Notes: (1) S1: SSRS with Blaine's fineness of 1766 g/cm^2 (filler); and S2: SSRS with Blaine's fineness of 7970 g/cm^2 (cement substitution); (2) C/A coarse aggregate; F/A fine aggregate; (3) Powder = OPC + S2 + filler (S1 or FA).

each group, the OPC was partially replaced by S2 (fineness of 7970 cm^2/g) with various ratios, changing from 0 to 0.5 (increment 0.1). A SP dosage of 1.5 % powder mass was added to all SCC mixtures to maintain concrete workability. In summary, a total of 12 mixtures were generated for this study as shown in Table 3.

2.2 Testing items and methods

In this experiment, following testing procedures were adopted:

(1) *Workability*: Slump flow test, slump flow test and V-funnel test as per JSCE [18].

(2) *Setting time*. Measuring the initial and final setting times according to ASTM C403 [19].

(3) *Mechanical properties tests*. The compressive strength test and ultrasonic pulse velocity (UPV) test were together performed on the cylindrical specimens at different curing ages (1-, 7-, 28-, 56-, and 91 days).

(4) *Durability tests*. The water absorption, electrical resistivity, resistance to sulfate attack were measured following the relevant ASTMs.

Table 4 shows the details of mechanical properties and durability for SCC used in this study.

Each reported measurement was triplicated and the average values were reported.

3 Results and discussion

3.1 Workability

In this study, the workability in term of flowability/ filling ability of SCC mixtures was discussed through on measurement of slump flow, V-funnel test, and T_{500} slump-flow time. The slump flow (SF), known as the mean diameter of mass concrete after removing the standard cone demonstrates the flowability of SCC under its own weight. As reported in Table 3, the F-mix and S-mix have the SF values in ranges of 568–698 mm and 523–623 mm, respectively. These SF ranges were totally conformed the SCC requirements of 500–700 mm, recommended by JSCE. Out of the required range, the phenomenon of bleeding or segregation of fresh SCC would be taken place.

In general, flowability of SCC is mainly influenced by material characteristics (particle shape and particle-size distribution, surface texture), mixing water, and chemical admixture as well. The F-mix (using FA as filler) exhibits a greater slump flow than the S-mix (using S1 as filler) at any cement replacement level. This observation indicated that FA provides an important impact in filling the voids with aggregates; and less paste volume therefore required for lubricating aggregate particles [17]. Moreover, small size particles in spherical shapes of FA in nature tends to reduce the size and volume of voids, resulted in decreasing friction of aggregate system; and hence this in turn enhanced the flowability [25]. Besides, to attain an equivalent workability, SCC composites containing FA commonly requires a lower dosage of SP than other mineral admixtures, previously published [26]. In the present study, SP content was almost kept at constant for all mixtures (1.5 % mass of powder), therefore a better SF was acquired for F-mix.

In addition, increasing S2 replaced OPC in mixture leads to change the filling capacity with different ways. For F-mix, as the cement replacing ratio of 0.2 or less, the slump flow is higher than that of the control (pure OPC); whilst, above this replacement ratio, loss of workability was clearly observed. The reason for this may be attributed to the ultra fine of cement substitution (S2) at significantly high level, and its rough texture which tends to require more mixing water. The variation of slump flow obtained in the experiment for F-mix is in agreement with those by Wang and Lin [27]. On the other hand, an increase in slump flow with higher S2 percentage replacing to OPC in blends is observed for the S-mix.

In addition to the slump flow test, measurement of the V-funnel and slump-flow times were carried out to investigate the fluidity performance which indicates the segregation resistance ability of SCC. The V-funnel time (T_{VF}) is defined as elapse time in seconds from opening the bottom gap of the V-funnel apparatus to the moment when the light at the bottom is seen from the top) for all SCC mixtures; meanwhile, the slump-flow time refers to the times to reach the slump flow of 500 mm, called as T_{500}. Fig. 2 plots the relationship between the T_{500} and T_{VF} based on testing data of this study. It can be revealed that the obtained times (T_{500} and T_{VF}) are mostly within the targeted range for SCC, recommended by JSCE. This result deduces that most of SCC

Table 4 Testing items and number of specimens (100 × 200 mm cylinder) for hardened SCCs

Testing items	Testing ages (days)	ASTM standards	No. of specimens
Compression test	1, 7, 28, 56, and 91	ASTM C39 [20]	180
UPV test		ASTM C597 [21]	108
Absorption test	28, 56, and 91	ASTM C642 [22]	180
Electrical resistivity test	1, 7, 28, 56, and 91	ASTM WK37880 [23]	36
Sulfate resistance test	28	ASTM C1012 [24]	

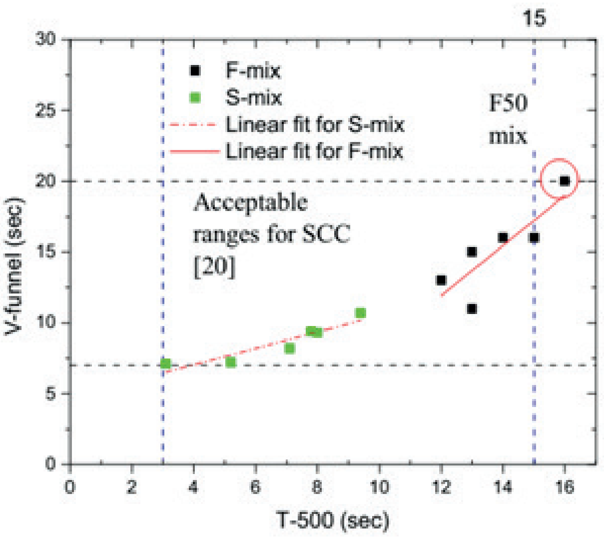

Fig. 2 Relationship between T500 times and V-funnel times (TVF) for all SCC mixtures

mixtures perform excellent fluidity with maintained homogeneity in fresh state; only F50 mixture failed the acceptance due to the T_{500} over the limitation (>15 s), unexpected for construction due to stickiness. A tendency of higher viscosity was observed for SCC prepared with FA (F-mix), evidenced by the more both T_{500} times and T_{VF} in comparing with S-mix. Moreover, the longer T_{500} time usually accompanied with extension of T_{VF}. This correlation was in agreement with previous publications [25, 28].

3.2 Setting time

Fig. 3 shows the initial setting (IS) and final setting (FS) times for all SCCs mixtures obtained from the experiment. It is clearly seen that in the case of the control, the setting times of S-mix are shorter than those of F-mix (the time differences are 6.67 *hours* and 4.85 *hours* for IS and FS, respectively). Latent hydration rate of FA in nature is possibly attributed to the retardation of solidification for F-mix.

Nevertheless, when increasing ratios of SSRS (S2) substituting to OPC, the setting times of the two SCC composites changed in different ways. For instance, as a given S2 replacement ratio, the S-mix had a faster IS and a slower FS times than those of the respective F-mix. Moreover, at S2 replacement level of 30 % or less, the IS and FS times of S-mix were increased by up to 1.3 (for IS) and 1.5 (for FS) times of the control (without S2). This result was inversely varied when observed on the F-mix in which the setting times (IS and FS) were mostly reduced as demonstrated in Fig. 3. Meanwhile, at S2 replacement ratio beyond 30 %, the setting times of both SCC mix groups (F-mix and S-mix) sharply decreased.

It is generally known that replacing OPC with mineral admixtures (e.g., slag, fly ash, silica fume) tends to retard the hydration of concrete due to lack of OPC since cement was partially replaced by other admixtures [29]. In addition, presence of SP in concrete mixtures modified with mineral admixture could cause a further delay on setting time, depending on type and dosage of SP used, type of cement and temperature [30]. Absorption of SP over cement particles' surface resulted in limitation of inter-particle contact and higher "effective superplasticizer dosage" (denoted as mass ratio between SP and OPC) comparing to pure OPC mixture would be responsible for slow hydration of cement paste.

Increasing EAF stainless steel slag content (from 0 % to 60 %) in blended cement resulted in extending hardening times, reported by Saly et al. [10]. In contract, according to the testing results, acceleration of setting process of the S2-blended mixtures was recognized. This characteristic would be linked to significantly large specific surface area of the cement substitution in comparison with OPC (7970 cm^2/g and 3800 cm^2/g). Very fine particles of the S2 slag could require more water demand, and produced a denser paste that could accelerate the setting process. In this case, effectively dispersing cement particles in water pushing the hydrated reaction rate might be additional factor for reducing time of setting [29]. These effects, hence, could effectively overcome the influence of OPC reduction and higher effective SP dosage in SCC mixtures containing high amount of mineral admixture [31]. It can be concluded that the interaction effect between the slag replacement and SP used were considerably attributed to speed up the setting time.

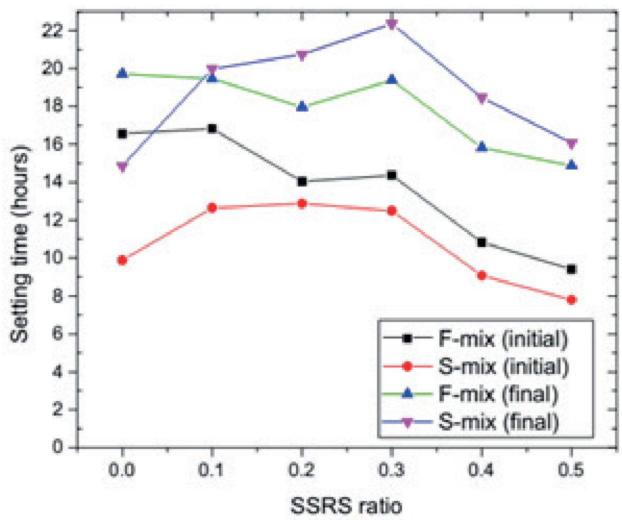

Fig. 3 Initial and final setting times for F-mix and S-mix

3.3 Compressive strength

3.3.1 Effect of SSRS replacing ratio on compressive strength

Effect of cement substitution level on compressive strength of both SCCs is demonstrated in Figs. 4 and 5. The highest strength for each SCC was observed on the controls (69.48 MPa for F-mix and 38.12 MPa for S-mix); the more reduction of compressive strength was realized at all testing ages on the specimens with higher ratio of S2 replacing to OPC. In particular, for F-mix, at 50 % cement substitution, the relative strength (defining as the strength ratio of S2-blended specimens and the control) at 1-, 7-, and 91 days is 0.38, 0.53, and 0.74, respectively; the corresponding relative strength for S-mix is 0.35, 0.67, and 0.7. The strength loss causing by cement substitution was extremely high as early ages (1-, 7 days), especially at high level of S2 replacement. At longer ages, the strength gain was gradually enhanced as a result of additional hydration of the cement replacement, which is popularly known being much slower activity at early ages than that of Portland cement. This is consistent with previous works conducting on steel/stainless making slag concrete [10, 32]. Moreover, the relative strength of F-mix is obviously increased with ages; meanwhile, for S-mix, there is marginal variation on relative strength after 7 days, demonstrated in Fig. 4. This is an indication of faster strength development of S-mix comparing to F-mix, supported by the fact that strength gain after 28 days ($f_c(t) / f_c(28)$) of the F-mix is much higher than that of S-mix. Comparing to the strength evolution of normal concrete, provided by ACI-209 [33], faster strength development was observed on F-mix; while a slower rate of strength formation was occurred for S-mix (see Fig. 5). The difference in strength evolution between two SCCs could result from higher reaction degree of slag (S1) than FA at room temperature.

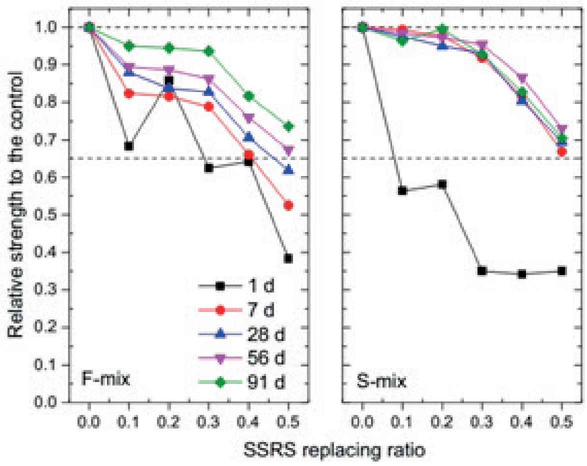

Fig. 4 Variations of relative strength to the controls for F-mix and S-mix

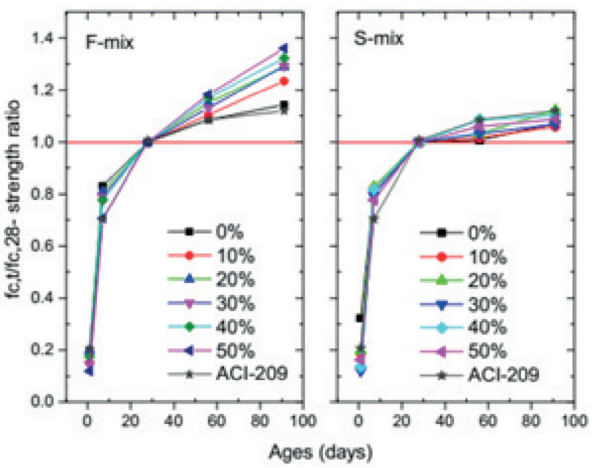

Fig. 5 Profile of strength development ratio (strength ratio between at testing ages and 28 days, $f_c(t) / f_c(28)$

3.3.2 Effect of fillers on compressive strength

Fig. 6 shows the comparison on compressive strength between F-mix and S-mix in term of strength ratio ($R_{F/S} = f_{c,F}/f_{c,S}$) at various ages. It can be seen that at the same level of cement substitution, the F-mix specimens have the compressive strength to be as much as 1.03–1.91 times of the respective S-mix ones. With the exception of the strength after 1 day (unstable), the difference in strength between the two SCCs increases along with the curing ages. At 7 days, the strength ratio $R_{F/S}$ is mostly below 1.5; meanwhile, the strength ratio $R_{F/S}$ could reach to 1.9 after 91 days. This strength ratio implies that a better strength development of the F-mix is more pronounced as a result of pozzolanic activity of FA at later ages. Besides, finer FA particles promoted the filling effect compared to those of the S1 slag. In other words, the hydrated characteristic

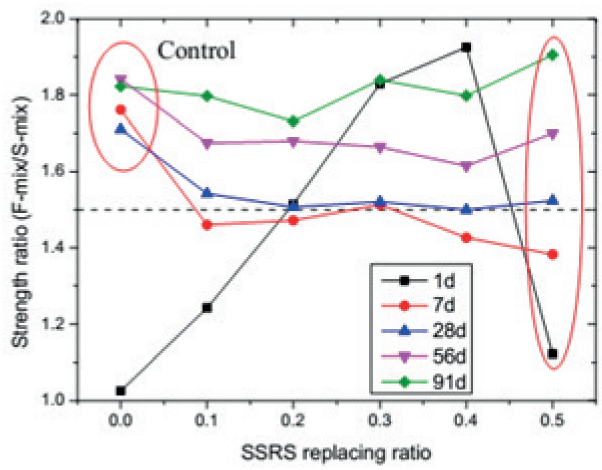

Fig. 6 Comparison of compressive strength between F-mix and Smix at various ages

of the filler had an additional impact on development of mechanical strength of SCC accompanied with the binders. Regarding to the mechanism of pozzolanic reaction, FA consumes the $Ca(OH)_2$ to form calcium silicate hydrate (C-S-H) and improves microstructure of the interaction transition zone (ITZ) at the later ages [29]. Contrary to this, steel slag has oxide constituents to be similar to cement, which is CaO-rich, and low rate of hydration due to low C_3S and β-C2S content. During hydrated reaction of steel slag, the $Ca(OH)_2$ is generated along with C-S-H [9]. As a result, the ITZ improvement of the slag was not as good as the FA. The observation from this study is consistent with earlier research, reported by Mengxiao et al. [34].

3.4 Ultrasonic pulse velocity (UPV)

It is widely accepted that UPV is one of performance-based specification of mechanical strength of concrete; the higher UPV the higher compressive strength is, but not necessary in similar variation. The factors significantly influencing to compressive strength might have minor effect on UPV and vice versa. Fig. 7 demonstrates evolution of UPV transmitted through the SCC specimens prepared with different cement replacing ratios. Obviously, UPV steadily develops with ages along with the hydration process of cementitious materials, but substantially decrease as cement replacing ratio increases. The trend in UPV variation could be found elsewhere [35]. At early ages (1 day), when only OPC participated the reaction and fly ash/ slag might be not reacted yet, UPV of two SCCs (F-mix and S-mix) are similarly low, ranging between 3000–3700 m/s; meaning that the different use of fillers (FA and S1) did not make the differentiation in UPV. After first-seven days, however, the UPV of F-mix considerably increases by 24 % and 39 % corresponding to the cement replacing ratio of 0 and 0.5, respectively; and the respective increasing rate for S-mix is 24 % and 33 %. UPV thereafter is continuously growing but with a slow rate. This tendency of UPV development is also in agreement with that of compressive strength mentioned above, merely not necessary similar proportion. In addition, at a given level of cement substitution, UPV in concrete with FA filler (F-mix) is higher than that of concrete containing S1 (S-mix). After 28 days, all the F-mix samples have UPV above 4500 m/s, categorized an "excellent" quality concrete [35]; meanwhile, for S-mix, only specimens with S2 replacement of 0.3 or less could meet the equivalent quality. The reason for this could be attributed to the better filling effect of hydrated products when FA slowly reacted with $Ca(OH)_2$ in comparing to the S1 as role of a filler.

Moreover, Fig. 8 illustrates the correlations between UPV and compressive strength for two SCCs based on obtained data. It is recognized that best-fit exponential functions could express well the UPV-strength relationship, evidenced by excellent coefficient of determination (R^2 = 09819 and R^2 = 0.9677, for F-mix and S-mix, respectively), as seen in Eqs. (1) and (2). An analogous formula expressed well the UPV-compressive strength relationship has been published in the literature [7] (see Fig. 8).

For F-mix:

$$f_c = 0.0685 \times e^{0.0014 \times UPV}; (R^2 = 09819). \quad (1)$$

For S-mix:

$$f_c = 0.070 \times e^{0.0013 \times UPV}; (R^2 = 0.9677). \quad (2)$$

3.5 Water absorption

The measurement of water absorption (WA) for concrete specimens at 28-, 56-, and 91 days were shown in Fig. 9. Generally speaking, water absorption is closely related

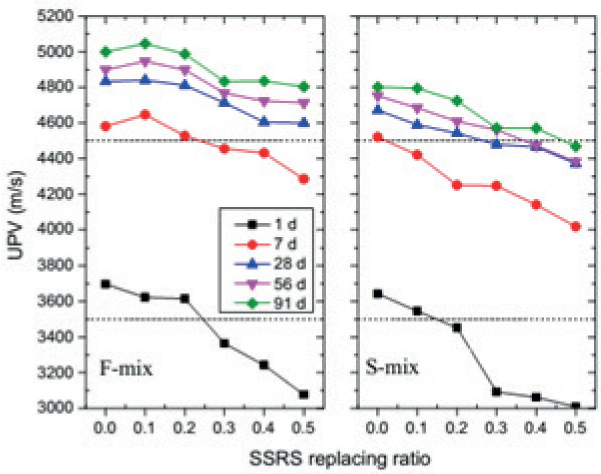

Fig. 7 The evolution of UPV of F-mix and S-mix with various cement replacing ratios

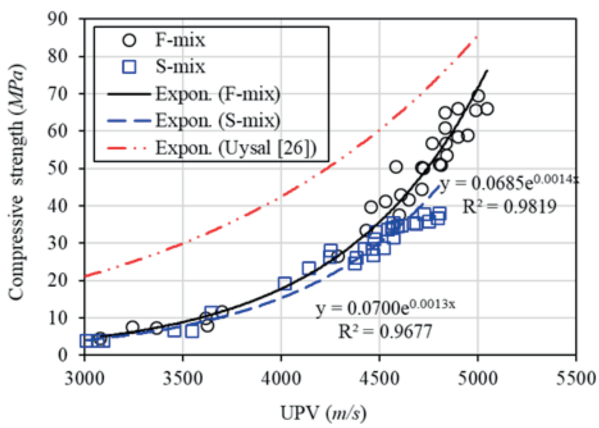

Fig. 8 The correlations between UPV and compressive strength for F-mix and S-mix

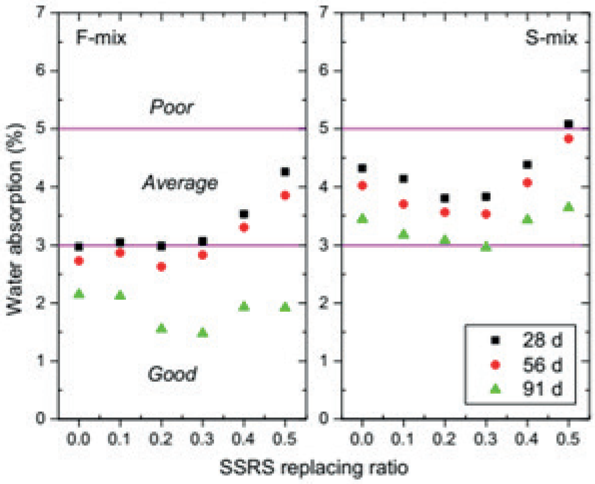

Fig. 9 Water absorption of two SCCs at various ages

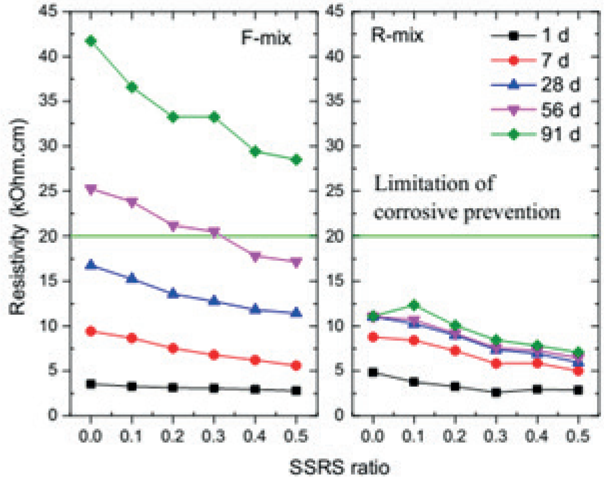

Fig. 10 Result of electrical resistivity for F-mix and S-mix measured at various ages

to the volume of pores within microstructures including structural pores, capillary pores, and ITZ pores. According to CEB-FIB [36], water absorption is a good indicator to access the relative quality of concrete: a concrete is categorized as good, average, poor as its water absorption is below 3 %, 3–5 %, and greater than 5 %, respectively. As expected, water absorption reduced in according with the curing ages increased as a result of filling porosity with solid hydrated products. There is a considerable decrease in water absorption between 56- and 91 days for F-mix, exhibited an effective pozzolanic reaction of FA at later ages. After 91 days, the F-mix performs as a "good" quality concrete, whilst the S-mix is classified as "average" one due to water absorption between 3–5 %. This is supported by the fact that the compressive strength of F-mix is higher than that of S-mix as mentioned above.

Moreover, regarding effect of cement replacing ratio, when increasing S2 substituting OPC up to 30 % the 91-day WA of both SCCs (F-mix and S-mix) are sustainably decreased, implied that voids within paste matrix was effectively filled by growing amount hydrated products. In a previous study, Hadjsadok et al. [37] specified that a slight reduction of water absorption (via sorptivity coefficient) was measured for slag-cement concrete. In the present study, the lowest WA is observed on SCCs containing 30 % reducing slag (S2) replacement; and beyond this level, the WA gradually increased associated with rapid reduction of mechanical strength (Section 3.3). Low reaction degree of the slag used in comparing to OPC could be responsible for raising up WA of concrete made of high-volume stainless steel slag. From testing results, for the two SCCs, the optimum level of cement replacement is 30 % due to producing smallest water absorption.

3.6 Resistivity of concrete

Physically, a cement-based material like concrete is electrically conductive as presence of water-filled pore system containing mobile ions. Resistivity of electricity (*RE*, inverse of conductivity) is reported to correlate well with corrosive rate of embedded reinforcement in concrete [38]. The resistivity for two SCCs with different cement replacement ratios was plotted in Fig. 10. In general, The RE-value increases over time of curing. Particularly, at early ages (1- and 7 days), the resistivity of F-mix and R-mix are comparable and below 10 kΩ.cm. Nevertheless, the difference in RE measured on two SCCs becomes considerable after 28 days. Depending on amount of slag substitution, the 28-day RE of concrete made from F-mix is varied from 11.42-16.75 kΩ.cm; and the respective RE for concrete made from S-mix was 5.94-11.07 kΩ.cm. The RE for F-mix is continuously growing up to 28.5-41.75 kΩ.cm after 91 days. Meanwhile, for S-mix, there is a minor change with duration between 28- and 91 days, and below the limitation of corrosive prevention of embedding steel (20 kΩ.cm), recommended by CEB-192 [38]. This range of resistivity is consistent with those in our previous study, conducted on concrete containing stainless steel slag [10]. This result confirms that SCC incorporating with FA improved well the corrosion resistance issued from the pozzolanic activity of mineral admixture. On the other hand, at any testing ages, the resistivity of concrete in this study substantially decreases with an increases in cement replacement ratio. For example, when S2 replacing to OPC shifting from 0 to 0.5 the 28-day RE of concrete made of F- mix and S-mix decrease by 32 % and 46 %, respectively. An analogous RE reduction was also found at 91 day ages. The trend in RE variation is similar to that of compressive strength as mentioned before. In fact, resistivity and compressive strength are both directly related to the pore volume within the microstructure of concrete, even thought these relationships are not necessarily proportioned. Regarding this perspective, regressive analysis on the obtaining data verifies that logarithmic function could describe well the correlations between surface resistance and compressive strength, as seen in Fig. 11.

3.7 Resistance to sulfate attack

The degradation of two SCCs represented the accumulated weight loss over immerging-drying circles in a 5 % Na_2SO_4 solution are in Fig. 12. In general, specimens with more cement replacing ratio are potentially vulnerable in aggressive media. For instance, there is an increase of 30 % and 37 % in weight loss when cement replacement ratio varying from 0 to 0.5 for F-mix and S-mix, respectively. Moreover, the maximum total weight loss of F-mix was extremely lower than that of S-mix (2.31 % and 4.1 %) in the same condition. On the mechanism, hydrated products of Portland cement such as calcium hydroxide and alumina-bearing phase easily reacts with sulfate ions (SO_4^{2}-) from outside environment to generate expansive-crystalline ettringite and gypsum which possibly cause deterioration of hardened concrete [39]. In corporation with fly ash in concrete basically resulted in improvement of resistance to sulfate attack, reported elsewhere [40]. The reason for this is due to pozzolanic reaction of mineral admixture which accompanied with pore refinement of paste matrix during the portlandite consumption; and this consequently in turn enhance the sulfate resistance of concrete.

4 Conclusions

In this study, two S2-blended SCCs (F-mix and S-mix) prepared with different fillers (FA and slag S1) were developed to compare their performance involving the fresh characteristics and hardened properties. From experimental results, several conclusions are remarked:

(1) Due to spherical shape particles of FA, the F-mix exhibits a greater slump flow than the S-mix at any cement replacement level. Higher viscosity was observed for SCC incorporated with FA than with slag.

(2) In case of without cement substitute, the setting times of S-mix are shorter than those of F-mix. However, when increasing S2 content substituting to OPC, the setting times of SCC changed in different manners; the S-mix had a faster IS time and a slower FS than those of the F-mix. Moreover, with S2 percentage of 30 % or less, the IS and FS times of S-mix were extended to 1.3 and 1.5 times of the control, respectively; this trend was inversely when observed on the F-mix from which the setting times were mostly reduced in comparing to the respective control. The interaction effect between the very fine slag powder and SP were responsible for shortening setting time.

(3) The more reduction of compressive strength for the two SCCs was realized on the specimens with higher ratio of S2 replacing to OPC. The strength loss causing by cement substitution was extremely high as early ages (1 and 7 days); for longer ages, the strength gain was gradually enhanced as a result of hydration of the slag S2. Moreover, at the same level of cement substitution, the compressive strength of F-mix is 1.03–1.91 times of the respective S-mix due to additional pozzolanic effect FA at later ages.

(4) UPV in SCC made with F-mix is higher than that with S-mix due to better filling effect of FA comparing to slag S1. Moreover, the correlations between UPV and

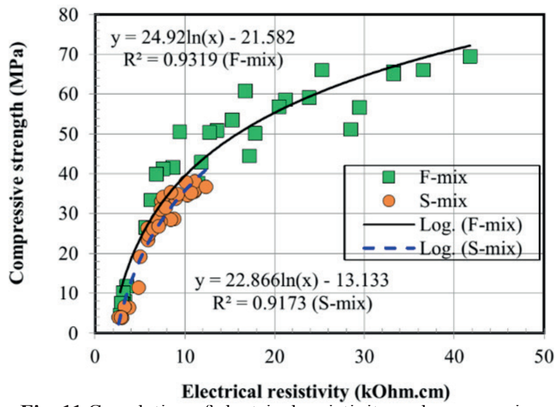

Fig. 11 Correlation of electrical resistivity and compressive strength for F-mix and S-mix

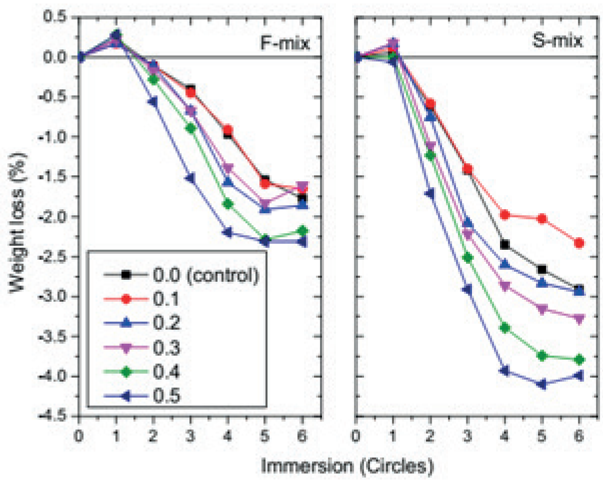

Fig. 12 Measurement of accumulated weight loss of SCC specimens as soaked in sulfate solution

compressive strength for two SCCs could be reasonably established in exponential functions with excellent coefficient of determination ($R^2 > 0.97$).

(5) There is a considerable decrease in water absorption between 56- and 91 days for F-mix, exhibited an effective pozzolanic reaction of FA at later ages. After 91 days, the F-mix have the water absorption below 3 %, performed a "good" quality concrete; whilst the S-mix belongs to an "average" one. From the testing results, for both SCCs, the optimum level of cement replacement by S2 is 30 % due to producing the smallest WA.

(6) The resistance of electricity (RE) increases over time of curing. The difference in RE measured on two SCCs becomes considerable after 28 days. Presence of FA improved well the corrosion resistance issued by its pozzolanic activity. In addition, logarithmic functions could describe well the correlations between the surface resistance and compressive strength ($f_c = a \cdot \ln(RE) + b$).

(7) Specimens with more cement replaced by slag S2 are potentially vulnerable in the sulfate solution. When the ratio of slag replacing cement varies from 0 to 0.5, there is an increase by 30 % and 37 % in weight loss for F-mix and S-mix, respectively. Moreover, the highest weight loss of F-mix was extremely lower than that of S-mix (2.31 % and 4.1 %). This difference resulted from presence of fly ash in SCC which basically improves the resistance to sulfate attack.

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