Chapter 6

Development of Sustainable High-Strength Self-Consolidating Concrete Utilising Fly Ash, Shale Ash and Microsilica

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Additional information is available at the end of the chapter

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Abstract

With high flowability and passing ability, self-consolidating concrete (SCC) does not require compaction during casting and can improve constructability. The favourable properties of SCC have enabled its widespread adoption in many parts of the world. However, there are two major issues associated with the SCC mixes commonly used in practice. First, the cement content is usually at the high side. Since the production of cement involves calcination at high temperature and is an energy-intensive process, the high cement content imparts high embodied energy and carbon footprint to the SCC mixes. Besides, the exothermic reaction of cement hydration would cause high heat generation and early thermal cracking problem that would impair structural integrity and necessitate repair. Second, the strength is usually limited to around grade 60, which is considered as medium strength in nowadays achievable norm. With a view to develop sustainable high-strength self-consolidating concrete (HS-SCC), experimental research utilising fly ash (FA), shale ash (SA), and microsilica (MS) in the production of SCC has been conducted, as reported herein.

Keywords: embodied carbon, embodied energy, fly ash, high-strength self-consolidating concrete, microsilica, shale ash, supplementary binder materials, sustainability

1. Introduction

Self-consolidating concrete (SCC) was first developed in Japan [1, 2] with greatly enhanced flowability and passing ability compared to conventional concrete. With high flowability and passing ability, SCC possesses superior capability to deform and flow, fills up constricted spaces and far-reaching corners, passes through small clearance between objects including reinforcing bars, and achieves proper consolidation without compaction applied [3]. These allow proper placement of concrete even at locations of congested reinforcement and sophisticated formwork shape. At the same time, the concreting operations would be much quieter without the noise generated from concrete compaction, and part of the labour input for concreting can be saved [4]. The production of SCC was mainly enabled by the advent of superplasticising admixtures. With the adoption of appropriate dosage of superplasticiser and water to binder ratio, the workability of concrete can be dramatically improved while the strength can be maintained at the desired level or even increased. The favourable properties of SCC have enabled its widespread adoption in many parts of the world [5]. In recent years, guidelines and specifications of SCC have been developed in Japan [6], Europe [7], USA [8], China [9] and many parts of the world.

Nevertheless, there are two major issues associated with the SCC mixes commonly used in practice. The first issue is that the cement content is usually at the high side, and the adverse effects of high cement content are twofold. Since the production of cement involves calcination at high temperature which is an energy-intensive process [10], the high cement content imparts high embodied energy (EE) and carbon footprint to the SCC mixes [11]. Besides, since the hydration of cement is an exothermic chemical reaction, the high cement content would generate a large amount of heat during concrete hardening and increase the temperature [12]. When the temperature drops to the ambient subsequently and if the thermal contraction is constrained, early thermal cracking would result and that would impair structural integrity and necessitate repair [13].

The second issue is that the strength of concrete is usually limited in practical applications to around grade 60, which is considered as medium strength in nowadays achievable norm [14]. It is well known that the strength of concrete can be increased by decreasing the water to cementitious materials (W/CM) ratio. In the past, the practical limit of W/CM below which the concrete would be insufficiently workable was rather high. That was due to the limited efficiency of the then plasticisers or superplasticisers (SP) available. With the advancement of superplasticising technology over the past decades, lower W/CM ratio could be achieved while the concrete could remain highly workable, and this can be translated to high-strength performance. However, though different high-strength SCC mixes had been developed in laboratories [15, 16], the same range of strength has not yet been commonplace in practice. One of the main reasons of limited strength is that the W/CM ratio has not been minimised by effective utilisation of SP. As will be illustrated later in this chapter, with the increasing usage of cementitious materials with high fineness, instead of the conventional way of dosing the superplasticiser (SP) based on the mass content of cementitious materials, the SP can be more effectively utilised with its dosage being set based on the specific surface area of cementitious materials.

To address the above two issues, the authors have conducted research on improving the sustainable performance and mechanical strength of SCC, as reported in this chapter. With respect to the first issue, the cement consumption is reduced with the incorporation of sustainable binder materials including fly ash (FA), shale ash (SA) and microsilica (MS). With respect to the second issue, the compressive strength of SCC was improved by lowering the W/CM

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ratio through rational mix design and use of polycarboxylate-ether-based SP. The objective of the study is to develop sustainable high-strength self-consolidating concrete (HS-SCC). A series of 12 SCC mixes incorporating FA, SA and MS were produced for laboratory testing. In the study, the sustainability performance is quantitatively represented by the embodied energy (EE) and the embodied carbon (EC) per cubic metre of concrete, the workability and flowability is measured by the slump and slump flow values from standardised tests, the segregation stability is determined by the visual observation of signs of segregation and the strength is measured by the 7-day and 28-day cube compressive strength values.

2. Use of sustainable binder materials

Supplementary cementitious or binder materials have been increasingly used in recent years to yield various beneficial effects on the performance of concrete [17]. For such materials which are naturally occurring or are industrial by-products, their embodied energy and carbon emission are usually much lower than those of silicate cement. The use of these materials as part of the binder to reduce cement consumption can promote the sustainability of concrete, and for this reason they are referred to as sustainable binder materials herein. The different physical properties and chemical reactivity of sustainable binder materials would affect the performance of SCC in different manners. From chemistry viewpoint, common supplementary binder materials can be broadly classified into three types. The first type is silica dominated (mainly single composition of SiO_2), as exemplified by MS, recycled glass powder, perlite and quartz powder [18]. The second type is alumino-silicate dominated (mainly binary composition of Al_2O_3-SiO_2), as exemplified by activated clays and metakaolin [19]. The third type is calcium-alumino-silicate dominated (mainly ternary composition of CaO-Al_2O_3-SiO_2), as exemplified by FA and slags such as ground granulated blast-furnace slag (GGBS) [20]. While the chemical composition of supplementary binder materials determines their pozzolanic reactivity in reacting with calcium hydroxide formed during cement hydration to produce extra cementitious products, the physical characteristics, mainly the granulometry, strongly influence the rate of pozzolanic reaction and various performance attributes of the concrete.

In this study, FA, SA and MS were employed and their effects on SCC are discussed in the following. FA is produced mainly from power stations during the burning of pulverised coal. The ash particles are predominantly spherical in shape and their fineness resembles that of cement. Depending on the source and classification, the silica content of FA would be in the range of 50–70%. Due to its rounded shape, the workability of SCC would not be adversely affected by adding FA. The strength development of concrete with FA is slower than cement concrete, and longer curing period is necessary. The benefits of FA in concrete production are rather established [21, 22]. Particularly, it is very effective in reducing the heat generation of mass concrete during curing to prevent the early thermal cracking problem.

SA is produced by the combustion process of oil shale that contains fossil energy. It is yielded from the solid residue (known as spent shale) resulted from the burning of oil shale [23]. The disposal of SA has been an environmental problem faced by countries that produce shale oil [24]. Though SA may be ground to similar size as cement grains and utilised in the manufacturing of bricks [25], its use in the production of SCC has been much less explored [26]. Due to the minerology of shale, SA contains relatively high content of calcium oxide, usually in the range of 10–40%. The pozzolanicity of SA is similar to that of GGBS, and it has a silica content of 30–40%. In terms of chemical composition, SA can be classified as calcium-alumino-silicate dominated, with a subtle content of aluminium oxide. The addition of SA in concrete had been reported to increase the concrete strength, reduce the permeability and improve frost resistance [27]. However, the alkali content in SA is generally at the high side, and the content of SA in concrete should be limited to prevent expansive alkali-silicate reaction [28].

MS (also called condensed silica fume) is a by-product of the smelting process used to produce silicon metal and ferrosilicon alloys. MS is characterised by the high content of reactive silica of over 85% and the extremely fine particle size in the order of 0.2 μ. The high fineness of MS allows it to fill the voids between larger cement particles and increases packing density. The displaced water becomes excess water to lubricate the solid particles. From mix design perspective, the water demand for packing is greatly reduced and a lower W/CM can be used for achieving higher strength. The high fineness and large specific surface area risk of MS also mitigate the plastic settlement and segregation problems. The use of MS in concrete production is rather established, and it is among the common constituent materials for making high-strength concrete [29, 30]. The use of MS as well as the combined use of MS and FA in producing SCC had been investigated and confirmed to be effective by the authors [31, 32].

3. Use of superplasticising admixtures

Plasticising and superplasticising admixtures have taken an indispensable role in advancing the concrete technology and development of SCC. Before the 1960s, workability improving admixtures based on hydroxycarboxylic acids or lignosulphonates had been developed. They were usually known as plasticisers or water reducers, and they would allow the W/CM ratio to be reduced by 5–10% without adversely affecting the workability of concrete. In the 1960s–1970s, a newer generation of workability improving admixtures based on sulphonated formaldehyde condensates of melamine or naphthalene was developed. These admixtures are generally named superplasticisers (SP) or high-range water reducers because of their superior performance compared to their predecessors. Such SP could allow the W/CM ratio to be reduced by as much as 20–30% without affecting the workability [33]. Terminologically, SPs derived from sulphonated melamine formaldehyde condensates are sub-classified as melamine-based superplasticisers (abbreviated as SMF), while SPs derived from sulphonated naphthalene formaldehyde condensates are sub-classified as naphthalene-based superplasticisers (abbreviated as SNF). SMF and SNF have similar performance and may be blended together in usage [34].

In the 1980s, manufacturers started works to develop polycarboxylate-ether-based SP (abbreviated as PCE), but initially there were serious problems of severe retardation and excessive air entrainment [35]. It was only until around the turn of century, PCE became available in the market and these products were dubbed the third-generation superplasticisers or hyperplasticisers. The PCE remarkably outperformed the existing SP. Their use would allow the W/CM ratio to be reduced by up to 40% without adversely affecting the workability of concrete. The molecular structure of PCE is characterised by an active-monomer (such as polymethacrylate acid, or abbreviated as PMAA) formed main chain, attached with numerous graft copolymers (such as polyethylene glycol, or abbreviated as PEG) formed long side chains. Such long side chains are absent in SMF and SNF molecules.

PCE improve the workability of concrete mixes by dual effects, namely the dispersion effect and steric hindrance or steric repulsion effect. This is in contrast to SMF and SNF which improve the workability of concrete mixes only by dispersion effect. The dispersion effect is explained as follows. There are four main types of minerals in ordinary Portland cement, namely belite (C_2S), alite (C_3S), aluminate (C_3A) and ferrite (C_4AF) [36]. Belite and alite are negatively charged, while aluminate and ferrite are positively charged. Because of the opposite electrostatic potentials, the cement grains tend to coagulate together, making it less readily to thoroughly mix with water to form a uniform paste [37]. With the addition of SP, the SP molecules are adsorbed onto the surfaces of cement grains, and they impart negative charges to all the cement grains. The electrostatic repulsion derived from the negative charges disperses the cement grains apart. For PCE, it is the main chain of PCE molecule that is adsorbed and imparts negative charges to cement grains, whereas the side chains act as physical barriers to separate the cement grains further apart [38]. Such steric hindrance further promotes dispersion and prolongs workability retention [39, 40].

In determining the SP dosage to concrete, attention should be paid to the quantities of SP demand for given levels of workability, the saturation SP dosage beyond which further addition of SP would yield no return, and the maximum SP dosage beyond which further addition of SP would cause segregation. Conventionally, the SP demand, saturation dosage and maximum dosage are expressed in percentage by mass of cementitious materials. However, as SP is a surfactant adsorbed onto the surface of cementitious materials, its effectiveness should be dependent on the amount of SP per surface area of cementitious materials [41]. Therefore, the SP demand, saturation dosage and maximum dosage should be controlled by the fineness and the content of each cementitious material. This forms the basis to rationalise the usage of SP.

4. Method

4.1. Materials employed

A total of 12 concrete mixes were produced for testing. The materials employed were as follows. The cement used was an ordinary Portland cement that complied with the requirements in European Standard EN 197. It has a solid density of 3.1 and a specific surface of 350 m^2/kg. The fly ash (FA) used was produced from coal-fired power station and the properties complied with the requirements in European Standard EN 450. The shale ash (SA) used was produced from shale oil fuelled power plant and the properties have been investigated in this research. To show the morphology of SA particles, **Figure 1** depicts the scanning electron

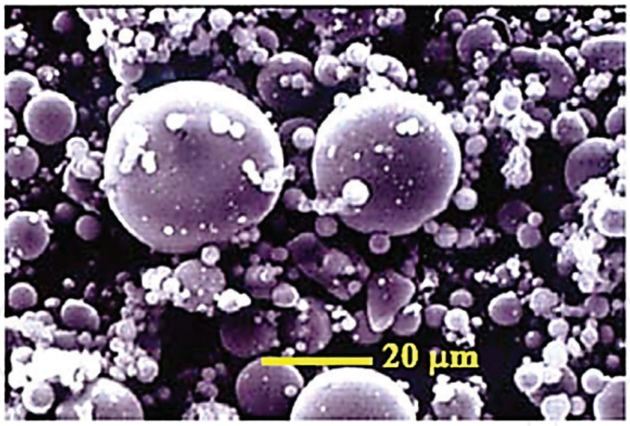

Figure 1. Morphology of SA.

microscopy image of the SA. The microsilica (MS) used was produced from ferrosilicon plant and the properties complied with the requirements in European Standard EN 13263. **Table 1** lists the chemical compositions in percentage of the cement, FA, SA and MS. Regarding the physical properties, the cement, FA, SA and MS had specific surface areas of 595, 415, 570 and 20,000 m^2/kg, and had specific gravities of 3150, 2110, 2800 and 2200 kg/m^3.

The coarse aggregate was crushed granitic rock with a maximum size of 10 mm, while the fine aggregate used was crushed granitic rock fine with a maximum size of 5 mm. The properties and grading of the fine and coarse aggregates have been tested to comply with European Standard EN 12620. The SP used was polycarboxylate-ether-based complying with European Standard EN 934. It is a white-colour milky liquid that can be added into the mixing water or directly to the wet concrete. The recommended SP dosage by the manufacturer was typically 0.5–3.0% by mass of the cementitious materials content. Such polycarboxylate-ether-based SP is very effective and it allows adoption of low W/CM ratios.

4.2. Experimental programme

The experimental programme encompassed 12 SCC mixes. For all concrete mixes, the W/CM ratio by mass was ranging from 0.28 to 0.33, and the paste volume was ranging from 0.32 to 0.35. The fine to total aggregate (F/T) ratio was fixed at approximately 0.4 for the majority of concrete mixes, except for one of the mixes with W/CM ratio of 0.33 the F/T ratio was raised to 0.5. The contents of supplementary binder materials in mass percentage of the total binder were as follows: the FA content varied among 0 and 25%, the SA content varied among 0, 15, 30 and 45%, and the MS content varied among 0, 5 and 10%. One of the SCC mixes was cement concrete and did not contain any supplementary binder materials, six mixes featured binary blending of FA or SA, and five mixes featured ternary blending of FA and MS. **Table 2** summarises the mix parameters of the experimental programme. The SP dosage of the majority of mixes was 3.0%, except the dosage was lowered to 1.5% by mass for the mixes with SA due to the higher inherent workability of those mixes. It should be noted that the dosage was adjusted based on the surface area of the solid particles present in the concrete and the actual achieved workability compared to the target workability. The mix proportions are listed in **Table 3**.

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Minerals	Cement	Fly ash (FA)	Shale ash (SA)	Microsilica (MS)
SiO_2	18.8	48.8	24.8	92.1
Al_2O_3	3.9	25.2	5.9	1.2
CaO	62.1	2.4	50.5	1.1
Fe_2O_3	2.8	5.3	4.6	1.2
MgO	2.6	2.4	6.5	0.8
Na_2O	0.2	0.9	0.1	1.1
K_2O	1.1	3.6	2.1	0.7
SO_3	0.8	0.5	4.4	1.3

Table 1. Chemical compositions (in %) of cement and supplementary binder materials.

Mix no.	W/CM ratio	Paste volume	F/T ratio	FA content (%)	SA content (%)	MS content (%)
1	0.30	0.32	0.39	0	0	0
2	0.26	0.35	0.40	25	0	0
3	0.28	0.35	0.40	25	0	0
4	0.30	0.35	0.40	25	0	0
5	0.32	0.34	0.39	0	15	0
6	0.32	0.34	0.39	0	30	0
7	0.32	0.34	0.39	0	45	0
8	0.28	0.35	0.40	25	0	5
9	0.28	0.35	0.40	25	0	10
10	0.30	0.35	0.40	25	0	5
11	0.30	0.35	0.40	25	0	10
12	0.33	0.35	0.50	25	0	5

Note: The FA, SA and MS contents are expressed in percentage by mass of total binder.

Table 2. Concrete mix parameters.

4.3. Embodied energy and carbon

To study the embodied energy (EE) and carbon emission of the SCC mixes, the data in the literature: Embodied Carbon: The Inventory of Carbon and Energy [42] were referred to. **Table 4** lists the embodied energy (*EE*) and embodied carbon (*EC*) of the constituent materials. Here, the embodied energy is expressed in terms of MJ/kg of material, and the embodied carbon is expressed in terms of $kgCO_2$/kg of material. It can be seen that the tabulated values for cement are generally one to two orders higher than those of FA, SA and MS, which originate from industrial by-products. Therefore, blending with supplementary binder materials to reduce the cement consumption is an effective means to enhance the sustainability of concrete.

Mix no.	Mass content (kg/m³)					
	Cement	FA	SA	MS	Water	SP
1	492	0	0	0	150	7.4
2	421	140	0	0	146	17.7
3	408	136	0	0	152	17.1
4	395	132	0	0	158	16.6
5	452	0	80	0	152	7.2
6	380	0	163	0	146	5.7
7	320	0	262	0	150	6.3
8	376	134	0	27	150	16.9
9	345	133	0	53	149	16.5
10	365	130	0	26	156	16.4
11	335	129	0	52	155	16.2
12	342	117	0	23	161	14.7

Table 3. Concrete mix proportions.

Based on the listed values in **Table 4**, the embodied energy and embodied carbon of the SCC mixes may be computed as follows, where *EE* is in MJ/m^3, *EC* is in kgCO_2/m^3 and *W*, *C*, *FA*, *SA*, *MS* and *A* are the contents of water, cement, FA, SA, MS and aggregate, respectively, in kg/m^3.

$$EE = 0.010\,W + 4.500C + 0.100FA + 0.030SA + 0.850MS + 0.083A \quad (1)$$

$$EC = 0.001\,W + 0.730C + 0.008FA + 0.002SA + 0.020MS + 0.005A \quad (2)$$

4.4. Test procedures

Laboratory pan-type mixer was employed to mix the concrete, with a total duration of mixing of not less than 5 minutes for each mix. The workability of the fresh SCC mixes was measured

Material	Embodied energy (MJ/kg)	Embodied carbon (kgCO_2/kg)
Water	0.010	0.001
Cement	4.500	0.730
FA	0.100	0.008
SA	0.030	0.002
MS	0.850	0.020
Rock aggregate	0.083	0.005

Table 4. Embodied energy and embodied carbon of constituent materials.

by the slump and flow tests as stipulated in European Standard EN 12350: Part 2 and Part 8. The same equipment was used for the slump and flow tests. The slump cone had a base diameter of 200 mm, a top diameter of 100 mm and a height of 300 mm. A smooth steel plate of size 1× 1 m was placed on level ground for carrying out the test. The size of steel plate was sufficiently large to cater for the extent of flow of concrete. Concrete was first filled into the slump cone without tamping. When the slump cone was full, the top surface of concrete was trowelled flat and the slump cone was lifted steadily to allow the concrete to flow under its own weight to form a patty. After the flow had ceased, the slump of concrete was measured as the difference between the height of slump cone and the highest point of the patty. Besides, the slump flow (or flow in short) of concrete was measured as the average diameter of the patty in two orthogonal directions. The slump and flow values were measured and reported to the nearest 5 mm. In addition, any sign of segregation instability was observed by visual inspection particularly around the rim of the slumped patty.

The compressive strength of the SCC mixes was measured in accordance with European Standard EN 12390: Part 3 and Part 4. Cubes of size 100 mm were cast from the fresh SCC mixes and then covered to protect against loss of moisture by evaporation. One day after casting, the cubes were demoulded and were cured by immersing in lime-saturated water curing tank at a temperature of 27 ± 2°C. Until the required age of testing at 7 days or 28 days, the cubes were taken out from the curing tank, wiped dry and underwent the compressive strength test. The mean compressive strength was obtained by averaging the test results of a set of three cubes. If there was any individual cube strength deviating from the average cube strength by more than 10%, the individual result would be discarded and the average cube strength would be taken as the average of the remaining two cubes. All strength results presented in this chapter are the mean compressive strength so evaluated.

5. Results and discussions

5.1. Workability and flowability

The experimental results of workability and strength of the SCC mixes are presented in **Table 5**. It is noted that the slump values fell in the range from 220 to 260 mm, and the flow values were within the range from 620 to 775 mm. No sign of segregation instability was observed for all the SCC mixes. Basically, all the concrete mixes achieved the required workability and flowability of being self-consolidating. Such workability and flowability regime also offers potential applications for tremie concrete mixes and pumped mixes. According to the relevant European guidelines [7], SCC are classified into three flow classes, namely class SF1 for flow value between 550 and 650 mm, class SF2 for flow value between 660 and 750 mm and class SF3 for flow value between 760 and 850 mm. The flow classification of each SCC mix is indicated in **Table 5**. It is worthwhile to note that for the SA concrete (Mixes 5, 6 and 7), the workability and flowability at the presence of SA were favourable such that the SP dosage was set at a low level (circa 1.5% by mass of the cementitious materials content). Therefore, the use of SA can economise the material cost of SCC by consuming less amount of SP.

Mix no.	Slump (mm)	Flow (mm)	Flow class	7-day mean cube strength (MPa)	28-day mean cube strength (MPa)	28-day to 7-day strength ratio
1	230	660	SF2	67.4	80.2	1.19
2	220	620	SF1	78.2	98.0	1.25
3	235	665	SF2	74.6	96.1	1.29
4	225	670	SF2	63.3	81.6	1.29
5	250	700	SF2	72.7	86.7	1.19
6	225	650	SF1	73.7	91.8	1.25
7	255	730	SF2	75.2	83.4	1.11
8	250	660	SF2	74.6	101.4	1.36
9	225	620	SF1	81.4	108.5	1.33
10	235	660	SF2	77.1	102.7	1.33
11	225	620	SF1	73.1	104.8	1.43
12	260	775	SF3	72.5	89.8	1.24

Table 5. Workability and strength results.

To reveal the relation between slump and flow, the variation of these two quantities is plotted in **Figure 2**. For ease of visualisation, the data points are divided into four groups, namely "Cement SCC" for Mix 1, "FA SCC" for Mixes 2–4, "SA SCC" for Mixes 5–7, and "FA + MS" SCC for Mixes 8–12. Besides, horizontal lines at flow levels of 550, 650 and 750 mm corresponding to the boundary values of flow classes are drawn. It can be seen from **Figure 2** that the slump and flow are positively correlated. Nevertheless, at a workability level of higher than 200 mm slump, the slump is less sensitive to the change in workability as compared to the flow. Hence, the flow value serves as a better measurement of the self-consolidating ability.

5.2. Compressive strength

The 7-day and 28-day mean cube compressive strength results are listed in **Table 5**. It can be seen that all 7-day strength results were higher than 60 MPa, and all 28-day strength results were higher than 80 MPa. Therefore, the SCC mixes do satisfy the requirement of high strength. The 7-day strength was ranging from 63.3 to 81.4 MPa. Mix 4 with W/CM ratio of 0.3 and with 25% FA content had the lowest 7-day strength, due to the relative slow strength development of FA concrete as expected. The 28-day strength was ranging from 80.2 to 108.5 MPa. Mix 1 without supplementary binder materials had the lowest 28-day strength, which demonstrated the more effective strength development at a later age of blended SCC mixes. Mix 9 with W/CM ratio of 0.28 and with 25% FA content and 10% MS content had the highest 7-day and 28-day strengths, which proved the beneficial effect of MS on strength enhancement. In particular, the use of SA up to even a high volume allowed the achievement of very high strength. At 30% SA content, the 28-day strength of Mix 6 was 91.8 MPa; where at 45% SA content, the 28-day strength of Mix 7 was 83.4 MPa. The 7-day compressive strength is plotted versus the 28-day compressive strength in **Figure 3**. In the figure, the line of

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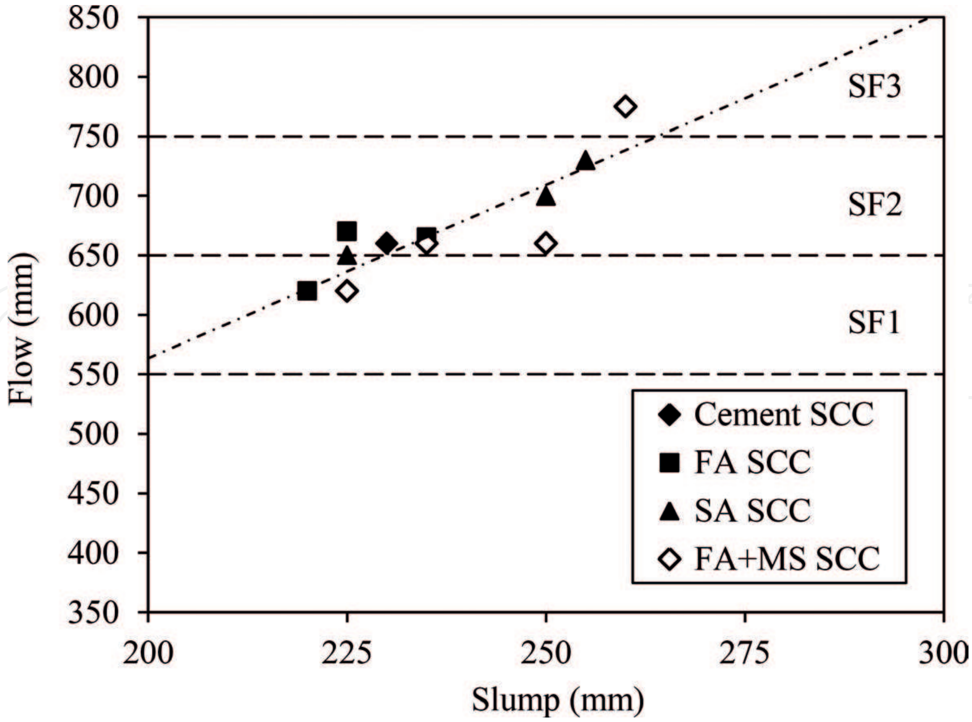

Figure 2. Plot of flow versus slump.

unity, the line of gradient of 1.2 and the trend line of data points are drawn for ease of visualisation. For each SCC mix, the ratio of 28-day strength to 7-day strength is computed and is listed in the last column of **Table 5**. The ratio ranged from 1.11 for Mix 7 with 45% SA content to 1.43 for Mix 11 with 25% FA content and 10% MS content.

It is evident from the strength results that the SCC mixes produced in the current experimental programme are suitable for adoption as high-strength SCC, or HS-SCC mixes. From the authors' experience in concrete production and testing, rational grade designation for Mixes 1–12 is assigned with reasonable allowance of standard deviations in strength results to account for the difference between the mean strength and the characteristic strength (grade strength). The grade designation based on concrete cube strength is listed in the second column of **Table 6**, where Mixes 1, 4 and 7 are designated as C70, Mix 5 is designated as C75, Mixes 6 and 12 are designated as C80, Mixes 2, 3, 8 and 10 are designated as C85, and Mixes 9 and 11 are designated as C90. These concrete grades are significantly higher than the grades of common SCC mixes employed in construction projects. It should be noted that the standard deviation of strength results can be established with a higher confidence level upon the availability of data from a larger sample population. Therefore, the grade designation herein would subject to alteration after further trial mixing and production.

5.3. Sustainability performance

The sustainability performance of the SCC mixes, evaluated through the *EE* and *EC* as per Eq. (1) and Eq. (2), is shown in **Table 6**. The *EE* was ranging from 1590 to 2359 MJ/m^3, whereas the *EC* was ranging from 243 to 368 kgCO$_2$/m^3. The cement SCC Mix 1 without supplementary binder materials gave rise to the highest *EE* and *EC* values. By blending with FA, SA and MS,

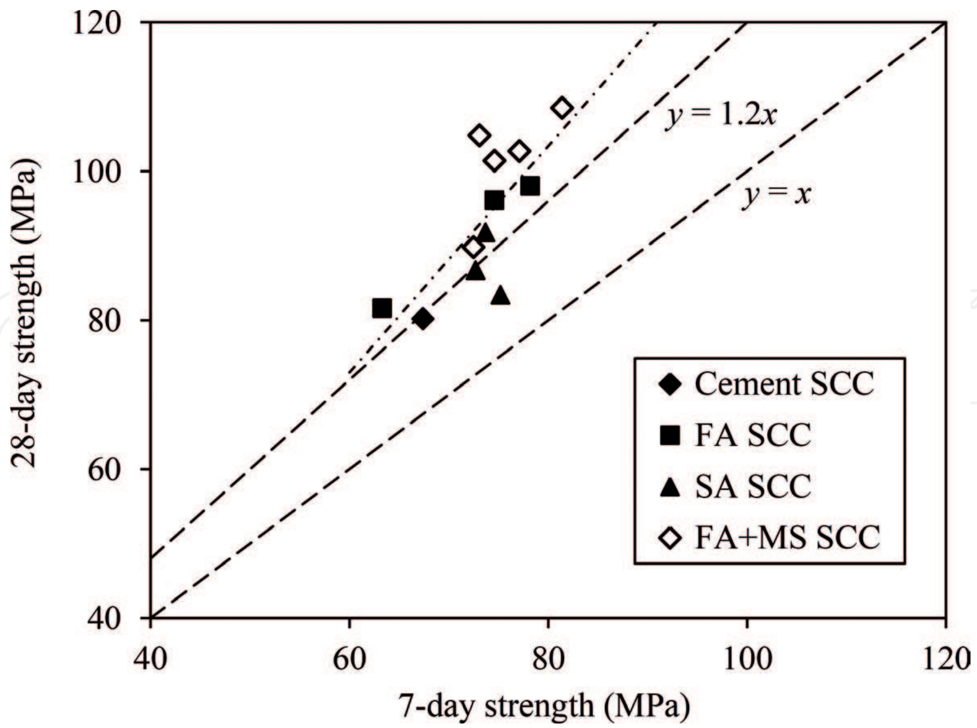

Figure 3. Plot of 28-day strength versus 7-day strength.

the *EE* and *EC* could be remarkably reduced, with the percentage decrease for each mix relative to Mix 1 listed in brackets in columns 3 and 4 of **Table 6** after the respective *EE* and *EC* values. As noted in the above, SA can be used at a high volume while capable of achieving high strength, consequently, the largest decrease in *EE* and *EC* was attained by Mix 7, which had the highest SA content of 45% by mass of binder. The corresponding reduction in *EE* and *EC* was as large as 32.6 and 34.0%, respectively. The variation of *EE* with the 28-day strength

Mix no.	Grade designation	Embodied energy (MJ/m³)	Embodied carbon ($kgCO_2/m^3$)	*EE* per strength (MJ/m³/MPa)	*EC* per strength ($kgCO_2/m^3$/MPa)
1	C70	2359 (±0%)	368 (±0%)	29.4 (±0%)	4.6 (±0%)
2	C85	2050 (−13.1%)	317 (−13.9%)	20.9 (−28.9%)	3.2 (−30.4%)
3	C85	1991 (−15.6%)	308 (−16.3%)	20.7 (−29.6%)	3.2 (−30.4%)
4	C70	1932 (−18.1%)	298 (−19.0%)	23.7 (−19.4%)	3.7 (−19.6%)
5	C75	2182 (−7.5%)	339 (−7.9%)	25.2 (−14.3%)	3.9 (−15.2%)
6	C80	1855 (−21.4%)	286 (−22.3%)	20.2 (−31.3%)	3.1 (−32.6%)
7	C70	1590 (−32.6%)	243 (−34.0%)	19.1 (−35.0%)	2.9 (−37.0%)
8	C85	1870 (−20.7%)	285 (−22.6%)	18.4 (−37.4%)	2.8 (−39.1%)
9	C90	1752 (−25.7%)	263 (−28.5%)	16.1 (−45.2%)	2.4 (−47.8%)
10	C85	1819 (−22.9%)	277 (−24.7%)	17.7 (−39.8%)	2.7 (−41.3%)
11	C90	1706 (−27.7%)	255 (−30.7%)	16.3 (−44.6%)	2.4 (−47.8%)
12	C80	1712 (−27.4%)	260 (−29.3%)	19.1 (−35.0%)	2.9 (−37.0%)

Table 6. Sustainability performance results.

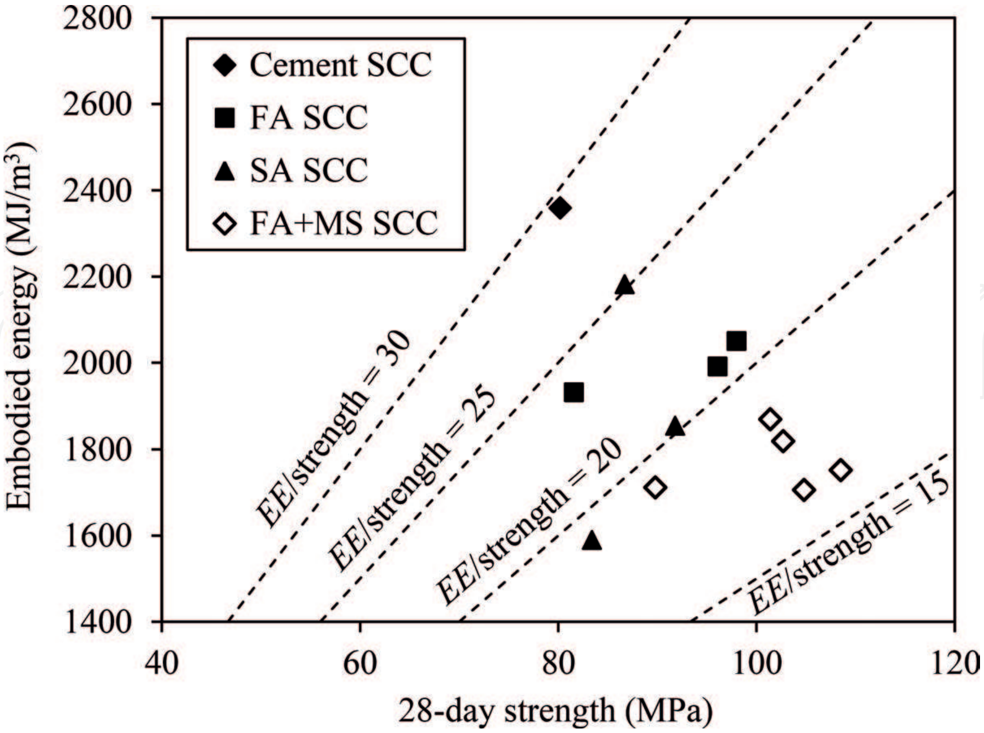

Figure 4. Plot of embodied energy versus 28-day compressive strength.

and the variation of *EC* with the 28-day strength are plotted in **Figures 4** and **5**, respectively. In these figures, moving vertically downwards and towards the right-hand side would indicate a more sustainable and higher strength concrete. It can be observed that Mix 1 performed the worst among all mixes in terms of both strength and sustainability, while the ternary blended (cement + FA + MS) mixes generally performed superior, as reflected by the group of data points close to the bottom right corner in the figures. The good overall performance is due to the effectiveness of FA in lowering the *EE* and *EC*, as well as the effectiveness of MS in improving the strength.

For comparison on an equal-strength basis, the *EE* per strength and the *EC* per strength at age of 28-days are evaluated and listed in the last two columns of **Table 6**. It is seen that the *EE* per strength was ranging from 16.1 to 29.4 (MJ/m^3)/MPa, whereas the *EC* per strength was ranging from 2.4 to 4.6 (kgCO_2/m^3)/MPa. Similar to the foregoing, the percentage decrease in *EE* and *EC* per strength relative to Mix 1 is listed in brackets in the last two columns of **Table 6**. This can reflect the concurrent improvement in strength and sustainability by blending with FA, SA and MS. The largest percentage reductions in *EE* and *EC* per strength were attained by Mixes 9 and 11, which contained 25% FA content and 10% MS content. To facilitate visualising the concurrent effects on strength and sustainability, family of straight lines of constant *EE*/strength ratio at equal intervals and family of straight lines of constant *EC*/strength ratio at equal intervals are plotted in **Figures 4** and **5**, respectively.

5.4. Additional investigation of rational SP dosage

To investigate the rationalisation of SP dosage, one of the SCC mixes, additional trial of Mix 2 was carried out with varied SP dosage while maintaining the proportions of other mix ingredients

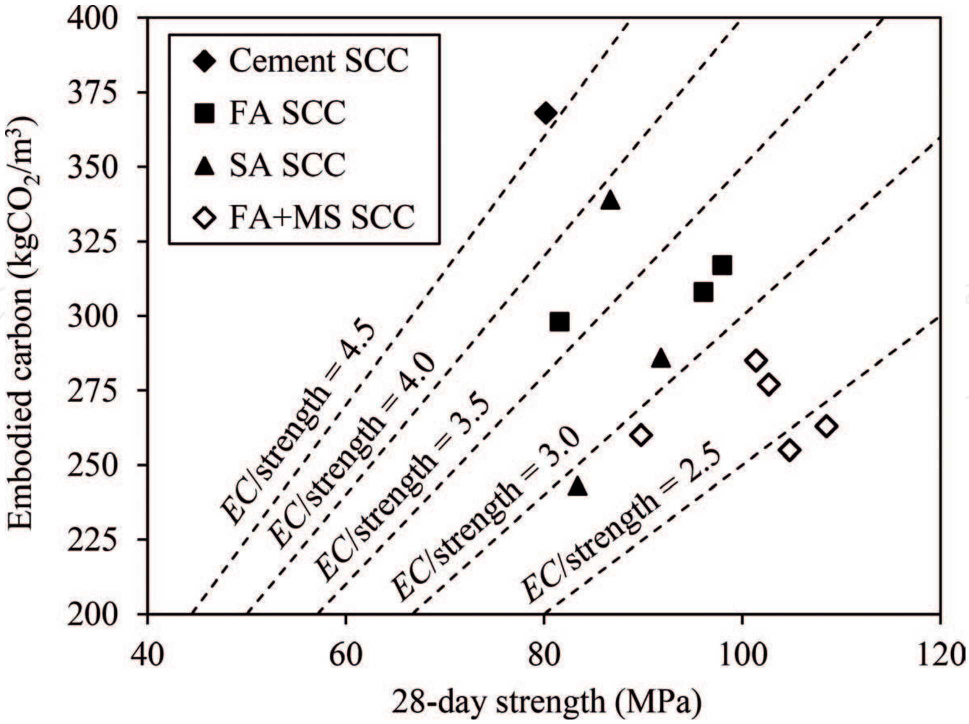

Figure 5. Plot of embodied carbon versus 28-day compressive strength.

unchanged. From the specific surface areas reported in Section 4.1, the SP dosage of Mix 2 in terms of liquid mass per surface area of cementitious materials was evaluated to be 57 × 10^{-6} kg/m^2. Two trial mixes, labelled as Mix 2a and Mix 2b, were conducted with the respective SP dosage set at 76 × 10^{-6} kg/m^2 and 96 × 10^{-6} kg/m^2 area of cementitious materials (approximately correspond to 4% and 5% by mass of cementitious materials, respectively). The slump and flow results of Mix 2a were 255 and 725 mm, respectively, while the slump and flow results of Mix 2b were 240 and 770 mm, respectively. No sign of segregation was observed. It should be noted that when determining the SP dosage of SCC mixes containing materials of high fineness such as MS, the SP dosage should better be set based on the specific surface area of cementitious materials, so as to more effectively utilised the SP. In any case, the above additional investigation indicated possibility of further increasing the flowability at constant W/CM ratio, or conversely, possibility of further reducing the W/CM ratio for achieving even higher strength while maintaining the flowability. Therefore, it should be viable to develop HS-SCC beyond grade C90 by rationalising the SP usage and further mix optimisation, and research along this direction is recommended.

6. Conclusions

With the aim to develop sustainable high-strength self-consolidating concrete (HS-SCC) mixes, the authors have conducted research on improving the sustainable performance and mechanical strength of self-consolidating concrete (SCC) mixes. Reduction in embodied energy and carbon emission of SCC mixes has been achieved by reducing the cement consumption with the incorporation of fly ash (FA), shale ash (SA) and microsilica (MS) as supplementary binder materials. High compressive strength of SCC mixes has been achieved

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by adopting low W/CM ratios through the use of polycarboxylate-ether-based superplasticiser (SP). A series of 12 SCC mixes incorporating FA, SA and MS have been produced for laboratory testing. From the experimental results, all the concrete mixes have attained the required workability and flowability of self-consolidating. The flow values have satisfied the respective ranges of slump-flow classes SF1, SF2 or SF3 according to the European guidelines for SCC, and there has been no problem of segregation instability as revealed from visual observations. The mean 28-day compressive cube strengths of the SCC mixes were within the range from 80.2 to 108.5 MPa, which could be designated as grade C70 to C90. Depending on the contents of respective supplementary binder materials, the use of FA, SA and MS has significantly lowered the embodied energy (EE) and embodied carbon (EC) of the SCC mixes by up to 32.6% and 34.0%, respectively. In particular, SA can be used at a high volume while capable of achieving high strength, thereby enabling great enhancement in sustainability performance. For comparison on an equal-strength basis, the EE per strength and the EC per strength at 28-day age have been evaluated. By so doing, the concurrent improvement in strength and sustainability by blending with FA, SA and MS has been clearly demonstrated, where reductions in EE per strength and EC per strength by up to more than 45% have been achieved. Overall speaking, the results have concluded successful development of sustainable HS-SCC with superior performance compared to the conventional SCC mixes. The mix design contained in this chapter may be adopted as reference HS-SCC mixes for practical use. Moreover, from additional studies, the authors have suggested rationalising the SP dosage based on the specific surface area of cementitious materials, instead of the conventional practice of dosing the SP based on the mass content of cementitious materials.

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Conflict of interest

The authors declare that there is no conflict of interest.

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