Computers and Concrete, *Vol. 19, No. 5 (2017) 489-499*
DOI: https://doi.org/10.12989/cac.2017.19.5.489

Durability assessment of self-compacting concrete with fly ash

Sahar Deilami[a], Farhad Aslani[*] and Mohamed Elchalakani[b]

School of Civil, Environmental and Mining Engineering, University of Western Australia, WA 6009, Crawley, Australia

(Received August 25, 2016, Revised January 18, 2017, Accepted January 19, 2017)

Abstract. Self-Compacting Concrete (SCC) is a new technology capable to flow without segregation or any addition of energy which leads to efficient construction and cost savings. In this study, the effect of replacing the Ordinary Portland Cement (OPC) with Fly Ash (FA) on the strength, durability of the concrete was investigated experimentally, and carbon footprint and cost were also assessed. Four different replacement FA ratios (0%, 20%, 40% and 60%) were used to create four SCC mixes. Standard test methods were used to determine the workability, strength, and durability of the SCC mixes including resist chloride ion penetration, water permeability, water absorption, and initial surface absorption. The axial cube compressive strength tests were performed on the SCC mixes at 1, 7, 14, 28 and 35 days. Replacing the OPC with FA had a significant positive impact on chloride iron penetration resistance and water absorption but had a considerable negative impact on the compressive strength. The SCC mix with 60% FA had 36.7% and 15.8% enhancement in the resistance to chloride ion penetration and water absorption, respectively. Evaluation of the carbon footprint and the cost of each SCC mixes showed the CO_2 emissions mixes 1, 2, 3 and 4 were significantly reduced by increasing the FA content from 0% to 60%. Compared with the control mix, the cost of all mixes increased when the FA content increased, but no significant differences were seen between the estimated costs of all four mixes.

Keywords: self-compacting concrete; durability; fly ash; resist chloride ion penetration; water permeability; water absorption; initial surface absorption

1. Introduction

Self-compacting concrete (SCC) was first developed around 30 years ago in Japan with the aim of enhancing the mechanical characteristics and durability of concrete (Khayat 1999, Ahmadi *et al.* 2007, Ryan and O’Connor 2016). SCC has been increasingly used in construction due to its advantages. SCC has the capability to flow and completely fill air voids without requiring any mechanical vibration or compaction. It also has an excellent workability, segregation resistance and less bleeding (Khayat 1999, Kapoor *et al.* 2003, Nazmy *et al.* 2003, Ahmadi *et al.* 2007, Aslani and Nejadi 2013, Ryan and O’Connor 2016).

SCC is composed of powder materials supplemented with mineral additives. These mineral additives not only raise the slump of concrete but also lower the construction costs by reducing the cement content which is the costly component of concrete (Aslani and Samali 2014).

Durability, workability, and strength of concrete have been identified as issues of concern by industry during the last decade, and this also applies to SCC. To overcome these issues, fine materials, and other additives have been incorporated into concrete, including FA (Dhiyaneshwaran *et al.* 2013, Khan and Sharma 2015, Zhao *et al.* 2015, Ryan and O’Connor 2016). FA is often used in SCC due to its water reducing properties. Replacement of aggregates with mineral additives such as FA leads to high-strength SCC with a minor effect on its early age strength (Sri Ravindrarajah *et al.* 2003).

FA improves the flowability, workability, and durability of SCC mixes, as it shows a pozzolanic and hydraulic behaviour as an additive cementitious material (Nath and Sarker 2011, Jino *et al.* 2012, Balakrishnan and Paulose 2013, Dhiyaneshwaran *et al.* 2013, Swamy *et al.* 2015, Khan and Sharma 2015, Güneyisi *et al.* 2015, Mahalingam *et al.* 2016).

Durability and strength characteristics of SCC improves by using mineral admixtures such as FA. Also, the durability of concrete is defined as the capability of concrete to resist chemical attack, abrasion, and weathering action or any other condition of service (ACI.CT-13 2013). Permeable voids, water absorption (WA), acid attack, and resist chloride ion penetration (RCP) have significant effects on the durability of concrete. In most tests on durability, greater absorbent voids, and WA were recorded for SCC with high FA content compared to normal vibrated concrete, when the testing was carried out at the same strength level (Dinakar *et al.* 2008, Amrutha *et al.* 2011 and Jino *et al.* 2012). However, SCC mixes with high FA content presented lower chloride ion penetration (Dinakar *et al.* 2008). Particularly, increasing the wet curing period together with high volume FA in SCC could potentially reduce the chloride permeability and permeable voids in the same strength level, when compared to normal concrete.

∗Corresponding author, Senior Lecturer
E-mail: farhad.aslani@uwa.edu.au
[a]Ph.D. Student
E-mail: sahar.deilami@research.uwa.edu.au
[b]Senior Lecturer
E-mail: mohamed.elchalakani@uwa.edu.au

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

Table 1 Chemical compositions of OPC & FA

Chemical compositions	SIO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Mn_2O_3	SO_3	S	CI
PC-CEM I 42.5 N BS EN 197 (2000)	21.29	4.89	3.42	64.16	1.41	-	2.53	-	0.01
FA-ASTM C618ClassF	70(min)	-	-	-	-	-	5	N/A	-

Table 2 Content proportions of SCC mixes

Mixes	FA (%)	FA (%)	FA (kg/m^3)	Water	SP	w/b	w/c
Mix1	0%	0%	0	173	8.8	0.31	0.31
Mix2	20%	20%	110	173	8.8	0.31	0.39
Mix3	40%	40%	220	173	8.8	0.31	0.52
Mix4	60%	220	330	173	8.8	0.31	0.78

Table 3 Properties and laboratory trail result of Mix1

Materials	Source	SSD wt (kg)	Wat.Abs %	Dry wt (kg)	Moist. %	Corrected (kg)	Batch wt (kg)
Cement (OPC)	RAK CC/UCC	550	-	550	-	550	44
FA	Ash Res/Cemex	-	-	-	-	0	0
Free Water	DEWA	173	-	183	-	154	12.32
Aggregate 20 mm	Unimix	376	0.4	374	-	374	29.92
Aggregate 10 mm	Unimix	271	0.6	296	-	269	21.52
0-5 mm C.sand	Unimix	-	-	-	-	0	0
0-5 mm W.sand	S.R RAK	477	0.7	473	7	506	40.49
D.sand	Al Ain	477	0.9	472		472	37.76

Table 4 Properties and laboratory trail result of Mix2

Materials	Source	SSD wt (kg)	Wat.Abs %	Dry wt (kg)	Moist. %	Corrected (kg)	Batch wt (kg)
Cement (OPC)	RAK CC/UCC	440	-	440	-	440	35.20
FA	Ash Res/Cemex	110	-	110	-	110	8.8
Free Water	DEWA	173	-	183	-	154	12.32
Aggregate 20 mm	Unimix	376	0.4	374	-	374	29.92
Aggregate 10 mm	Unimix	271	0.6	269	-	269	21.52
0-5 mm C.sand	Unimix	-	-	-	-	-	-
0-5 mm W.sand	S.R RAK	477	0.7	473	7	506	40.49
D.sand	Al Ain	477	0.9	472	-	472	37.36

Hence, the SCC mixes with high volume FA can be considered in the category of very low chloride permeability (Amrutha *et al.* 2011).

Segregation and bleeding resistance of SCC can be obtained by reducing the water content and increasing the fine powder materials such as FA, Viscosity Modifying Additives (VMA) and superplasticizers (Shen *et al.* 2016). Incorporation of FA in SCC mixes could reduce the chance of bleeding and segregation with improved filling and passing ability of concrete (Balakrishnan and Paulose 2013). VMA as a mineral admixture effects on workability, stability, durability and segregation of SCC. Besides, a little change on VMA effects on fresh properties of SCC. The SCC mixes containing VMA and FA presents the better workability and durability properties with increasing the FA content. Also, the increase of superplasticizer content improves the workability properties of SCC. Also, increasing the FA content reduces the saturated WA and compressive strength value of SCC mixes (Dhiyaneshwaran *et al.* 2013).

Stability and flowability are important properties of SCC (Aslani and Nejadi 2012a, b, c, d, e, Aslani and Nejadi 2013a, b, Aslani 2013, Aslani and Maia 2013, Aslani and Natoori 2013, Aslani and Bastami 2014, Aslani *et al.* 2014a, b, 2015). The high flowability and high stability of SCC can be achieved by increasing the mineral fines and admixtures into the concrete by affecting the viscosity of the mixes (NRMCA 2004). However, there are no changes can be observed on flowability and stability of the SCC with the incorporation of FA with ground granulated blast furnace slag (GGBS) in the SCC. The integration of FA with GGBS in SCC indicated a reduction of strength and increase of porosity of SCC in the early curing time; however, no major changes observed at the later curing period. The incorporation of FA with GGBS presented the considerable RCP and drying shrinkage due to the higher carbonation depth of SCC mixes when compared with the control SCC (Zhao *et al.* 2015).

Durability properties of SCC mixes containing mineral additives indicated a good relationship between the strength and absorption of concretes. In most cases, the use of mineral admixtures such as FA, lime powder and metakaolin presented a reduction in the absorption and sorptivity value of SCC mixes whereas the strength value increased. Also, the type and amount of mineral additives have an important role on durability properties of SCC. Therefore, with replacing the 10% FA content with metakaolin, the highest strength can be obtained comparing with the other mixes, in the different curing period as result of increasing density and filling ability of metakaolin particles (Khan and Sharma 2015).

Incorporation of high raw FA content in concrete presented the lower compressive strength comparing with SCC mixes containing 30% raw FA. Due to the pozzolanic reaction of raw FA, additional compressive strength observed at later curing period. Also, a reduction of permeability of concrete mixes with raw FA content observed, due to the pozzolanic reaction of raw FA which refined the pore system of concrete (Mahalingam *et al.* 2016).

The main purpose of this study is to examine the durability of SCC concrete with different proportions of FA (0%, 20%, 40%, and 60%). In this study, the significant effort has been placed on investigating the effect of using FA as an additive on workability, strength, and durability of SCC specimens. The test results are presented and discussed.

2. Experimental study

2.1 Materials

In this experimental study Ordinary Portland Cement (OPC) and FA Class F have been used. Table 1 shows the chemical composition of the OPC type CEM I 42.5 N

Table 5 Properties and laboratory trail result of Mix3

Materials	Source	SSD wt (kg)	Wat.Abs (%)	Dry wt (kg)	Moist. %	Corrected (kg)	Batch wt (kg)
Cement (OPC)	RAK CC/UCC	330	-	330	-	330	26.4
FA	Ash Res/Cemex	220	-	220	-	220	17.6
Free Water	DEWA	173	-	183	-	154	12.32
Aggregate 20 mm	Unimix	376	0.4	374	-	374	29.92
Aggregate 10 mm	Unimix	271	0.6	269	-	269	21.52
0-5 mm C.sand	Unimix	-	-	-	-	-	-
0-5 mm W.sand	S.R RAK	477	0.7	473	7	506	40.49
D.sand	Al Ain	477	0.9	472	-	472	37.76

Table 6 Properties and laboratory trail result of Mix4

Materials	Source	SSD wt (kg)	Wat.Abs %	Dry wt (kg)	Moist. %	Corrected (kg)	Batch wt (kg)
Cement (OPC)	RAK CC/UCC	220	-	220	-	220	17.6
FA	Ash Res/Cemex	330	-	330	-	330	26.4
Free Water	DEWA	173	-	183	-	154	12.32
Aggregate 20 mm	Unimix	376	0.4	374	-	374	29.92
Aggregate 10 mm	Unimix	271	0.6	269	-	269	21.52
0-5 mm C.sand	Unimix	-	-	-	-	-	-
0-5 mm W.sand	S.R RAK	477	0.7	473	7	506	40.49
D.sand	Al Ain	477	0.9	472		472	37.76

complying with BS EN 197-1 (EN 2011) and FA Class F to ASTM-C618 (ASTM 2015). The OPC was provided by Unimix Cement Company, in the United Arab Emirate.

2.2 Aggregate

The crushed RAK rock coarse aggregate was used with the size of 20 mm and 10 mm. Crushed sand (0-5 mm), Washed sand (0-5 mm) and Dune sand as fine aggregates were also used and provided by Unimix in the United Arab Emirates in accordance with BS EN 1881: Part 101 (EN 1983) and BS EN 1141 (EN 2011).

2.3 Mix proportions

Four different replacement ratios of OPC with FA (0%, 20%, 40% and 60%) were used. The content proportions of all mixes are given in Table 2. Also, Mix1 with 0% FA content was considered as the control SCC mix in this experiment as shown in Table 2. The properties and the primarily test results of all mixes and materials used in this study are given in Tables 3 to 6.

2.4 Sample preparation and curing conditions

The number of 60 cube specimens with 150 mm dimension was used for compressive strength test based on the BS EN1881-101 (EN 1983) and BS EN 1881-125 (EN 1983) sampling preparation test methods. The axial crushing of the cube specimens has done by UTM machine with 3000 kN capacity. The compressive strength test performed on SCC cube specimens at 1, 7, 14, 28 and 35

Fig. 1 Resist chloride ion penetration test

Fig. 2 Water permeability test

Fig. 3 Water absorption test

days. Four different tests have been done on the concrete cube specimens to check the durability of the 4 mixes after 28 days. Resist chloride ion penetration (RCP), water permeability (WP), water absorption (WA), and initial surface absorption (ISA) tests performed on 16 cube specimens to examine the durability of the SCC mixes.

The RCP test was based on the BS EN 1881 Part 101 (EN 1983) with AMD 6728 (1991) sampling method and ASTM C 1202 (ASTM 1997) CI 8 and CI 9 test specimen preparation methods. In this durability test, cube specimens saturated for 3 hours with water without any air. The boiled water is also added without air for 16 to 18 hours. Then the cube specimens cut to 100 mm diameter and 50 mm thick cylinders. The 60 mV differential voltage was applied to the samples for 6 hours as shown in Fig. 1.

The WP test followed BS EN 12390-8 (EN 2000) test specimen preparation method, where the water with the pressure of 5 bars (500 kPa) is applied to the surface of the

Fig. 4 Initial surface absorption test

Fig. 5 U-box test

Fig. 6 V-funnel test

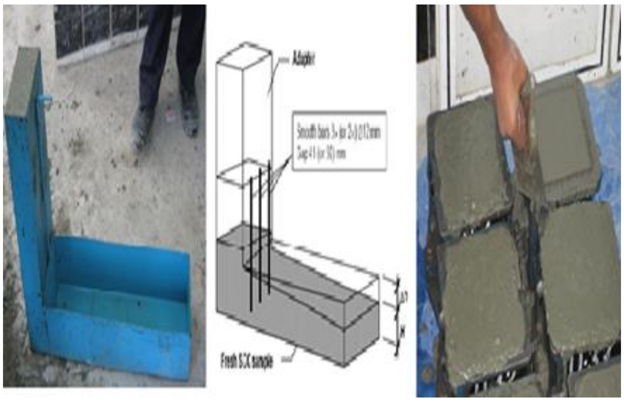

Fig. 7 V-L-box test

cube specimens for 72 hours as shown in Fig. 2. The cube specimen is then split open, and the depth of penetration of the water is measured.

The WA test followed BS EN 1881 Part 101 (EN 1983) sampling method and BS EN 1881 Part 122 (EN 1983) Clause 4.1 test specimen preparation. Also, the 75 mm diameter core made from the cube specimens. The cores were placed in the oven with a constant temperature of 105°C for 72 hours. After that the cores were placed in the cooling device at room temperature for 24 hours as shown in Fig. 3. The weight of samples was measured two times before and after placing the samples in the water.

The ISA test was in accordance with 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. This durability test was also performed by applying water at a constant pressure head to the surface of the cube specimens as shown in Fig. 4.

2.5 Test methods

The compressive strength test performed on 150 mm cube specimens, in accordance with BS EN1881-116 (EN 1983) and ASTM C109 (ASTM 2000) test methods. The cube specimens were loaded in testing device under load control at the rate between 0.2 to 0.4 MPa/s until failure. In the durability test, the WA test was in accordance with BS 1881 Part 122 (EN 1983) Clause 5. The WP is also based on BS EN 12390-8 (EN 2000) test method for determining the depth of penetration of water under pressure in hardened concrete. Rapid chloride ion penetration test followed the ASTM C 1202 (ASTM 1997) Clause 10 test method. Also, the ISA test was in accordance with BS EN Part 208 (EN 1996) Clause 8.5 & 8.6 test method.

2.6 Properties of fresh concrete

Based on the current SCC European Standards, some workability tests performed to determine the fresh properties of the SCC. In accordance with BS EN 206-9 (EN 2010) statement, the slump flow test must be done based on the BS EN 12350-8 (EN 2010) standard. To evaluate the SCC characteristics, some experiments are usually performed under different laboratory conditions. It is important to test and measure the liquidity, segregation, placement and compacting of fresh concrete as defined and developed in the European guidelines BS EN 206-9 (EN 2010) for SCC.

According to the BS EN 206-9 (EN 2010), the flowability and compactability under its own weight and its stability are the main properties of SCC. In this experimental study, slump flow, V-funnel, U-box, and L-box tests were performed to identify the workability of the SCC as shown in Figs. 5 to 7. The test procedure is as follow: slump flow test and measurement of the time taken by concrete to flow to 50 cm diameter disc (T50 cm); U-box and measurement of difference in height between the two side of concrete, V-funnel flow tests and measurement of the time taken by concrete to flow through V-funnel after 10 s (T10 s) and time taken by concrete to flow through V-funnel after 5 min (T5 min); and L-box test (time taken to reach 200 mm distance T200 mm, time taken to reach 400 mm distance T400 mm and blocking ratio of heights at the

Table 7 Fresh properties test results

Fresh properties	Mix1	Mix2	Mix3	Mix4
Slump flow test (mm)	805	765	740	775
V-funnel (sec)	2.9	4.12	3.98	4.31
U-box (mm)	Failed	2	15	3
L-box 200 mm (sec)	0.93	2.18	2.42	2.14
L-box 400 (sec)	2.68	5.15	6.13	4.77
H1 (mm)	72	70	60	72
H2 (mm)	71	79	90	75
H2/H1	0.98	0.9	0.67	0.96

two edges of L-box (H2/H1). To evaluate the properties of fresh concrete the following tests were carried out:

- Slump flow test in accordance with BS EN 12350-8 (EN 2010)
- V-funnel test in accordance with BS EN 12350-9 (EN 2010)
- U-box test in accordance with BS EN 12350-1 (EN 2010)
- L-box test in accordance with BS EN 12350-10 (EN 2010)

3. Experimental results and discussion

3.1 Properties of fresh concrete

The obtained workability test results of SCC mixes in this experimental study are given in Table 7. The test results for properties of concrete obtained by the slump flow test, U-box test, L-box, and V-funnel test. The flowability of fresh concrete mixes was defined by the slump flow value. This important test will be generally considered for all the SCC mixes, to check the fresh concrete properties which meet the required limits in the specifications. The slump flow test allows the concrete to assess the horizontal free flow of the SCC in the absence of obstructions. The unconfined flowability, of SCC mixes determined by the slump flow test, and the obtained values were between 640-800 mm. Based on the BS EN 12350-8 (EN 2010) a slump flow value range from 640 to 800 mm was recommended for SCC with good workability. A slump flow value of at least 640 mm is required for SCC. Meanwhile, the greater value is the higher its ability to fill the formwork under its own weight. Obtained slump flow value results of SCC successfully met the recommended values of 640 to 800 mm. The slump flow time taken to reach a diameter more than 640 mm for all mixes was less than 5 minutes.

The U-box test is also performed to evaluate the self-compatibility and filling ability of SCC mixes. The differences in height H2/H1 determined for each mix and the values are given in Table 7. The obtained U-box results of all mixes presented the difference height of less than 30 mm. In accordance with BS EN 12350-1 (EN 2010) standard the U-box results of Mix2, Mix3 and Mix4 all met the required limit of less than 30 mm. Hence, based on the BS EN 12350-1 (2010) the better flowability and self-compatibility of Mix2 and Mix4 can be observed.

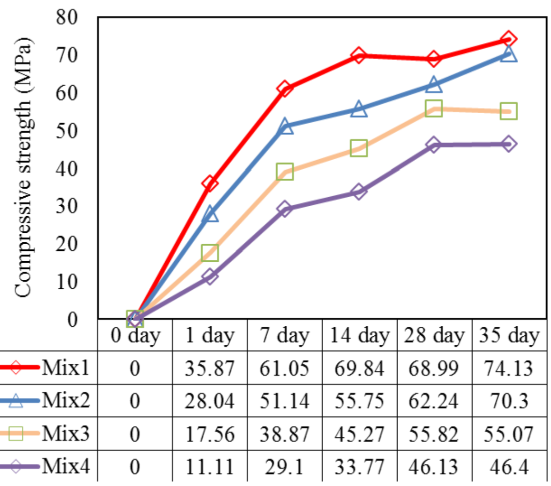

Fig. 8 Strength development for SCC with 0%, 20%, 40%, and 60% FA. (remove the target strength line)

To measure the stability and flowability of concrete, the V-funnel test was also performed. The delivered time in seconds between the openings of the bottom gate and the time when light observed from the top is V-funnel flow time. The V-funnel time of less than 9 sec is suggested for SCC based on the BS EN 12350-9 (EN 2010). The V-funnel flow times for all the four mixes were in the range 2.9-4.31 sec, which is favorably lower than the maximum stipulated flow time of 9 sec.

The L-box test also is done to assess the confined flowability of concrete between reinforcement, it subject is to block the concrete by reinforcement. Based on the BS EN 12350-10 (EN 2010), the blocking ratio (H2/H1) needs to be more than 80%. Table 7 presents that SCC mixes (Mix1, Mix2, and Mix4) confirmed the recommended value of greater than 80%. The L-box ratios H2/H1 for the SCC mixes were more than 0.8 which is, in accordance with BS EN 12350-10 (EN 2010) standard and. Only Mix3 failed to meet such requirement where H2/H1=0.67, this it can be classified as "blocked". Obtained results of slump flow test, U-box test, V-funnel test and L-box test are given in Table 7.

3.2 Compressive strength

Fig. 8 shows the variation of compressive strength at 1, 7, 14, 28 and 35 days on 150 mm concrete cube specimens for different proportion of SCC mixes with FA replacement ratios of 0%, 20%, 40%, and 60%. Table 8 presents the compressive strength of SCC mixes obtained at different curing time. The compressive strength values of all SCC mixes increased with increasing the curing times. However, SCC mixes with different FA content presented the lower compressive strength values comparing with the control SCC.

Fig. 9 shows that the increase of FA content to 20%, 40%, and 60% induced reductions in compressive strength at 28 days of 10%, 19%, and 33%, respectively. Also, the control SCC showed the lower compressive strength value at 28 days compared with 14 days. The comparison of

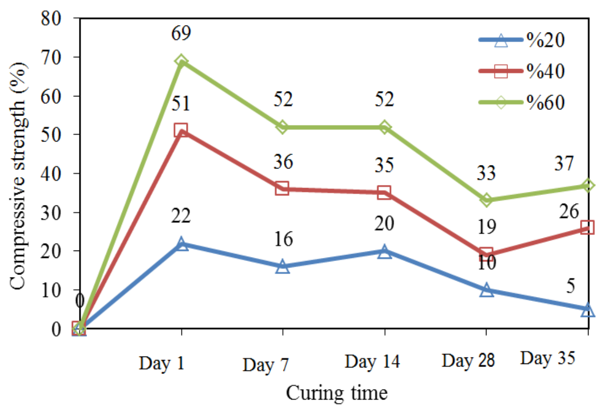

Fig. 9 Compressive strength reduction chart

Table 8 Compressive strength test results of SCC mixes with different proportion of FA in different periods

Testing time (day)	Compressive strength test (MPa)	Mix1	Mix2	Mix3	Mix4
1	Average	35.87	28.04	17.56	11.11
	Standard deviation	1.61	1.22	0.6	0.11
7	Average	61.05	51.14	38.87	29.1
	Standard deviation	2.98	6.73	0.1	0.42
14	Average	69.84	55.75	45.27	33.77
	Standard deviation	0.32	7.91	1.5	0.93
28	Average	68.99	62.24	55.82	46.13
	Standard deviation	3.16	2.94	2.9	1.47
35	Average	74.13	70.3	55.07	46.4
	Standard deviation	1.55	1.6	2.62	1.91

obtained results in different ages indicated the highest mean value 74.13 MPa for the control SCC. Hence, with increasing the curing time, higher compressive strength values were obtained for the control SCC comparing with the other SCC mixes.

This results confirm the one mentioned by several researchers (Liu 2010, Nath and Sarker 2011, Siddique 2011, Dhiyaneshwaran *et al.* 2013, Bingöl and Tohumcu 2013, Nagaratnam *et al.* 2014 and Mahalingam *et al.* 2016) which presents the reduction of compressive strength value of SCC mixes by increasing the FA content. Similar observations have been noted by (Felekoglu *et al.* 2006) which presents the lower compressive strength values of SCC mixes containing FA at the early curing time. The same results also reported by (Liu 2010, Nagaratnam *et al.* 2014, Mahalingam *et al.* 2016) where they indicated the increase of compressive strength of SCC mixes containing FA in the long term which is confirmed with the obtained results shown in Fig. 8. Hence, these results may be defined by the slow pozzolanic reaction of FA, and cement paste of SCC mixes (Felekoglu *et al.* 2006, Nagaratnam *et al.* 2014, Bradu and Florea 2015).

The compared results reveal a considerable reduction of compressive strength value of SCC mixes with the higher replacement of FA content. Thus, the pozzolanic behaviour of FA is caused to increase the compressive strength at longer curing period.

Table 9 Durability test results of SCC mixes

Mixes			Mix1	Mix2	Mix3	Mix4
Rapid chloride ion penetration test (coulombs)	Rapid chloride ion penetration value		2364	1942	2099	1498
	Chloride permeability based on charge passed table (ASTM C 1202.1997)		Moderate	Low	Moderate	Low
Water permeability test (mm)	Maximum depth of penetration (mm)		10	12	21	14
	Specimen dimension (mm)		150×150×150			
Water absorption test	Corrected absorption		1.9	1.7	2	1.6
	Measured absorption		1.6	1.4	1.7	1.3
	Density (kg/m^3)		2360	2300	2270	2370
	Dimension (mm)	H	150	150	150	150
		D	74	74	74	74
Initial surface absorption test (ml/m^2.sec)	10 minutes		0.02	0.04	0.04	0.02
	30 minutes		Concrete too impermeable to be sensitive to a longer term test			
	60 minutes					

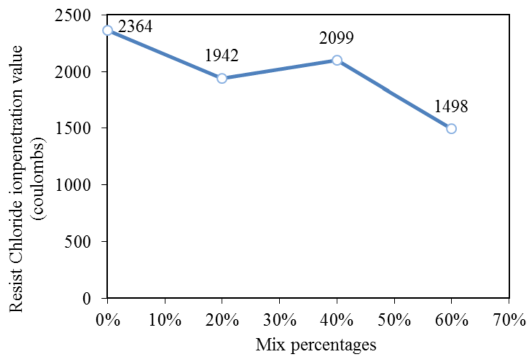

Fig. 10 Resist chloride ion penetration test results

3.3 Durability

Four durability tests performed on the concrete cube specimens to check the durability of all mixes after 28 days. Moreover, the durability of SCC has been investigated with the same grade of conventional concrete in this experimental program. Table 9 presents a summary of the durability test results of SCC mixes.

3.4 Resist chloride ion penetration (RCP)

The RCP of the SCC mixes with different FA content (0%, 20%, 40% and 60%) evaluated after 28 days curing period is listed in Table 9. The increase of FA content has resulted a higher RCP value comparing with the control SCC. Moreover, with increasing the FA content to 60%, the chloride ion penetration of SCC was significantly decreased. The results indicated a lower number of chloride ions passing through the concrete and therefore a better quality of SCC concrete has been achieved. Fig. 10 shows that the increase of FA content to 20%, 40%, and 60% induced enhancements in RCP of 17.9%, 11.2%, and 36.7%, respectively. Hence, Mix4 with 60% FA has the lowest amount of chloride ion penetration (in coulombs) thus it presents the best durability when compared with the other mixes.

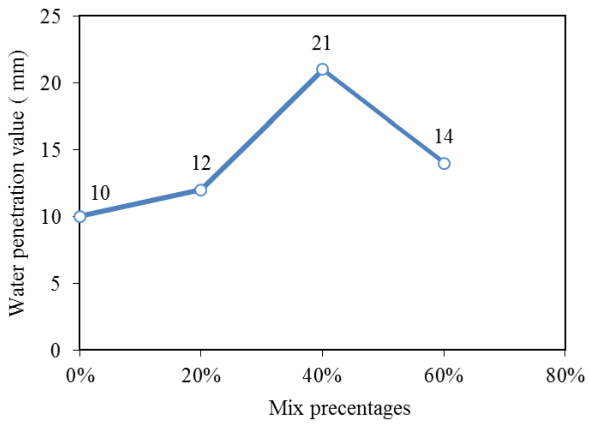

Fig. 11 Water penetration test results

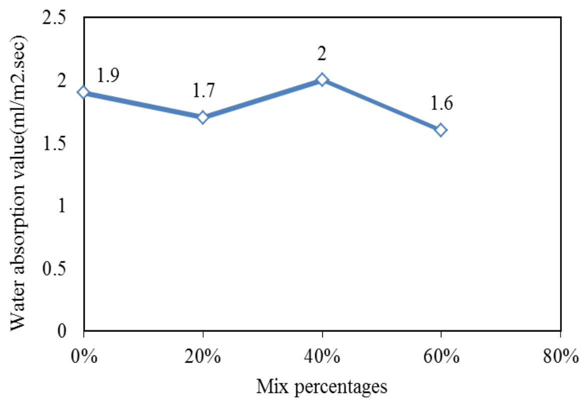

Fig. 12 Water absorption test results

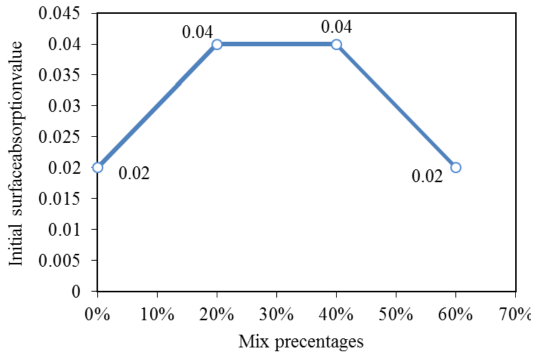

Fig. 13 Initial surface absorption test results

Due to the obtained results the charge passed values ranges for the control SCC and Mix3 were within “Moderate” category of chloride ion permeability and Mix2 and Mix4 were within “Low” category chloride ion permeability. Therefore, by increasing the FA content, the reduction of RCP obtained due to the chemical and pozzolanic reaction of some chlorides with cement and FA. Similar results are also reported by (Nath and Sarker 2011, Mahalingam *et al.* 2016, Dinakar *et al.* 2008, Zhu and Bartos 2003, Naik *et al.* 1994, Amrutha *et al.* 2011, Da Silva and Brito 2015) which indicated a significant reduction of RCP value with increasing the FA content due to the pozzolanic reaction of FA with the pore structure enhancement.

3.5 Water permeability (WP)

The WP values of SCC mixes evaluated and are given in Fig. 11. Table 9 presents the upward trend of water penetration value with increasing the FA proportions. The obtained results revealed the highest depth of water penetration value for Mix3 with 40% FA. The control SCC mix presented the minimum permeability value compared with all SCC mixes. In this experiment with increasing the FA content, the maximum depth water penetration was increased, however, a reduction observed by increasing the FA content to 60%. Hence, FA was an important factor for obtaining the required WP in this experiment.

Due to finesse features, hydration process and the pozzolanic reaction of FA with cement paste, the extra bond produced and pores within the concrete filled to increase the WP. In comparison with the available results by (Naik *et al.* 1994, Trezos *et al.* 2010, and Seshadri Sekhar *et al.* 2010), it is confirmed that transport of pores in concrete that occurred due to the pozzolanic reaction between the cement paste and FA content which had considerably reduced the permeability. Also, (Naik *et al.* 1994) tested concrete mixes with FA proportions more than 50% and indicated the reduction of air and WP at 91 days. Also, (Trezos *et al.* 2010) indicated that the WP results of SCC with increasing the curing period (7, 14, 28 and 56 days).

In comparison with the previous research, a reduction of WA was expected with increasing the FA content. However, the obtained results were have not shown this phenomenon. It appears that testing WP at 28 days was not sufficient curing period for the latent pozzolanic activity of FA blended cement to take place.

3.6 Water absorption (WA)

The WA of all the SCC mixes are shown in Table 9. The WA value of all SCC mixes is presented in Fig. 12. It is seen that there is a general trend of reduction in the WA (except for Mix3 with 40% FA) with increasing the FA content. The WA reduced by 10.5% and 15.8% at 20% and 60% FA content. The WA of Mix3 with 40% FA content presented the highest value comparing with the other SCC mixes. However, it can be seen that increasing the FA content to 60% has resulted the lowest value 1.6%.

Bradu and Florea (2015) indicated the direct correlation of WA with voids, and confirmed that the pore system of concrete generated the movement of fluid easily and enhanced the absorption process. In contrast to the obtained results in this experiment, (Bradu and Florea 2015) found higher WA values for SCC mixes with FA. Also, Bradu and Florea (2015) confirmed the contrary correlation of compressive strength and WA in comparison with the obtained results in this study.

In the other literature, a reduction of WA value observed with replacing the OPC with FA content up to 30%, which is caused to more rapid flowability of water to the concrete (Dhiyaneshwaran *et al.* 2013). Also, Assie *et al.* (2007) found higher WA values with increasing the amount of FA in the conventional vibrated concrete which confirmed the obtained results in this study.

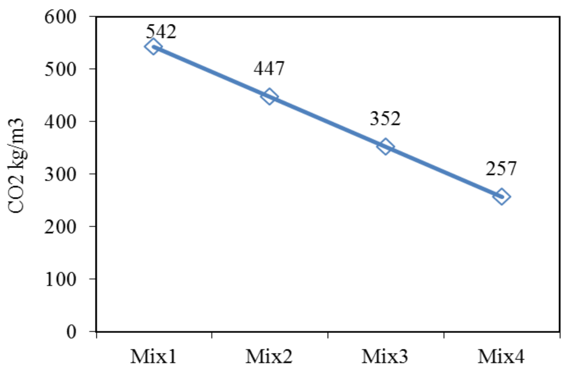

Fig. 14 Carbon emissions of all mixes

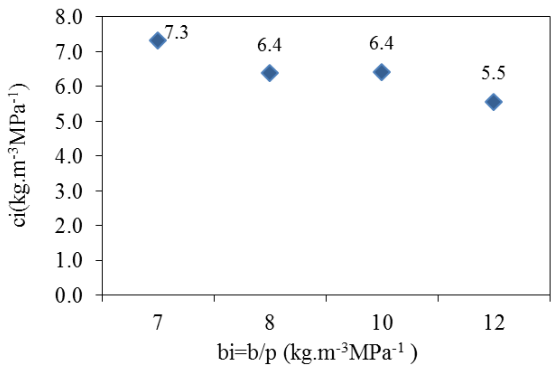

Fig. 16 CO_2 intensity indicator (ci=c/p) versus binder intensity (bi=b/p)

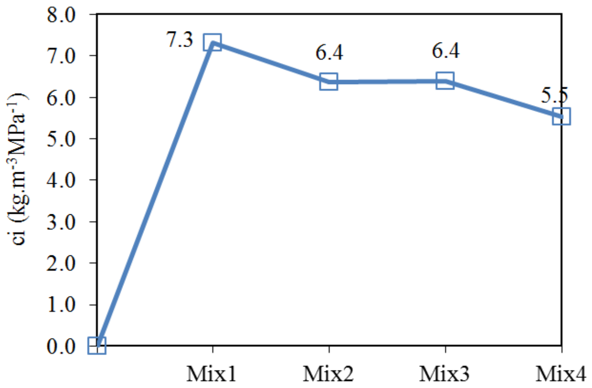

Fig. 15 CO_2 intensity indicator (ci=c/p) for all mixes

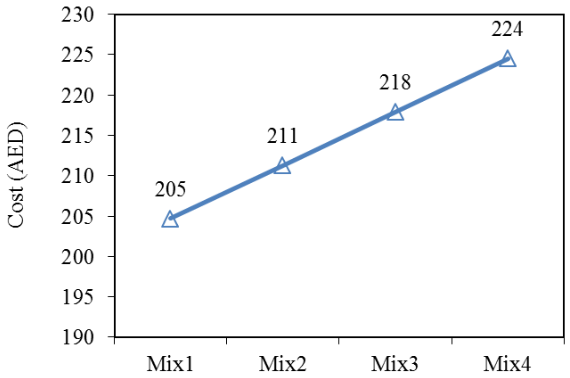

Fig. 17 Cost per cubic meter of all mixes

3.9 Initial surface absorption (ISA)

The ISA test results obtained and are given in Table 9. The ISA values of SCC mixes are varied with different FA proportions. The ISA values decreased to the same value of control SCC, with increasing the FA content to 60%. Moreover, the same ISAT value can be seen for both Mix 2 and Mix 3.

Fig. 13 presents the highest ISA rate of 0.04 ml/m^2, for Mix2 and Mix3, while Mix1 and Mix4 have the lowest ISAT rate of 0.02 ml/m^2. As expected, obtained result indicated, the best value for the mixes with the highest FA content. Hence, the ISA rate for Mix2 and Mix3 was increasing while ISA value was decreasing for the one with highest FA content. So, the ISA rate is reduced by increasing the FA content to 60%.

It can be observed that the presence of FA caused pozzolanic activity which helped to reduce permeability and ISA value. In this experiment, there is slightly difference between the normal concrete and the concrete has FA content in the ISA test. Due to the obtained results in this study, similar observations are reported by (Dinakar *et al.* 2008) which confirmed the initial absorption value of SCC mixes slightly greater than the control SCC. The comparison of obtained results indicated an increase in ISA values with increasing the FA content.

Previous experimental research by (Khan and Sharma 2015), indicated the contrary relationship between strength and ISA. This result confirmed the one revealed by Dinakar *et al.* (2008) while low strength concrete presents the higher initial water absorption value which is compared with high strength concrete. Additionally, (Khan and Sharma 2015) had also presented reductions of ISAT values for SCC mixes at 60 days compared with 28 days.

A considerable scatter in the durability test results was found when increasing the FA content from 0% to 60% (see Figs. 9 to 11). More research is required to better understand the effect of FA on WP, WA, RCP, and ISA.

3. Carbon emissions and costs

The carbon footprint of all mixes are presented in Fig. 14. The carbon emission of Mix1 with 100% OPC is 542 kg/m^3 which presented the highest carbon emission value comparing with Mix2, Mix3 and Mix4. The obtained carbon emission value for Mix4 with 60% FA content is 257 kg/m^3 whereas the emission for Mix2 and Mix3 containing lower FA content are 447 kg/m^3 and 352 kg/m^3. Hence, the reduction of carbon emission can be seen by increasing the FA content. Due to the obtained results, (Elchalakani *et al.* 2014) is also estimated the highest carbon emission 386 kg/m^3 for Mix1 comparing with the other mixes, whereas the emission for mixes containing 80% GGBS with no waste material was 153 kg/m^3.

Fig. 15 presents the CO_2 intensity indicator (ci=c/p) value of all 4 mixes. In this regard, *c* presented the total CO2 (kg.m^{-3}) released to produce the SCC, and p is the average compressive strength at 35 days (MPa) in this study. It can be seen that all four mixes obtained the values more than the international future benchmark of ci=5.0

kg.m^{-3}MPa^{-1} which is against the proposed value by (Damineli *et al.* 2010). Moreover, the carbon emission value of Mix 4 with 60% FA content was 5.5 (kg.m^{-3}) which was reasonably lower than the emission value of other mixes containing minor FA content, and it was very close to the international future benchmark of ci=5.0 kg.m^{-3}MPa^{-1}. Also, this result achieved from the lowest 35 days' compressive strength of 46.4 MPa for Mix4 containing 60% FA content.

The CO_2 intensity indicator against the binder intensity (bi=b/p) is presented in Fig. 16, whereas the *b* indicated the entire usage of the binder material as well as OPC and FA (kg.m^{-3}). The binder intensity of all four mixes obtained between the range of bi=7.0 to 12.0 kg.m^{-3}MPa^{-1}. Besides, the workable SCC mixes produced with carbon emission of greater than 5.0 kg.m^{-3}MPa^{-1}.

Fig. 17 presents the estimated cost for producing one cubic meter of all four mixes. It can be seen that, the estimated cost for control mix with no FA is 205 AED/m^3 which is considerably lower than the other mixes. The estimated cost for Mix 4 containing 60% FA is 224 AED/m^3 whereas the cost for Mix 2 and Mix3 are 211 AED/m^3 and 218 AED/m^3. In addition, minor differences can be seen between the estimated cost of Mix3 and Mix4. It can be observed that the estimated cost of Mix2, Mix3 and Mix 4 are costlier comparing with control mix. Thus, the estimated cost is increased, by increasing the FA content of mixes. Although, the control mix presented the lower cost value compared with the other mixes, but they are still workable.

4. Conclusions

The following conclusions can be made with the present scope of investigation:

• The WP results showed the higher value for all SC mixes comparing with the control concrete. Moreover, the increase of WP can be seen by increasing the FA content in this experiment. However, the increase of FA to max 60% presented the lower penetration value comparing the Mix3 with 40% FA content. Hence, it can be observed that the pozzolanic reaction of cement with FA was because of the transportation of pore system of concrete which leads to decrease the water penetration value.

• The WA value of SCC mixes with 40% FA was higher than the control mix. However, obtained results showed the lower WA value for Mix2 and Mix4 comparing the control mix. The results indicated the direct correlation of WA with voids. Moreover, the pore system of concrete is responsible for transporting the fluids and increases the WA value.

• The RCP test results indicated a reduction of penetration by increasing the FA content. As can be seen, Mix2 and Mix4 were placed in the "Low" category of chloride ion permeability, while Mix1 and Mix3 were placed in the "Moderate" category of chloride ion permeability. Increasing the FA to 60% presented the lowest penetration value comparing with the other SCC mixes. The results showed that increasing the FA content can increase the pozzolanic reaction with cement paste and lead to reduce the permeability value. Hence, in this experiment, the increase of FA content presented significantly lower chloride ion permeability compared with control SCC.

• It was found that replacing the OPC with FA had a significant positive impact on RCP and WA but had a considerable negative impact on the compressive strength of SCC. The SCC mix with 60% FA content had 36.7% and 15.8% enhancement in the RCP and WA, respectively.

• In the ISA test, with increasing the FA content to 40%, the ISA value obtained the same value of Mix2 with 20% FA content which was higher than the control concrete. However, with increasing the FA content to 60%, the ISA reached to the same value of normal concrete.

• A considerable scatter in the durability test results was found when increasing the FA content from 0% to 60%. More research is required to better understand the effect of FA on WP, WA, RCP, and ISA.

• A reduction of carbon footprint value was found by increasing the FA content from 0% to 60%. However, compared with the control mix, the slightly higher cost of all mixes was obtained by increasing the FA content.

References

ACI.CT-13 (2013), *ACI Concrete Terminology-An ACI Standard*, American Concrete Institute, 24.

Ahmadi, M., Alidoust, O., Sadrinejad, I. and Nayeri, M. (2007), "Development of mechanical properties of self compacting concrete contain rice husk ash", *J. Civil Environ. Struct. Constr. Architect. Eng.*, **1**(4), 100-103.

Amrutha, N.G., Narasimhan, M. and Rajeeva, S. (2011), "Chloride-ion impermeability of self-compacting high-volume fly ash concrete mixes", *J. Civil Environ. Eng.*, **11**(4), 29-33.

Aslani, F. (2014), "Experimental and numerical study of time-dependent behaviour of reinforced self-compacting concrete slabs", Ph.D. Dissertation, University of Technology, Sydney, Australia.

Aslani, F. and Nejadi, S. (2012a), "Mechanical properties of conventional and self-compacting concrete: An analytical study", *Constr. Build. Mater.*, **36**, 330-347.

Aslani, F. and Nejadi, S. (2012b), "Bond characteristics of steel fibre reinforced self-compacting concrete", *Can. J. Civil Eng.*, **39**(7), 834-848.

Aslani, F. and Nejadi, S. (2012c), "Bond behavior of reinforcement in conventional and self-compacting concrete", *Adv. Struct. Eng.*, **15**(12), 2033-2051.

Aslani, F. and Nejadi, S. (2012d), "Shrinkage behavior of self-compacting concrete", *J. Zhejiang Uni. Sci. A*, **13**(6), 407-419.

Aslani, F. and Nejadi, S. (2012e), "Bond characteristics of reinforcing steel bars embedded in self-compacting concrete", *Austr. J. Struct. Eng.*, **13**(3), 279-295.

Aslani, F. and Nejadi, S. (2013a), "Self-compacting concrete incorporating steel and polypropylene fibers: Compressive and tensile strengths, moduli of elasticity and rupture, compressive stress-strain curve, and energy dissipated under compression", *Compos. Part B-Eng.*, **53**, 121-133.

Aslani, F. and Nejadi, S. (2013b), "Creep and shrinkage of self-compacting concrete with and without fibers", *J. Adv. Concrete Technol.*, **11**(10), 251-265.

Aslani, F. (2013), "Effects of specimen size and shape on compressive and tensile strengths of self-compacting concrete with or without fibers", *Mag. Concrete Res.*, **65**(15), 914-929.

Aslani, F. and Maia, L. (2013), "Creep and shrinkage of high strength self-compacting concrete experimental and numerical analysis", *Mag. Concrete Res.*, **65**(17), 1044-1058.

Aslani, F. and Natoori, M. (2013), "Stress-strain relationships for steel fibre reinforced self-compacting concrete", *Struct. Eng. Mech.*, **46**(2), 295-322.

Aslani, F. and Bastami, M. (2014), "Relationship between deflection and crack mouth opening displacement of self-compacting concrete beams with and without fibres", *Mech. Adv. Mater. Struct.*, **22**(11), 956-967.

Aslani, F., Nejadi, S. and Samali, B. (2014a), "Short term bond shear stress and cracking control of reinforced self-compacting concrete one way slabs under flexural loading", *Comput. Concrete*, **13**(6), 709-737.

Aslani, F., Nejadi, S. and Samali, B. (2014b), "Long-term flexural cracking control of reinforced self-compacting concrete one way slabs with and without fibres", *Comput. Concrete*, **14**(4), 419-443.

Aslani, F. and Samali, B. (2014), "Flexural toughness characteristics of self-compacting concrete incorporating steel and polypropylene fibers", *Austr. J. Struct. Eng.*, **15**(3), 269-286.

Aslani, F., Nejadi, S. and Samali, B. (2015), "Instantaneous and time-dependent flexural cracking models of reinforced self-compacting concrete slabs with and without fibres", *Comput. Concrete*, **16**(2), 223-243.

Assie, S., Escadeillas, G. and Waller, V. (2007), "Estimate of self-compacting concrete potential durability", *J. Constr. Build. Mater.*, **21**(10), 1909-1917.

ASTM C1202 (1994), *Standard Test Method for Electrical Indication of Concrete Ability to Resist Chloride Ion Penetration*, Pennsylvania, U.S.A.

ASTM C1202 (1997), *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, Pennsylvania, U.S.A.

ASTM C1202 (1997), *Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration*, Pennsylvania, U.S.A.

ASTM 1478.1 (2000), *Chemical Admixtures for Concrete, Mortar and Grout-Admixtures for Concrete*, Pennsylvania, U.S.A.

ASTM C109(2000), *Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*, Pennsylvania, U.S.A.

ASTM C494 (2001), *Standard Specification for Chemical Admixtures for Concrete*, Pennsylvania, U.S.A.

ASTM C618 (2015), *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, Pennsylvania, U.S.A.

Balakrishnan, D. and Paulose, K. (2013), "Workability and strength characteristics of self compacting concrete containing fly ash and dolomite powder", *Am. J. Eng. Res.*, **24**(4), 43-47.

Bingöl, A. and Tohumcu, I. (2013), "Effects of different curing regimes on the compressive strengthproperties of self compacting concrete incorporating fly ashand silica fume", *J. Mater. Des.*, **51**, 12-18.

Bradu, A. and Florea, N. (2015), "Water absorption of self compacting concrete containing different levels of fly ash", **61**(4), 107-114.

Claisse, P., Ganjian, E. and Adham, T. (2003), "In situ measurement of the intrinsic permeability of concrete", *Mag. Concrete Res.*, **55**(2), 125-132.

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

Damineli, B., Kemeid, F., Aguiar, P. and John, V. (2010), "Measuring the co-efficiency of cement use", *Cement Concrete Compos.*, **32**, 555-562.

Dhiyaneshwaran, S., Ramanathan, P., Baskar, I. and Venkatasubramani, R. (2013), "Study on durability characteristics of self-compacting concrete with fly ash", *Jord. J. Civil Eng.*, **7**(3), 342-353.

Dinakar, P., Babu, K. and Santhanam, M. (2008), "Durability properties of high volume fly ash self compacting concretes", *Cement Concrete Compos.*, **30**(10), 880-886.

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.

BS EN 116 (1983), *Testing Concrete, Method for Determination of Compressive Strength of Concrete Cubes*, London, U.K.

BS EN 122 (1983), *Testing Concrete, Method for Determination of Water Absorption*, London, U.K.

BS EN 1881-101 (1983), *Testing Concrete, Method of Sampling Fresh Concrete on Site*, London, U.K.

BS EN 1881-125 (1983), *Testing Concrete, Methods for Mixing and Sampling Fresh Concrete in the Laboratory*, London, U.K.

BS EN 1881-208 (1996), *Testing Concrete, Recommendations for the Determination of the Initial Surface Absorption of Concrete*, London, U.K.

BS EN 208 (1996), *Testing Concrete, Recommendations for the Determination of the Initial Surface Absorption of Concrete*, London, U.K.

BS EN 12390-8 (2000), *Testing Hardened Concrete, Depth of Penetration of Water Under Pressure*, London, U.K.

BS EN 934-2 (2001), *Admixtures for Concrete, Mortar and Grout. Concrete Admixtures, Definitions Requirements, Conformity, Marking and Labelling*, London, U.K.

BS EN 12350-1 (2010), *Testing Fresh Concrete, Self-Compacting Concrete, U-BoX Test*, London, U.K.

BS EN 12350-10 (2010), *Testing Fresh Concrete, Self-Compacting Concrete, L box Test*, London, U.K.

BS EN 12350-8 (2010), *Testing Fresh Concrete, Self-Compacting Concrete, Slump-Flow Test*, London, U.K.

BS EN 12350-9 (2010), *Testing Fresh Concrete, Self-Compacting Concrete, V-Funnel Test*, London, U.K.

BS EN 206-9 (2010), *Concrete, Additional Rrules for Self-Compacting Concrete (SCC)*, London, U.K.

BS EN 206-9 (2010), *Concrete, Additional Rules for Self-Compacting Concrete (SCC)*, London, U.K.

BS EN 1141 (2011), *Fibre Ropes, Polyester, 3-, 4-, 8- and 12-Strand Ropes*, London, U.K.

BS EN 197-1 (2011), *Cement, Composition, Specifications and Conformity Criteria for Common Cements*, London, U.K.

Felekoglu, B., Tosun, K., Baradan, B., Altun, A. and Uyulgan, B. (2006), "The effect of fly ash and limestone fillers on the viscosity and compressivestrength of self-compacting repair mortars", *Cement Concrete Res.*, **36**(9), 1719-1726.

Güneyisi, E., Gesoglu, M., Al-Goody, A. and Ipek, S. (2015), "Fresh and rheological behavior of nano-silica and fly ash blended self-compacting concrete", *J. Constr. Build. Mater.*, **95**, 29-44.

Jino, J., Maya, T. and Meenambal, T. (2012), "Mathematical modeling for durability characteristics of fly ash concrete", *J. Eng. Sci. Technol.*, **4**(1), 353-361.

Kapoor, Y., Munn, C. and Charif, K. (2003), "Concrete in hot and aggressive environments", *Proceedings of the 7th International Conference*.

Khan, R. and Sharma, A. (2015), "Durability properties of self compacting concrete containing fly ash, lime powder and metakaolin", *J. Mater. Eng. Struct.*, **2**(4), 206-212.

Khayat, K. (1999), "Workability, testing, and performance of self-consolidating concrete", *ACI Mater. J.*, **96**, 346-353.

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

Mahalingam, B., Nagamani, K., Kannan, K.L. and Bahurudeen, M. (2016), "Assessment of hardened characteristics of raw fly ash blended self compacting concrete", *Presp. Sci.*, **8**, 709-711.

Nagaratnam, B.H., Faheem, A., Rahman, M.E., Mannan, M.A. and

Leblouba, M. (2014), "Mechanical and durability properties of medium strength self-compacting concretewith high-volume fly ash and blendedaggregates", *Period. Polytech. Civil Eng.*, **59**(2), 155-164.

Naik, T., Singh, S. and Hossain, M. (1994), "Permeability of concrete containing large amount of fly ash", **24**(5), 913-922.

Nath, P. and Sarker, P. (2011), "Effect of fly ash on the durability properties of high strength concrete", *Proceedings of the 12th East Asia-Pacific Conference on Structural Engineering and Construction*, **14**, 1149-1156.

Nazmy, A., Ashraf, M.B. and Khalad, M.E. (2003), "Emerging technologies in structural engineering", **2**.

NRMCA (2004), *Self Consolidating Concrete*, National Ready Mixed Concrete Associasion.

Ryan, P. and O'Connor, A. (2016), "Comparing the durability of self-compacting concretes and conventionally vibrated concretes in chloride rich environments", *J. Constr. Build. Mater.*, **120**, 504-513.

Seshadri Sekhar, T., Sravana, P. and Srinivasa, R. (2010), "Some studies on the permeability behaviour of self compacting concrete", Ph.D. Dissertation, J.N.T. University, Hyderabad, India.

Shen, L., Struble, L. and Lange, D. (2016). "Testing static segregation of SCC", University of Illinois, Illinois, U.S.A.

Siddique, R. (2011), "Properties of self-compacting concrete containing class F fly ash", *J. Mater. Des.*, **32**(3), 1501-1507.

Sri Ravindrarajah, D.R., Siladyi, D. and Adamopoulos, B. (2003), "Development of high-strength self-compacting concrete with reduced segregation potential", *Proceedings of the 3rd International RILEM Symposium*, Reykjavik, Iceland, August.

Swamy, R., Ratnam, M.K.M.V. and Rangaraju, D.U. (2015), "Effect of mineral admixture on properties of self compacting concrete", *J. Innov. Res. Sci. Technol.*, **1**(11), 503-511.

Trezos, K., Sfikas, I. and Pavlou, D. (2010), "Water permeability of self compacting concrete", *s.l.*, *s.n.*, 1-10.

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**, 67-74.

Zhu, W. and Bartos, P. (2003), "Permeation properties of self compacting concrete", *Cement Concrete Res.*, **33**(6), 921-926.

CC