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Mechanical and durability properties of self-compacting concrete with blended binders

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Abstract. Over the past three decades, self-compacting concrete (SCC), which is characterized by its superior rheological properties, has been gradually used in construction industry. It is now recognized that the application of SCC using supplementary cementitious materials (SCM) is highly attractive and promising technology reducing the environmental impact of the construction industry and reducing the higher materials costs. This paper presents an experimental study that investigated the mechanical and durability properties of SCCs manufactured with blended binders including fly ash, slag, and micro-silica. A total of 8 batches of SCCs were manufactured. As series of tests were conducted to establish the rheological properties, compressive strength, and durability properties including the water absorption, water permeability, rapid chloride permeability and initial surface absorption of the SCCs. The influences of the SCC strength grade, blended types and content on the properties of the SCCs are investigated. Unified reactive indices are proposed based on the mix proportion and the chemical composition of the corresponding binders are used to assess the compressive strength and strength development of the SCCs. The results also indicate the differences in the underlying mechanisms to drive the durability properties of the SCC at the different strength grades.

Keywords: self-compacting concrete; durability; compressive strength; rheological properties; hydration

1. Introduction

The rapid urban population increase and industrial growth in past decades result in the high priority in the development of concrete construction. Self-compacting concrete (SCC), is a type of a high flowing concrete which is characterized by its favorable fresh concrete properties, such as the superior filling ability, passing ability and segregation resistance (Benaicha *et al*. 2015, Bouzoubaa and Lachemi 2001, Jawahar *et al*. 2013, Liu 2010, Rama *et al*. 2017, Sabet *et al*. 2013). Owing to its technological advances, SCCs can easily spread into place under its self-weight, fill the formworks and encapsulate the reinforcements without any vibration or consolidation efforts (Benaicha *et al*. 2015, Bouzoubaa and Lachemi 2001, Farhang and Fathi 2017, Fathi and Lameie 2017, Gesoğlu *et al*. 2009, Jawahar *et al*. 2013, Khan *et al*. 2016, Sabet *et al*. 2013, Vakhshouri and Nejadi 2017, Zhao *et al*. 2015). Therefore, SCCs are widely utilized in cast-in-situ scenarios for different construction configurations and offer significant benefits.

With respect to its mix proportion, the ingredients required to manufacture a SCC is same as those used for a conventional concrete. However, in order to attain the special behavior of SCCs (i.e., higher fluidity) without comprising their mechanical strength, SCCs are usually composed of higher content of binders and costly chemical admixtures with limiting amounts of aggregate (Sabet *et al*. 2013, Sethy *et al*. 2016, Uysal and Sumer 2011, Zhang *et al*. 2003). It is worth mentioning that the major obstacle that hinders the application of SCCs in modern construction work is due to the large quantities of the binder usages in the concrete, which result in a higher materials cost (25-50% higher than conventional concrete) (El-Chabib and Syed 2012, Uysal and Sumer 2011) and also environmental problems, for instance, pollutants emitted by cement plants to the atmosphere.

In the recent years, through the growing environmental awareness and initiatives, with the aim of conserving natural resources (i.e., limestone and coal sources), minimizing the environmental impacts of cement industry (i.e., CO_2 emission and energy demand) and reducing the potential cost of materials, supplementary cementitious materials (SCM), such as fly ash, slag and micro-silica (silica fume), which are industrial by-products of thermal power stations, have been widely employed to partially replace the ordinary Portland cement (OPC) to produce concrete (Dadsetan and Bai 2017, Long *et al*. 2015). Moreover, the proper incorporations of SCMs in a concrete can ensure the mechanical strength of the concrete due to the self-cementing (i.e., slag) or pozzolanic (i.e., fly ash, slag and MS) nature (Fathi and Lameie 2017, Le and

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Ludwig 2016, Uysal and Sumer 2011, Zhao *et al*. 2015) of the SCMs and also enhance the durability of the concrete through the filler-effected offered by the SCMs. Therefore, the use of SCMs to partially replace cement in SCCs is a highly attractive and promising technology. A careful literature reveals that a number of previous of studies have been conducted to investigate the behavior of SCCs produced by blending OPC with SCMs and they indicate the use of SCM partially replacing OPC alter the properties of a SCC at its fresh and hardened stage. The proper inclusion of fly ash and GGBFS in SCCs with lower than 30% cement replacement ratio can significantly improve the fluidity and durability of SCCs but result in lower early age mechanical strength (i.e., 5 to 10% lower) and rate of strength development (Almuwbber *et al*. 2018, Atiş and Bilim 2007, Da Silva and De Brito 2015, Dave *et al*. 2017, Deilami *et al*. 2017, Elchalakani *et al*. 2014, Jawahar *et al*. 2013, Vakhshouri and Nejadi 2017). However, this slight compromise of the mechanical properties of the SCC at the early-curing stage can overcome after the concrete age of 28 days through the prolonged reactions supported by the SCMs (Ponikiewski and Gołaszewski 2014, Uysal and Sumer 2011). Owing to its abundant silicates content to supply the pozzolanic reaction, the replacement of OPC by micro-silica in SCCs can even more effectively improve the mechanical strength of the SCCs (Dave *et al*. 2017, Gesoğlu *et al*. 2009, Hassan *et al*. 2012). Furthermore, due to the filler effect offered by the unreacted micro-silica in SCCs, the pore structure of the SCCs is well-refined which results in the enhanced durability of the concrete, such as reduced porosity (Bingöl and Tohumcu 2013, Yazıcı 2008), water absorption (Jalal *et al*. 2015, Sabet *et al*. 2013), carbonation (Khan and Siddique 2011, Turk *et al*. 2013) and chloride penetrations (Sabet *et al*. 2013, Wongkeo *et al*. 2014).

Depending on the types of SCMs, their effects on the behavior of the concrete are distinct due to the differences in their chemical and mineralogical compositions even at a same cement replacement ratio in a given SCC mix (Xie and Visintin 2018). This brings the difficulties to evaluate the performance of SCCs producing by blending OPC with SCMs of different types and contents. This further indicates that this is the need for a unified approach to properly assess the mechanical strength of SCCs with blended binders. In addition, it requires reducing the total aggregate content in a SCC with a higher compressive strength to attain the same rheological properties of its lower strength counterparts. This decrease in the aggregate content causes the increased volume of paste matrix and reduced amount of skeleton in the concrete and significantly affects the microstructure of the SCC. This subsequently could lead to differences in the durability properties of the SCC and the underlying actions. Although there have been studies on the properties of SCCs, there is little information regarding the aforementioned research gaps. To develop the needed knowledge of SCCs, this work is undertaken with the aims of:

1. experimentally studying the short- and long- term behavior of SCC with unary, binary and trinary binder system.

2. introducing a unified approach by looking into the fundamental chemical composition of the binder (i.e., oxides) to assess the mechanical and durability properties of the SCC with unary, binary and ternary binders based on the reactivity of the blended binders.

3. exploring the underlying mechanisms which predominates the pore-structure and durability of the SCCs at different strength grades.

Significantly, the outcomes of this work is expected to contribute to the field through:

1. establishing the understandings about the difference in mechanism governing the mechanical and durability-related properties of SCCs at different strength grades; and

2. reducing the need to conduct multiple-trial tests in order to reliably develop mix designs of SCCs as the proposed unified approach based on the fundamental chemical composition of the blended binder and mix proportion of SCC can serve as a baseline for future mix design of SCC; and

3. improving the transferability of the findings of existing and future studies on SCC via using the developed prediction method incorporations by providing simple means for expressing mix designs in terms of the chemical composition of the binder; and

4. promoting and standardizing the usage of industrial by-products, agricultural wastes in SCCs.

Table 1 Chemical composition and physical properties of the binders

Oxide compounds	OPC (wr%)	SF (wr%)	FA (wr%)	GGBFS (wr%)
Chemical composition				
SiO_2	21.3	92.5	59.88	33.1
Al_2O_3	4.89	0.35	27.67	13.33
Fe_2O_3	3.42	0.4	3.21	0.69
CaO	64.2	0.03	1.37	42.83
MgO	1.41	0.01	0.49	5.57
Mn_2O_3	-	-	0.05	-
SO_3	2.53	-	5	-
RM	3.31	0.00	0.49	1.86
SM	2.56	123.33	1.94	2.36
Physical properties				
Specific gravity	3.15	2.24	2.28	2.91
Blaine fineness (m^2/kg)	352	18000	275	425

2. Experimental program

2.1 Materials

2.1.1 Binders

Four different types of binder materials were used in the present study, namely ordinary Portland cement (OPC), fly ash (FA), micro-silica (MS) and ground granulated -furnace slag (GGBS). The chemical composition and physical properties of the four binders are reported in Table 1. To assess the hydraulic and pozzolanic actions of each binder material, two reactive indices namely, reactivity modulus (RM) and silica modulus (SM) (Badogiannis *et al*. 2005, Behim *et al*. 2013, Binici and Aksoğan 2006, Binici *et al*. 2007), which are determined using Eqs. (1)-(2),

Table 2 Mix proportion of the SCCs

Concrete series	OPC (kg/m^3)	SF (kg/m^3)	FA (kg/m^3)	GGBFS (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	fine aggregate (kg/m^3)	SP (kg/m^3)	w/b^*	RM	SM
C35	250		154	66	173	731	945	8.5	0.277	2.18	1.79
C48	350		142	61	170	706	912	8.8	0.242	2.43	2.38
C80	402	50		98	160	551	297	4.9	0.229	2.75	13.5
C90	400	64		96	155	562	303	5.3	0.221	2.68	16.3
O100	550				193	647	954	11	0.269	3.31	2.56
O90S10	495	55			193	647	954	11	0.269	2.98	14.6
O85S15	467.5	82.5			209	647	954	11	0.284	2.81	20.7
O80S20	440	110			209	647	954	11	0.284	2.65	26.7

*Including the water coming from the superplasticizer (i.e. 70% water by weight)

respectively, are also provided in Table 1.

$$RM = \frac{CaO + MgO + Al_2O_3}{SiO_2} \quad (1)$$

$$SM = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad (2)$$

Note that the higher of RM is associated with the higher CaO, which indicates the stronger hydration/self-cementing activity of the material. A material with a higher SM tends to act as a silica-rich precursor that undergoes more pozzolanic reaction. As can be seen from the calculated RM and SM values given in Table 1, both the OPC and GGBS exhibited relatively strong self-cementing activities owing to their higher RM. It is also worth mentioning that owing to their 21.3% and 33.1% of SiO_2 content, respectively, the OPC and GGBS also had pozzolanic reactivity, where the silicates in these two binder materials can be activated by the $Ca(OH)_2$ produced from hydration. The FA used in the present study contained abundant of SiO_2 and less than 15% of CaO and can be classified as class-F fly ash as per ASTM standard (ASTM International 2012), which exhibited a stronger pozzolanic reactivity. Owing to its significantly higher SiO_2 content (i.e., over 90%), the MS had the highest SM among all the four binder materials and this indicates only the pozzolanic reactivity of the material. I should be noted, due to its high fineness, the surface area of the MS is higher than other binders in the present study and this suggests that the MS could be higher-reactive than the FA and the GGBS as pozzolan.

2.1.2 Aggregates

The crushed RAK rock was used as the coarse aggregates for manufacturing SCCs in this study. The coarse aggregate had a nominal maximum grain size of 20 mm, a water absorption of 0.5% and a bulk specific gravity of 2.70. Natural river sand with a nominal maximum grain size of 4.75 mm, a water absorption of 0.85% and a specific gravity of 2.65 was sourced from Unimix in the United Arab Emirates and used as the fine aggregate for all concrete mixes. Both the coarse and fine aggregates were used at their air-dried conditions (i.e., <5% of water) for all the concrete mixes.

2.1.3 Superplasticizer

A high range water reducer used in the present study is a type of Polycarboxylic based superplasticizers GLM 504 and it was provided by BASF. This Polycarboxylate superplasticizer meets and exceeds all requirements of the following standards: ASTM C 494 (ASTM International 1999) Type F, BS EN 934-2 (EN 2001) and AS 1478.1 (Australian Standard 2000).

2.2 Mix designs and specimens preparation

As shown in Table 2, a total of eight unique batches of SCCs were designed to have unary, binary or ternary binders. The four batches of O-series of SCCs with binary binder system were manufactured using a constant binder content of 550 kg/m^3 with MS replacing cement by weight of 0, 10, 15 or 20% and designed to have a targeted slump flow of 750±15 mm. For the remaining four C-series of SCCs, through proper adjustments of their mixing parameters, an equivalent 28-day compressive strength (f'_c) of 35, 48, 80 or 90 MPa were achieved. C-series of SCC with trinary binder system was designed to study the effect of paste volume as well as the effect of blended supplementary cementitious materials with both hydraulic and pozzolanic reactivity on the properties of SCC. Note that aiming to maintain the self-compacting properties (i.e., fluidity) of the concrete, the content of the coarse and fine aggregates were designed to reduce accordingly with the increased targeted compressive strength of the C-series of SCC. A series of tests were undertaken on each batch of SCC to establish the properties of the fresh and hardened concrete, including rheological properties, compressive strength, water absorption, water permeability, rapid chloride permeability and initial surface absorption.

In the preparation of the SCCs, all the dry materials including the fine and coarse aggregates and binders were initially mixed in an 80-L capacity rotating pan mixer with fixed blades for approximately four minutes. Following this, the required mixing water was gradually added into the mix and wet mixing continued for another five minutes to form the concrete. Gentle external vibration was used throughout the pouring processes of all concrete mixes to ensure proper settlement of concrete.

2.3 Test methods and instrumentations

2.3.1 Rheological tests

The rheological properties of the fresh SCCs were assessed through slump flow, V-funnel, U-box, and L-box tests performed in accordance with British standard BS EN 12350 -8, -9, -1, -10 (EN 2010, EN 2010, EN 2010, EN 2010). The flowability of the SCC was evaluated using two methods including: 1) measuring of the time taken by concrete to flow to 500 mm diameter flow-table and 2) measuring the time taken by concrete to flow through V-funnel after 10 s (T10s) and after 5 min (T5 min), respectively. The filling ability of the SCC was assessed using U-box via measuring the difference in height between the two sides of concrete. L-box test was undertaken to establish the concrete passing ability around reinforcement through measuring the time taken for the SCC to reach 200 mm distance (T200 mm), time taken to reach 400 mm distance T400 mm and blocking ratio of heights at the two edges of L-box (H2/H1).

2.3.2 Compressive strength

Two primary types of specimens, namely cube and cylinder, were used for compression tests. Note that the compressive strengths of both the O- and C- series SCCs were obtained through testing the cubic specimens with 150 mm length at each given curing time. In addition, aiming to establish the relationship between cubic and cylindrical compressive strength of SCCs, the compression tests were also conducted using the cylindrical specimens with 100 mm diameter and 200 mm height for C- series SCCs at some give curing ages (i.e., 7, 14 and 28 days). The loading was applied at a rate of 0.3 MPa per second, as per the ASTM standard C39/C39M-05 (ASTM International 2005).

2.3.3 Water absorption and initial surface absorption

Absorption tests were conducted for all SCC mixes in compliance with ASTM standard C642-13 (ASTM International 2013). Cylindrical specimens with 75 mm diameter and 150 mm height that was drilled from the corresponding cubic SCC specimens were used for all the absorption tests. 48 hours after casting in ambient temperature, the hardened SCC cylindrical specimens were initially dried in the oven at a temperature of 105℃ over 72 hours, and then they were subsequently cooled at the ambient temperature (i.e., 25℃) for 24 hours to determine their oven-dried masses (M_O). Subsequently, the cylindrical specimens were immersed in tap water for 48 hours to establish their saturated surface-dry masses (M_S). The water absorption (Ai) of the SCC was then determined from Eq. (3), as per ASTM C642-13 (ASTM International 2013).

$$A_i = (M_S - M_O)/M_O \times 10 \tag{3}$$

The tests of initial rate of absorption (IRA) were performed as per BS EN 1881: Part 101 (EN 1983) with AMD 6728 (1991) sampling method and BS EN 1881: Part 208 (EN 1996) Clause 8.1.3 test specimen preparation method (ASTM International 2013) at the SCC age of 28 days. The test was carried out by applying water at a constant pressure head through a known surface area and the IRA of the SCC was defined as the rate of weight change of the dried specimen over the initial 60 seconds period. The set-up and specimen of the IRA test are illustrated in Fig. 1. The IRA was calculated by Eq. (4).

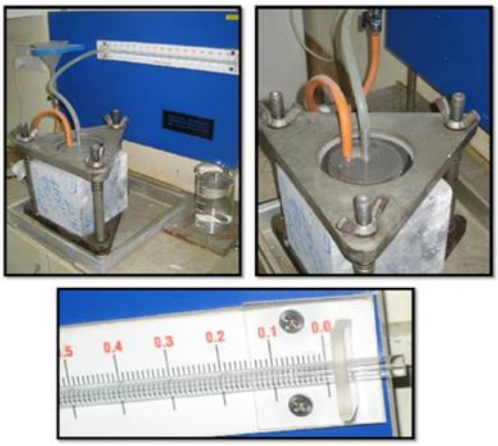


Fig. 1 Initial surface absorption test

Fig. 2 Water permeability test

$$I = \frac{1000(m_2 - m_1)}{A} \tag{4}$$

2.3.4 Water permeability

Water permeability test was conducted using a steady flow method. A head water pressure of 5 bar for 72 hours was used for the test. The water penetration depth was measured from the fracture surface of the specimens to establish the water permeability. The set-up and specimen of the water permeability test are illustrated in Fig. 2.

2.3.5 Rapid chloride permeability (RCP)

The RCP test was based on the BS EN 1881 Part 101 (EN 1983) and ASTM C 1202 (ASTM International 2017) CI 8 and CI 9 test specimen preparation methods. The cubic specimens were initially immersed in water under ambient temperature and vacuum condition for 3 hours. Following this, the specimens were moved to a hot water bath with using boiled water for another 16 to 18 hours and the inside of the hot water bath was also kept vacuuming. After the saturation and immersion, disc specimens with 100 diameter and 50 mm thickness were then cut from the corresponding cubic specimens for each SCC series to conduct the RCP tests. Each disc specimen was inserted into two half-cells and tightly clamped. A differential voltage of 60 mV was allowed to pass each specimen. A resistor is built into the circuit and the current was recorded

Table 3 Rheological properties of the fresh SCCs

Specimen series	First flow (mm)	Second flow (mm)	Third flow (mm)	V-Funnel (sec)	U-box (mm)	L-box (sec)		H1 (mm)	H2 (mm)	H2/H1
						200 mm	400 mm			
C35	745	740	660	3.59	7	2.45	4.16	71	68	96%
C48	700	735	690	2.99	9	2.71	5.12	79	71	90%
C80	780	730	660	4.68	19	1.58	2.45	82	66	80%
C90	760	710	620	5.61	54	1.16	6.16	56	17	30%
O100	>750									
O90S10										
O85S15										
O80S20										

Fig. 3 Rapid chloride permeability test

Table 4 Compressive strength of the SCCs

Specimen series	$f'_{c\text{-}cube}$ (MPa)						$f'_{c\text{-}cylinder}$ (MPa)		
	1-d	3-d	7-d	14-d	28-d	35-d	7-d	14-d	28-d
C35	7.0	-	35.8	50.5	53.5	56.3	34.0	42.2	49.8
C48	12.2		46.3	54.9	62.5	66.8	43.2	51.5	55.8
C80	31.4		69.9	80.8	84.6	85.3	59.1	75.4	76.4
C90	34.2		74.9	90.6	93.2	96.2	71.1	86.2	91.8
O100	-	27.8	44.1	46.2	49.2		-		
O90S10		30.6	47.5	49.3	51.8				
O85S15		29.8	48.1	48.5	54.8				
O80S20		28.3	49.2	55.3	56.5				

at intervals by connecting the resistor to a data logging system. The set-up and specimen of the RCP test are illustrated in Fig. 3.

3. Test results and discussions

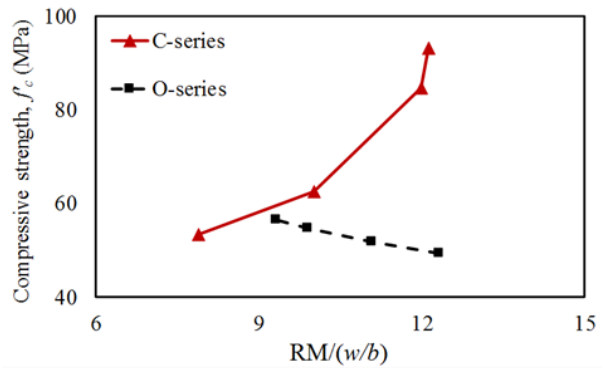
3.1 Rheological properties of fresh SCCs

The rheological properties of fresh SCCs are summarized in Table 3. As can be seen from the table, all the four C-series of SCCs attained over 700 mm first flow measured at 1-minute after the mixing and their slump flow values all exceeded the requirements of a 'workable mix' for a slump flow value range from 640 to 800 mm as reported in the British standard (EN 2010). It can also be seen from the table, the SCC at higher strength grade exhibited lower the second and third flow values compared to those of its lower strength counterparts. This is mainly due to the lower water content in the SCC which is designed to have a higher compressive strength. In addition the V-funnel, U-box and L-box test results given in Table 3 further indicate that the SCC designed to have a higher strength exhibited inferior self-compacting properties in terms of the longer passing time through the V-funnel, larger difference between the SCC in the compartment of the U-box that had been filled, and the lower blocking (H2/H1) ratio established using the L-box test. Note that the C90 series failed to meet the required filling ability and confined flowability for a workable SCC as reported in the British standard (EN 2010), in which the U-box result of the C90 SCC series was higher than 30 mm and the blocking ratio obtained from the L-box test was lower than 80%. No comprehensive rheological tests were carried out for the O-series SCC owing to their similar mix proportions to those of the flowable C48 and C90 series and the *w/b* ratio used for each of the O-series SCC was even higher. As reported in Table 3, the measured first flow values of all the O-series SCCs were higher than 750 mm which indicated the favourable rheological properties of the concrete.

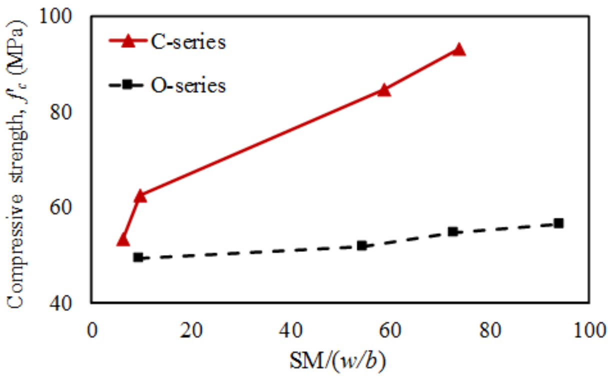
3.2 Compressive strength

The cubic compressive strengths ($f'_{c\text{-}cube}$) of the C-series of SCC were periodically measured up to the concrete age of 35 days and cylindrical compressive strengths ($f'_{c\text{-}cylinder}$) of the C-series of SCC were established through the compression tests at the concrete age of 7, 14 and 28 days. Table 4 reports the $f'_{c\text{-}cube}$ and $f'_{c\text{-}cylinder}$ of the C-series of SCCs at each given curing age, where the results were averaged from compression tests on three identical specimens. As presented in the table, all the four C-series of SCCs reached and exceeded their targeted 28-day $f'_{c\text{-}cube}$ through proper adjusting the mixing parameters.

For the O-series of SCCs, it is observed that the increased MS replaced cement ratio in conjunction with the increase in the *w/b* ratio resulted in the increase in f'_c of the SCC. This can be explained by the fact that with the increased MS replaced cement ratio, the coarser part of the supplementary MS acted as the micro-fillers remained in the matrix of the concrete and refined the microstructure of the concrete. And the finer part of the supplementary MS underwent pozzolanic reaction with $Ca(OH)_2$ produced



(a) Reactive modulus



(b) Silica modulus

Fig. 4 Relationship between the 28-day $f'_{c\text{-}cube}$ and the factor consisted of the reactive index and the inverse of water-to-binder ratio

from hydration to form additional C-S-H hydrates, which has higher compressive strength than $Ca(OH)_2$ crystalline (Struble and Tebaldi 2017). Therefore, even with a higher *w/b* ratio, the micro-filling effect provided by the MS and the formation of secondary C-S-H hydrates contributed to the higher f'_c of the SCC with a higher MS replaced cement ratio.

Aiming to investigate the effect of the blended binders on compressive strength of SCCs, a unified approach is proposed based on the mix proportion of concrete and the chemical composition of the corresponding binders. Regardless of the packing effect (i.e., the content of fine and coarse aggregates), the mechanical strength of a concrete generally depends on the reactivity of the binders and the *w/b* ratio used for its mix. As introduced in Section 2.1.1, the reactivity of each individual binder can be assessed using the RM or SM depending on the major type of reaction that it is prone to participate (i.e., hydration or pozzolanic reaction). The reactivity index (i.e., RM or SM) of the unary, binary or ternary binders can be calculated by adding up the reactivity index of each individual binder material as per their weight ratio. The calculated RM and SM of the binders for each SCC are summarized in Table 2. Owing to the well-known fact that the f'_c of a conventional concrete an increase in the *w/b* used for its mix (Nikbin *et al*. 2014), the inverse of *w/b* ratio is integrated with the RM or SM to form the reactive index expressed as $\frac{RM}{w/b}$ or $\frac{SM}{w/b}$ to assess the f'_c of the SCCs with blended binders. Fig. 4 (a)-(b) illustrates the relationship between the 28-day $f'_{c\text{-}cube}$ and the reactive indices. It is evident from Fig. 4(a) that the $f'_{c\text{-}cube}$ of the C-series of SCCs increased with an increase in the $\frac{RM}{w/b}$ as the consequences of the increased hydration activity of the binders together with the decreased *w/b* ratio used for the mix. It is worth noting that the $f'_{c\text{-}cube}$ increment with the increased $\frac{RM}{w/b}$ is more pronounced between the C80 and the C90 series of SCC compared to that between the C35 and the C48 series of SCC. This observation is due to the inclusion of the MS in the mixes of the C80 and C90 SCC series, in which the RM only represents the hydration reactivity and is not able to fully characterize the severe pozzolanic effect provided by the superfine MS. It is observed that the $f'_{c\text{-}cube}$ of O-series of the SCCs decreased with an increase in $\frac{RM}{w/b}$ as shown in Fig. 4(a). This can also be explained by the fact that the pozzolanic effect provided by the included MS cannot be completely characterized by the RM. However, it is evident from Fig. 4(b) that the $f'_{c\text{-}cube}$ of the C-series of SCCs increased with an increase in the $\frac{SM}{w/b}$. This indicates that the SCCs with blended binders of OPC, MS, FA and GGBS also underwent pozzolanic reactions due to the abundant SiO_2 in their binders. The index of $\frac{SM}{w/b}$ well-reflects the increase in the $f'_{c\text{-}cube}$ of the O-series of SCCs with the increased MS content due to the formation of additional pozzolanic products (i.e., C-S-H hydrates), as shown in Fig. 4(b).

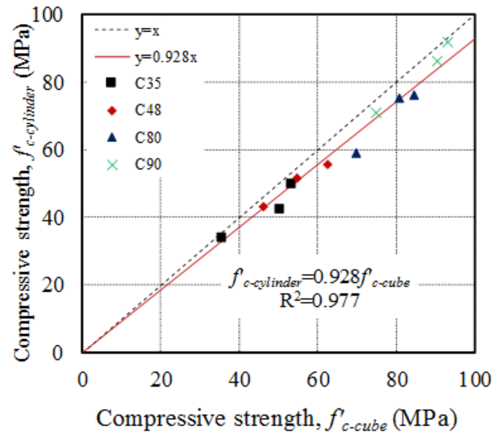


Fig. 5 Relationship between the cubic and cylindrical compressive strength of SCCs

3.3 The relationship between the cubic and cylindrical compressive strength

It is well understood that the shape of the test specimen (i.e., cube or cylinder) affects the concrete compressive strength. This is due to that the contact area between a standard cubic concrete specimen and the plates of the testing machine is more than that of its cylindrical specimen counterpart and results in a more confinement resist against concrete expansion seen in a cubic specimen, leading to the higher f'_c of the cubic specimen. The $f'_{c\text{-}cylinder}$ to $f'_{c\text{-}cube}$ ratio of the SCC was also established using the compression

Table 5 Change in compressive strength with curing age

Specimen series	Change in $f'_{c\text{-}cube}$			
	1 to 7 d	7 to 14 d	14 to 28 d	28 to 35 d
C35	415%	41%	6%	5%
C48	278%	19%	14%	7%
C80	122%	16%	5%	1%
C90	119%	21%	3%	3%
	3 to 7	7 to 14	14 to 28	
O100	59%	5%	7%	-
O90S10	55%	4%	5%	
O85S15	61%	1%	13%	
O80S20	74%	12%	2%	

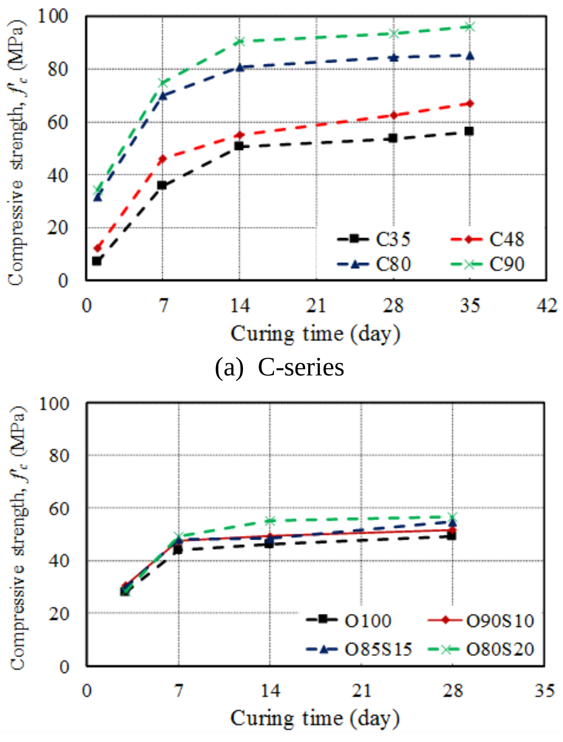


Fig. 6 Variation of compressive strengths of SCCs with curing age

strength of the C-series of SCCs at the concrete ages of 7, 14 and 28 days. Fig. 5 shows the relationship between the cubic and cylindrical compressive strength of the SCCs. The trendline expression shown in the figure indicates that the ratio between the $f'_{c\text{-}cube}$ and $f'_{c\text{-}cylinder}$ is around 0.928.

3.4 Variation of compressive strength with curing time

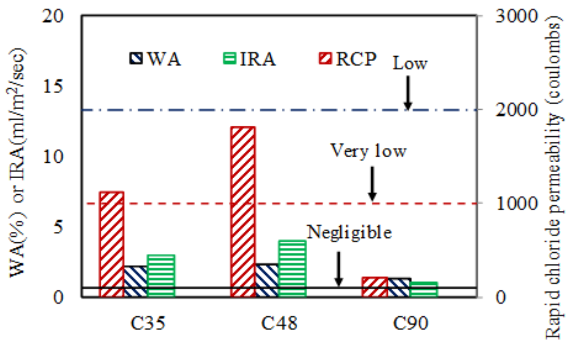
The variations of compressive strength of the C- and O-series of SCCs with curing time are shown in Fig. 6 (a)-(b), respectively and the relative strength gains are listed in Table 5. As shown in Table 5, for the C-series of the SCCs, the compressive strength gain was less significant for the SCC at a higher strength grade at the initial curing stage (i.e., for the curing age before 7 days), whereas no clear trend can be observed about influence of the concrete strength grade on the strength gain after the concrete age of 7 days. This observation can be attributed to the significantly higher early compressive strength of the concrete at a higher compressive strength, which consumed more raw materials and resulted in a subsequently lower rate of strength development in the following age. Table 5 also shows that for the O- SCC series, the increased the *w/b* ratio and MS content accelerated the early strength gain of the SCC. It is known that the increased MS content in a concrete mix significantly shortens the setting time and accelerates the hardening of the concrete as that the pozzolanic reaction of MS is very rapid at the early curing age (Ghafari *et al.* 2014, Jalal *et al.* 2015, Kadri and Duval 2009). Therefore, even with a higher *w/b* ratio used for its mix, the more significant strength gain at the early age of the O-SCC series is mainly due to the increased MS content in the mix.

3.5 Durability of the SCCs

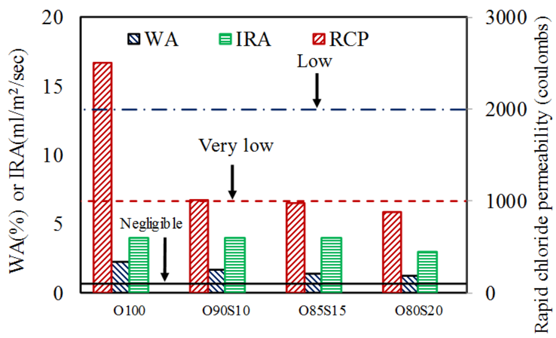
Table 6 shows the results of all the durability tests, including the water absorption (WA), initial rate of surface absorption (IRA), water permeability (WP) and rapid chloride permeability (RCP). Fig. 7(a)-(b) illustrates the WA, IRA and RCP values of C- and O- SCC series, respectively. As can be seen from Fig. 7(a), for the C-series of SCC, the C90 SCC series with a higher f'_c exhibited better durability properties, in terms of its lower WA, IRA and RCP values compared to those of C48 SCC series counterpart with a lower f'_c. This observation is in agreement with those reported in the literature (Chen and Wu 2013, Nikbin *et al.* 2014) and can be attributed to the decreased porosity with the increased compressive strength of the concrete (Da Silva and De Brito 2015, Lian *et al.* 2011, Yudenfreund *et al.* 1972). However, the C35 SCC series, which had a lower f'_c than the C48 SCC series, showed the improved durability properties than those of its C48 SCC series counterpart. To explain the potential underlying actions of these observations of the durability properties the C-series of SCCs, the constituent of the SCC and their effects on the pore structure of concrete are carefully inspected. It is known that a hardened concrete generally consists of three major components, namely paste matrix, aggregates (including both coarse and fine aggregates) and interfacial transition zone (ITZ) between the paste matrix and the aggregates and these are the three key phases which significantly affect the pore structure of a concrete (Gao *et al.* 2014, Scrivener *et al.* 2004). Based on the experimental results provided in the literature, the porosity of the paste in the concrete with a moderate compressive strength (i.e., around 55 MPa) is commonly within the range of 20% to 25% (Chen *et al.* 2013) and the porosity of normal weight natural aggregates is generally less than 3% (Elchalakani *et al.* 2016, Xie and Ozbakkaloglu 2016). Therefore, the porous paste predominates the overall porosity of the concrete with a low to moderate compressive strength, whereas the aggregates only have a minor effect on the overall porosity of the concrete. As the compressive strength reported in Table 4 and the mix proportion reported in Table 2, the C35 and C48 series of SCC both had a moderate 28-day f'_c (i.e., 53.5 and 63.5 MPa, respectively) and a nearly same aggregate

Table 6 Rheological properties of the fresh SCCs

Specimen series	Water penetration depth (mm)	Water absorption (%)	The Rapid Chloride Permeability (coulombs)	Initial surface absorption test (ml/m^2/sec)	Bulk density (kg/m^3)					
					1-d	3-d	7-d	14-d	28-d	35-d
C35	11	2.2	1124	0.03	2327		2382	2388	2373	2363
C48	15	2.3	1815	0.04	2330		2370	2383	2388	2390
C80	-	-	-	-	2430		2463	2477	2487	2453
C90	8	1.3	212	0.01	2460		2480	2500	2535	2457
O100	15	2.26	2510	0.04		2301	2275	2287	2292	
O90S10	7	1.68	1010	0.04		2287	2274	2295	2279	
O85S15	6	1.38	983	0.04		2309	2276	2283	2304	
O80S20	6	1.26	879	0.03		2267	2275	2283	2284	

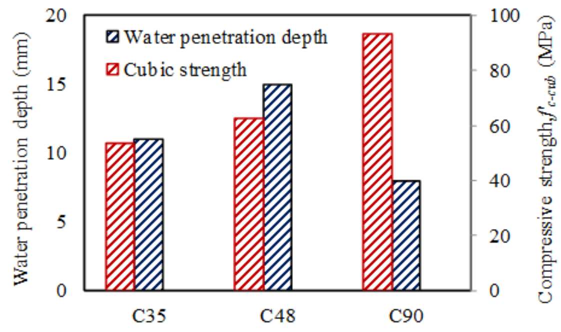


(a) C-series

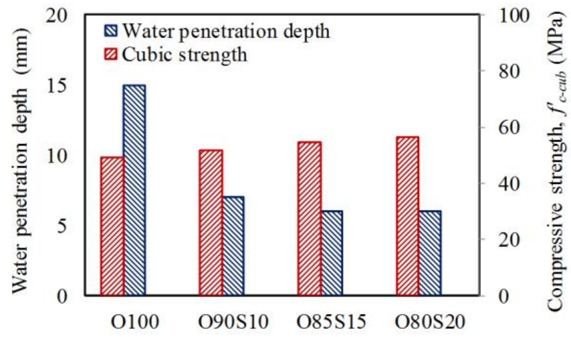


(b) O-series

Fig. 7 Water absorption, initial rate of absorption and rapid chloride permeability results



(a) C-series



(b) O-series

Fig. 8 Water penetration depth

weight fraction (i.e., 72% and 69%, respectively). This comparable aggregate weight fraction indicates the nearly same ITZ volume in both of the SCC. However, based on their mix proportions as shown in Table 2, it can is observed that the C48 contained 11.3% higher fraction of porous paste compared to the C35 series of SCC and this subsequently led to the inferior durability of the C48 even with a higher compressive strength. It is worth noting that as indicated in Fig. 7(a), The RCP results of the three C-series SCCs were all lower than 2000 coulombs, which suggest the favorable durability of the C-series SCCs according to ASTM standard C1202 -17a (ASTM International 2017). The water penetration depth (WPD) results of C-series of SCCs presented in Table 6 and shown in Fig. 8(a) are in support of the above-mentioned mechanisms.

It can be seen from Figs. 7(b)-8(b) that, for the O- series of SCCs, the concrete with a higher compressive strength exhibited better durability in terms of the relatively lower WA, IRA and RCP compared to those of its lower strength counterparts. Note that the slight increase in f'_c of O-series SCCs was associated with the increased MS replaced cement ratio. As explained in the previous section, the above observations can be attributed to the micro-filler effect provided by the unreacted MS and the additional hydrates from the pozzolanic reaction of the reacted MS which resulted in the refinements of the microstructure of the SCC with the decreased porosity. It is worth noting that with the inclusions of the MS, the O90S10, O85S15 and O80S20 had their RCP values approximately lower than 1000 coulombs which indicated the very lower chloride ion penetrated into the concretes as per the requirements given in ASTM standard C1202-17a (ASTM International 2017).

However, for O100 series of SCC, it exhibited an over 2000 coulombs RCP value which was experienced a low to moderate chloride ion penetrated into the concrete as per ASTM standard C1202-17a (ASTM International 2017). The WPD results reported in Table 6 and as illustrated in Fig. 8(b) further confirmed the refined microstructure of the SCC, in which the WPD decreased with increases in the f'_c and the MS replaced cement ratio.

4. Conclusions

This paper has reported the results of an experimental study to investigate the mechanical and durability properties of the SCC contained blended binders. Based on the results and discussions presented, the following conclusions can be drawn：

1. Through proper adjustments of the mixing parameters, such as progressively increased the binder content and reduced aggregate content for the mix, a high strength SCC can be produced without comprising the self-compacting properties of the concrete.
2. The inclusion of MS in a SCC mix can slightly increase the compressive strength of the concrete mixed using an even higher *w/b* ratio.
3. The hydraulic and the pozzolanic reactivity of blended binders and the related individual source materials can be characterized using the reactive modulus and the silica modulus, respectively. For a SCC prepared using blended binders, its compressive strength strongly correlates to the *w/b* ratio used for the mix and the reactivity of the blended binders.
4. A SCC prepared using higher reactive binders and a lower *w/b* ratio exhibits a very high initial compressive strength (i.e., before the concrete age of 1 day) and relatively slow compressive strength development over the following curing time. This is due to the more severe chemical reaction in the concrete at the very early stage which consumes more raw materials and deaccelerates the further rate reaction.
5. The inclusion of MS in a SCC mix significantly improves the durability properties of the concrete, including the lower water absorption (WA), initial rate of surface absorption (IRA), water permeability (WP) and rapid chloride permeability (RCP).
6. For concrete at a low to moderate strength grade, a SCC with a lower strength can be more durable than a SCC with a higher compressive strength. This can be achieved by properly reducing the paste volume in the concrete as the paste fraction predominates the overall porosity of the concrete at a low to moderate strength grade.
7. The proposed unified approach based on the fundamental chemical composition of the blended binder and mix proportion of SCC can serve as a baseline for future mix design of SCC.

References

Almuwbber, O., Haldenwang, R., Mbasha, W. and Masalova, I. (2018), “The influence of variation in cement characteristics on workability and strength of SCC with fly ash and slag additions”, *Constr. Build. Mater.*, **160**, 258-267.

ASTM International (1999), ASTM C 494-99. Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, 4.

ASTM International (2005), ASTM C39/C39M-05. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken.

ASTM International (2012), ASTM C618-12. Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken.

ASTM International (2013), ASTM C642-13. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken.

ASTM International (2017), ASTM C1202-17a, Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration, ASTM International, West Conshohocken.

Atiş, C.D. and Bilim, C. (2007), “Wet and dry cured compressive strength of concrete containing ground granulated blast-furnace slag”, *Build. Environ.*, **42**(8), 3060-3065.

Australian Standard (2000), AS 1478.1-2000. Chemical Admixtures for Concrete, Mortar and Grout Admixtures for Concrete, Standards Australia, Sydeny.

Badogiannis, E., Kakali, G., Dimopoulou, G., Chaniotakis, E. and Tsivilis, S. (2005), “Metakaolin as a main cement constituent. Exploitation of poor Greek kaolins”, *Cement Concrete Compos.*, **27**(2), 197-203.

Behim, M., Beddar, M. and Clastres, P. (2013), “Reactivity of granulated blast furnace slag”, *Slovak J. Civil Eng.*, **21**(2), 7-14.

Benaicha, M., Roguiez, X., Jalbaud, O., Burtschell, Y. and Alaoui, A.H. (2015), “Influence of silica fume and viscosity modifying agent on the mechanical and rheological behavior of self compacting concrete”, *Constr. Build. Mater.*, **84**, 103-110.

Bingöl, A.F. and Tohumcu, İ. (2013), “Effects of different curing regimes on the compressive strength properties of self compacting concrete incorporating fly ash and silica fume”, *Mater. Des.*, **51**, 12-18.

Binici, H. and Aksoğan, O. (2006), “Sulfate resistance of plain and blended cement”, *Cement Concrete Compos.s*, **28**(1), 39-46.

Binici, H., Temiz, H. and Köse, M.M. (2007), “The effect of fineness on the properties of the blended cements incorporating ground granulated blast furnace slag and ground basaltic pumice”, *Constr. Build. Mater.*, **21**(5), 1122-1128.

Bouzoubaa, N. and Lachemi, M. (2001), “Self-compacting concrete incorporating high volumes of class F fly ash: Preliminary results”, *Cement Concrete Res.*, **31**(3), 413-420.

Chen, X. and Wu, S. (2013), “Influence of water-to-cement ratio and curing period on pore structure of cement mortar”, *Constr. Build. Mater.*, **38**, 804-812.

Chen, Y.Y., Tuan, B.L.A. and Hwang, C.L. (2013), “Effect of paste amount on the properties of self-consolidating concrete containing fly ash and slag”, *Constr. Build. Mater.*, **47**, 340-346.

Da Silva, P. and De Brito, J. (2015), “Experimental study of the porosity and microstructure of self-compacting concrete (SCC) with binary and ternary mixes of fly ash and limestone filler”, *Constr. Build. Mater.*, **86**, 101-112.

Dadsetan, S. and Bai, J. (2017), “Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash”, *Constr. Build. Mater.*, **146**, 658-667.

Dave, N., Misra, A.K., Srivastava, A. and Kaushik, S. (2017), “Setting time and standard consistency of quaternary binders: The influence of cementitious material addition and mixing”, *Int. J. Sustain. Built Environ.*, **6**(1), 30-36.

Deilami, S., Aslani, F. and Elchalakani, M. (2017), “Durability assessment of self-compacting concrete with fly ash”, *Comput. Concrete*, **19**(5), 489-499.

El-Chabib, H. and Syed, A. (2012), “Properties of self-consolidating concrete made with high volumes of supplementary cementitious materials”, *J. Mater. Civil Eng.*, **25**(11), 1579-1586.

Elchalakani, M., Aly, T. and Abu-Aisheh, E. (2014), “Sustainable concrete with high volume GGBFS to build Masdar City in the UAE”, *Case Stud. Constr. Mater.*, **1**, 10-24.

Elchalakani, M., Basarir, H. and Karrech, A. (2016), “Green concrete with high-volume fly ash and slag with recycled aggregate and recycled water to build future sustainable cities”, *J. Mater. Civil Eng.*, **29**(2), 04016219.

EN (1983), BS EN 1881-101, Testing Concrete. Method of Sampling Fresh Concrete on Site, British Standards Institution, London, United Kingdom.

EN (2001), BS EN 934-2: Admixtures for Concrete, Mortar and Grout. Concrete Admixtures. Definitions, Requirements, Conformity, Marking and Labelling, British Standards Institution, London, United Kingdom.

EN (2010), BS EN 12350-1, Testing Fresh Concrete. Self-Compacting Concrete. u- Box Test, British Standards Institution, London, United Kingdom.

EN (2010), BS EN 12350-8,Testing Fresh Concrete. Self-Compacting Concrete. Slump-flow Test, British Standards Institution, London, United Kingdom.

EN (2010), BS EN 12350-9, Testing Fresh Concrete. Self-Compacting Concrete. V-Funnel Test, British Standards Institution, London, United Kingdom.

EN (2010), BS EN 12350-10, Testing Fresh Concrete. Self-Compacting Concrete. L Box Test, British Standards Institution, London, United Kingdom.

Farhang, K. and Fathi, H. (2017), “Performance of concrete structures with a combination of normal SCC and fiber SCC”, *Comput. Concrete*, **20**(6), 655-661.

Fathi, H. and Lameie, T. (2017), “Effect of aggregate type on heated self-compacting concrete”, *Comput. Concrete*, **19**(1), 33-39.

Gao, Y., De Schutter, G., Ye, G., Tan, Z. and Wu, K. (2014), “The ITZ microstructure, thickness and porosity in blended cementitious composite: Effects of curing age, water to binder ratio and aggregate content”, *Compos. Part B: Eng.*, **60**, 1-13.

Gesoğlu, M., Güneyisi, E. and Özbay, E. (2009), “Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume”, *Constr. Build. Mater.*, **23**(5), 1847-1854.

Ghafari, E., Costa, H., Júlio, E., Portugal, A. and Durães, L. (2014), “The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete”, *Mater. Des.*, **59**, 1-9.

Hassan, A.A., Lachemi, M. and Hossain, K.M. (2012), “Effect of metakaolin and silica fume on the durability of self-consolidating concrete”, *Cement Concrete Compos.*, **34**(6), 801-807.

Jalal, M., Pouladkhan, A., Harandi, O.F. and Jafari, D. (2015), “Comparative study on effects of Class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete”, *Constr. Build. Mater.*, **94**, 90-104.

Jawahar, J.G., Sashidhar, C., Reddy, I.R. and Peter, J.A. (2013), “Design of cost-effective M 25 grade of self compacting concrete”, *Mater. Des.*, **49**, 687-692.

Jawahar, J.G., Sashidhar, C., Reddy, I.R. and Peter, J.A. (2013), “Micro and macrolevel properties of fly ash blended self compacting concrete”, *Mater. Des.*, **46**, 696-705.

Kadri, E.H. and Duval, R. (2009), “Hydration heat kinetics of concrete with silica fume”, *Constr. Build. Mater.*, **23**(11), 3388-3392.

Khan, A., Do, J. and Kim, D. (2016), “Cost effective optimal mix proportioning of high strength self compacting concrete using response surface methodology”, *Comput. Concrete*, **17**(5), 629-638.

Khan, M.I. and Siddique, R. (2011), “Utilization of silica fume in concrete: Review of durability properties”, *Resour. Conserv. Recycl.*, **57**, 30-35.

Le, H.T. and Ludwig, H.M. (2016), “Effect of rice husk ash and other mineral admixtures on properties of self-compacting high performance concrete”, *Mater. Des.*, **89**, 156-166.

Lian, C., Zhuge, Y. and Beecham, S. (2011), “The relationship between porosity and strength for porous concrete”, *Constr. Build. Mater.*, **25**(11), 4294-4298.

Liu, M. (2010), “Self-compacting concrete with different levels of pulverized fuel ash”, *Constr. Build. Mater.*, **24**(7), 1245-1252.

Long, G., Gao, Y. and Xie, Y. (2015), “Designing more sustainable and greener self-compacting concrete”, *Constr. Build. Mater.*, **84**, 301-306.

Nikbin, I., Beygi, M., Kazemi, M., Amiri, J.V., Rabbanifar, S., Rahmani, E. and Rahimi, S. (2014), “A comprehensive investigation into the effect of water to cement ratio and powder content on mechanical properties of self-compacting concrete”, *Constr. Build. Mater.*, **57**, 69-80.

Ponikiewski, T. and Gołaszewski, J. (2014), “The influence of high-calcium fly ash on the properties of fresh and hardened self-compacting concrete and high performance self-compacting concrete”, *J. Clean. Prod.*, **72**, 212-221.

Rama, K.J., Sivakumar, M., Vasan, A., Kubair, S. and Murthy, R.A. (2017), “Plastic viscosity based mix design of self-compacting concrete with crushed rock fines”, *Comput. Concrete*, **20**(4), 461-468.

Sabet, F.A., Libre, N.A. and Shekarchi, M. (2013), “Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash”, *Constr. Build. Mater.*, **44**, 175-184.

Scrivener, K.L., Crumbie, A.K. and Laugesen, P. (2004), “The interfacial transition zone (ITZ) between cement paste and aggregate in concrete”, *Interf. Sci.*, **12**(4), 411-421.

Sethy, K.P., Pasla, D. and Sahoo, U.C. (2016), “Utilization of high volume of industrial slag in self compacting concrete”, *J. Clean. Prod.*, **112**, 581-587.

Struble, L. and Tebaldi, G. (2017), “Materials for sustainable infrastructure”, *Proceedings of the 1st GeoMEast International Congress and Exhibition*, Egypt.

Turk, K., Karatas, M. and Gonen, T. (2013), “Effect of fly ash and silica fume on compressive strength, sorptivity and carbonation of SCC”, *KSCE J. Civil Eng.*, **17**(1), 202-209.

Uysal, M. and Sumer, M. (2011), “Performance of self-compacting concrete containing different mineral admixtures”, *Constr. Build. Mater.*, **25**(11), 4112-4120.

Vakhshouri, B. and Nejadi, S. (2017), “Compressive strength and mixture proportions of self-compacting light weight concrete”, *Comput. Concrete*, **19**(5), 555-566.

Wongkeo, W., Thongsanitgarn, P., Ngamjarurojana, A. and Chaipanich, A. (2014), “Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume”, *Mater. Des.*, **64**, 261-269.

Xie, T. and Ozbakkaloglu, T. (2016), “Behavior of recycled aggregate concrete-filled basalt and carbon FRP tubes”, *Constr. Build. Mater.*, **105**, 132-143.

Xie, T. and Visintin, P. (2018), “A unified approach for mix design of concrete containing supplementary cementitious materials based on reactivity Moduli”, *J. Clean Prod.*, **203**, 68-82.

Yazıcı, H. (2008), “The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze-thaw resistance of self-compacting concrete”, *Constr.*

Build. Mater., **22**(4), 456-462.

Yudenfreund, M., Odler, I. and Brunauer, S. (1972), "Hardened portland cement pastes of low porosity I. Materials and experimental methods", *Cement Concrete Res.*, **2**(3), 313-330.

Zhang, M., Tam, C. and Leow, M. (2003), "Effect of water-to-cementitious materials ratio and silica fume on the autogenous shrinkage of concrete", *Cement Concrete Res.*, **33**(10), 1687-1694.

Zhao, H., Sun, W., Wu, X. and Gao, B. (2015), "The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures", *J. Clean. Prod.*, **95**, 66-74.

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