ANALYSIS OF SELF-COMPACTED CONCRETE USING FLY ASH AND SILICA AS PARTIAL CEMENT REPLACEMENTS

ASIF HAMEED[1], MOHSIN USMAN QURESHI[2 *], ALI MURTAZA RASOOL[3], JAVAID KHALID[4], ASADULLAH QAZI[1], MUHAMMAD USMAN RASHID[5], ZAFAR MAHMOOD[6]

[1] Civil Engineering Department, University of Engineering and Technology, Lahore, Pakistan
[2]Faculty of Engineering, Sohar University, Sohar, Oman
[3]National Engineering Services Pakistan (NESPAK), Lahore, Pakistan
[4]University of Central Punjab (UCP) and National College of Arts (NCA), Lahore, Pakistan
[5]Department of Civil Engineering, University of Management and Technology, Lahore, Pakistan
[6]College of Engineering, University of Buraimi, Buraimi, Oman

Self-compacting concrete (SCC) can compact itself under its weight without any external effort and has characteristics of flowability, passing-ability, viscosity, inhibiting segregation and filling narrow architectural sections, etc. SCC requires a larger quantitative proportion of fines e.g. pozzolans like fly ash, blast furnace slag, silica fume, metakaolin, rice husk, or non-pozzolanic materials like limestone and sandstone. However, a higher quantity of pozzolanas with lower water content may cause autogenous shrinkage. The objective of this research is to find the best mix design of SCC to reach the highest compressive and flexural strength while maintaining flowability, passing ability, and segregation resistance. For this purpose, first twenty-eight (28) mix designs were prepared and tested in a fresh state for assessing flowability, passing-ability, and segregation resistance properties. The results of these tests were found compatible with previous studies without any significant variations. Then, hardened concrete was tested by casting 448 cylinders for determining the compressive strength at 7, 14, 28, 56, and 90 days and 168 prisms were tested to determine the flexural strength at 28, 56, and 90 days. It was observed that two combinations i.e. 30%FA, 17.5%SF, and 25%FA, 7.5%SF replacement are the most favorable mineral fine admixtures in producing good quality SCC.

Keywords: *Self-Compacting Concrete (SCC), Fly Ash (FA), Silica Fumes (SF), Pozzolans, Coefficient of Variance*

1. Introduction

Placement of adequately compacted concrete has always remained of concern in heavily reinforced areas and narrow architectural sections [1]. Fact remains that achieving compaction needs proper vibration. With the normally vibrated mix (NVM), adequate compaction for durable concrete is difficult to achieve without skilled workers [2]. This inherent problem prompted the evolution of self-compacting concrete (SCC). The idea was conceived, and preliminary work was initiated in 1983. The necessity of using SCC was proposed in 1986 and the prototype was completed in 1988 [3]. A study on the workability of SCC was carried by many researchers including [4–6]. Employing its self-weight, SCC, in the presence of heavily congested reinforcement, has the potential to reach every corner of the formwork. Its use is beneficial owing to increased productivity, reduced requirement of skilled labor, shortened construction period, easier placing, better surface finishing, improved durability, ensured compaction especially in the confined zones, saved the cost of compaction, and absence of vibration eliminating noise pollution [7,8]. Self-compaction occurs due to the high deformability of paste or mortar and resistance to segregation between mortar and coarse aggregate when there is a flow of concrete through the confined zones of reinforcing bars [9]. Lower segregation is due to low water-cement ratio and high deformability is due to the use of superplasticizers [10]. As per EFNARC 2005 [11] guidelines for SCC mix design, incorporation or addition of mineral admixtures is one of the foremost and principal differences between SCC and conventional concrete. Many studies on the effects of mineral admixtures on the properties of SCC have been conducted [12–15]. According to these studies, the advantage of mineral admixture usage in SCC corresponds to features such as improved workability with reduced cement content. Reduction in the content of cement proves to be an economical solution since cement is the most expensive component of concrete. In addition to that, it also affects the concrete durability in a positive way by improving the particle packing alongside causing a decrease in permeability of the concrete [16]. Industrial by-products, bio-based materials or fine waste such as limestone powder, fly ash, silica fume, and granulated blast furnace slag are generally used as mineral admixtures in civil engineering [17–21]. Thereby, the workability of SCC is improved and the used amount of by-products or waste materials can be increased. Besides the economic benefits, such uses of

*Autor corespondent/*Corresponding author*,
E-mail: mqureshi@su.edu.om

by-products or waste materials in concrete reduce environmental pollution [22]. Fly Ash (FA) is a waste product that resulted by the burning of coal in electricity generating units. Similarly, Silica Fume (SF) is a by-product extracted from the exhaust gases of silicon, ferrosilicon, and other metal alloy smelting furnaces. However, high-quality condensed SF is used in concrete [23]. Having a considerable high degree of fineness as compared with cement, FA and SF can be utilized as filler materials for the production of SCC, which can fill the spaces between aggregate and reduce interstitial pores of the concrete. This high degree of fineness enhances the durability of concrete [24]. Recently, SCC is gaining popularity around the world due to various advantages associated with its use. However, in most developing countries, SCC has not gained confidence in its use due to lack of research.

Keeping in view these, the current research has been performed focusing on the use of FA and SF in SCC using locally available materials. Hence, an experimental program is designed with the main objective to determine the effectiveness of FA and SF in SCC, the fresh and hardened properties of SCC with FA and SF as filler and to optimize their quantities in SCC to find the most effective combination of FA and SF that can be used for preparing SCC.

2.Methodology

For determining the properties of SCC in the fresh and hardened state, some concrete mixes with FA, SF, and their varying combinations were prepared following the provisions of ACI 237R 2019 [25] and guidelines given in EFNARC 2005 [11]. The properties of materials used, the mixes prepared, and various tests carried out on the SCC in fresh and hardened state are discussed below.

2.1.Properties of Materials Used

2.1.1.Fine Aggregate

Coarse sand abundantly available in Pakistan was selected and to meet the grading requirement of ASTM C33 2018 [26], 15% of coarse sand was replaced with fine sand. The coarse sand had a bulk density of 1543 kg/m^3, a specific gravity of 2.70, water absorption of 1.35%, and a fineness modulus of 2.54. Whereas, the fine sand has a bulk density of 1596 kg/m^3, a specific gravity of 2.71, water absorption of 1.55%, and fineness modulus of 2.44. The gradation curve of fine aggregates used in this study is shown in Figure 1(a). It can be seen that percentage passing of fine aggregate having a combination of 85% coarse sand + 15% fine sand falls within upper & lower limit given by ASTM C33 2018 [26].

2.1.2.Coarse Aggregate

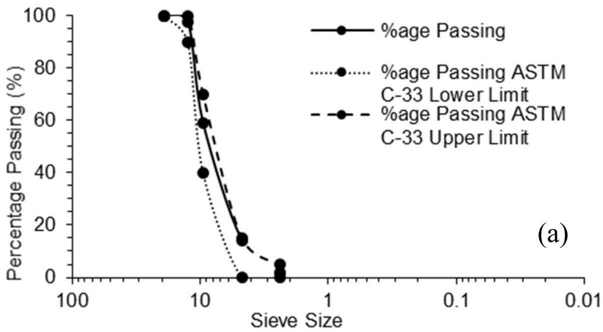
Crushed stone aggregates having maximum particle size passing BS Sieve No. ¾" (19 mm) were used in this study. The coarse aggregates had a bulk density of 1526 kg/m^3, a specific gravity of 2.62, water absorption of 1.53%, and fineness modulus of 2.44. The gradation curve of coarse aggregates is shown in Figure 1(b). It can be seen that the percentage passing of coarse aggregate falls within the upper and lower limit given by ASTM C33 2018 [26].

2.1.3.Cement

Type-1, Ordinary Portland Cement (ASTM C150 2020) [27] was used in this study. OPC is a general-purpose cement that is equally suitable for almost all normal uses excluding places where special properties are required. It has a specific gravity of 3.14, an initial setting time (the paste ceases to be fluid) of 120min, and a final setting time (the paste acquires a certain degree of hardness) of 420min.

2.1.4.Fly Ash (FA)

Class F, FA was used in this study. The results of X-ray powder diffraction (XRD) analysis conducted on FA is shown in Figure 2(a).The XRD diffractrograms proved helpful in the quantitative tracing of mineral constituents of fly ash. Spacing of the crustal lattice in degrees is expressed on the horizontal scale while the intensity of the diffracted X-ray in pulses per second is exhibited on the vertical scale. The chemical composition of FA along with the minimum and maximum percentages of chemicals required by ASTM C 618 2019 [28] are listed in Table 1.



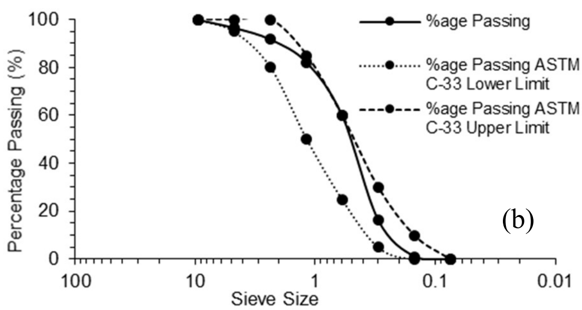


Fig. 1 - Gradation curve of mixed fine aggregates (a) and coarse aggregates (b)

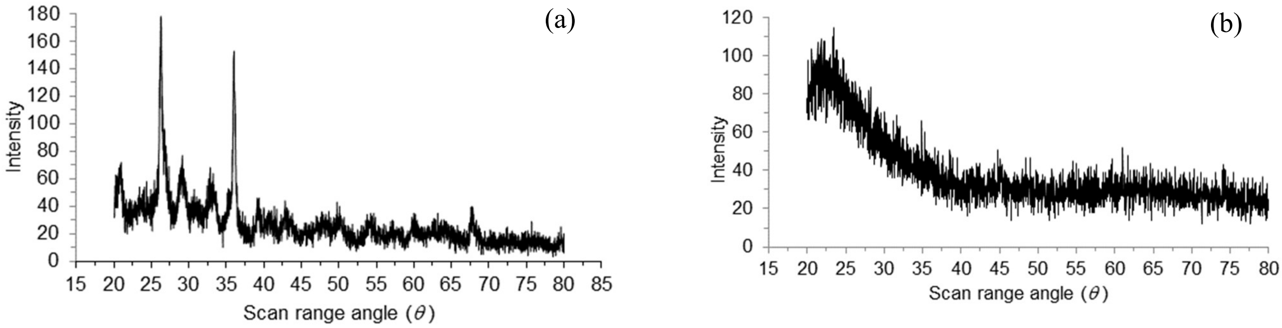


Fig. 2. - XRD diffractograms of Fly Ash (a) and Silica Fume (b)

Table 1

Chemical Composition of Fly Ash (FA)

Component	FA - Class F(% by weight)	ASTM C 618 Requirement (%)
Silicon Dioxide – SiO_2	54.60	
Aluminium Oxide – Al_2O_3	16.30	
Ferric Oxide – Fe_2O_3	05.70	
∑ (SiO_2 + Al_2O_3 + Fe_2O_3)	76.06	70.0 Minimum
Calcium Oxide - CaO	11.20	-
Magnesium Oxide - MgO	03.92	5.0 Maximum
Titanium Dioxide – TiO_2	0.216	-
Potassium Oxide– K_2O	01.48	-
Sodium Oxide – Na_2O	01.06	1.50 Maximum
Sulphur Trioxide- SO_3	02.35	5.0 Maximum
LOI (1000^{O}C)	01.15	6.0 Maximum
Moisture	03.44	3.0 Maximum

2.1.5. Silica Fume (SF)

The diffractogram of X-ray powder diffraction (XRD) analysis conducted on SF is shown in Figure 2(b) and the chemical composition of SF is listed in Table 2

Table 2

Chemical Composition of Silica Fume (SF)

Component	SF % by weight
SiO_2	95.5
Al_2O_3	0.6
Fe_2O_3	1.2
MgO	0.4
CaO	0.4
Na_2O + K_2O	0.9
SO_3'	-

2.1.6. Admixtures

Poly Carboxylate Ether (PCE), a third-generation superplasticizer (High Range Water Reducer, HRWR, admixture) is based on Carboxylate Acid derivatives. It is compatible with both SF and FA. Its addition improves concrete quality in both fresh and hardened states and is most suitable for SCC. Its normal dose is 0.8 to 2.0% by weight of cement and is added in water before its addition to the dry mix. Freshly prepared concrete needs to be cured properly to prevent plastic and drying shrinkage. The Viscosity Modifying Admixture (VMA) is used to increase the viscosity to prolong slump retention in the free-flowing SCC. It is primarily HRWR, besides having the characteristics of retarder and slump retaining. VMA is Modified Lignosulphonate based brown liquid (Chemplast P 200 complying with ASTM C494 2019 [29] Types A & D). Apart from giving improved workability at reduced water content, it reduces segregation and bleeding, improves the surface finish, and reduces shrinkage and creep. This VMA is also compatible with SF and is added to the water or into the concrete mixer. For achieving higher strength and durability, the amount of water is reduced by 25%. Its, recommended dose is 0.8% to 2.0% by weight of cement [30]. Although the recommended dosages of HRWR admixture and VMA are 0.8 to 2.0%. However, in current study, the adjustments of the quantities of HRWR and VMA (in combination, not more than 4.25%) are made to achieve the required flowability and stability of SCC and to satisfy the fresh properties as per EFNARC and ACI codes.

2.2. Mix proportioning

The concrete mix/mix design was prepared as per provisions of EFNARC 2005; ACI 237R 2019 [11,25]. Control mix design (01) was prepared without the incorporation of SF or FA. Total 28 mix designs were prepared by the replacement of cement with different percentages of FA and SF. Based on the mix design, 448 cylinders & 168 prisms were casted. In all mixes, the amount of admixtures (i.e. PCE & VMA) were varied as the requirements of SF and FA changed according to their behavior, e.g. an increase in the percentage of FA require more PCE and lesser VMA dose. A summary of SCC mixture constituents having pozzolans and mineral admixtures is given in Table 3.

Table 3

Mixes design proportions

Mix Design	Mix indicatives	PC	SF	FA	Water binder ratio	Fine Agg.	Coarse Agg.	HRWR Admix.	VMA
		kg/m³	kg/m³	kg/m³	-	kg/m³	kg/m³	%age	%age
1	C 100 FA 0 SF 0	475	-	-	0.327	954	830	2.00	1.50
2	C 80 FA 20 SF 0	380	-	95.0	0.327	934	830	2.00	1.50
3	C 75 FA 25 SF 0	356	-	119.0	0.327	919	830	2.00	1.50
4	C 70 FA 30 SF 0	333	-	143.0	0.327	904	830	2.00	1.50
5	C 65 FA 35 SF 0	309	-	166.0	0.327	888	830	2.00	1.50
6	C 90 FA 0 SF 10	428	47.5	-	0.327	890	830	2.00	1.25
7	C 87.5 FA 0 SF 12.5	416	59.4	-	0.327	864	830	2.00	1.00
8	C 85 FA 0 SF 15	404	71.3	-	0.327	838	830	2.00	1.00
9	C 82.5 FA 0 SF 17.5	392	83.1	-	0.327	812	830	2.00	1.00
10	C 80 FA 0 SF 20	380	95.0	-	0.327	786	830	2.00	0.75
11	C 82.5 FA 10 SF 7.5	392	36.6	47.5	0.327	886	830	2.00	1.25
12	C 77.5 FA 15 SF 7.5	368	36.6	71.3	0.327	871	830	2.50	1.00
13	C 72.5 FA 20 SF 7.5	344	36.6	95.0	0.327	856	830	3.00	0.75
14	C 67.5 FA 25 SF 7.5	321	36.6	117.8	0.327	841	830	3.00	0.50
15	C 62.5 FA 30 SF 7.5	297	36.6	142.5	0.327	826	830	4.00	0.25
16	C 80 FA 10 SF 10	380	47.5	47.5	0.327	860	830	2.50	1.25
17	C 75 FA 15 SF 10	356	47.5	71.5	0.327	845	830	2.75	1.00
18	C 70 FA 20 SF 10	333	47.5	95.0	0.327	830	830	3.00	0.75
19	C 65 FA 25 SF 10	309	47.5	118.8	0.327	815	830	3.25	0.50
20	C 60 FA 30 SF 10	285	47.5	142.5	0.327	799	830	4.00	0.25
21	C 77.5 FA 10 SF 12.5	368	59.4	47.5	0.327	834	830	2.50	1.25
22	C 72.5 FA 15 SF 12.5	344	59.4	71.3	0.327	819	830	2.75	1.00
23	C 67.5 FA 20 SF 12.5	321	59.4	95.0	0.327	804	830	3.00	0.50
24	C 62.5 FA 25 SF 12.5	297	59.4	117.8	0.327	789	830	3.50	0.25
25	C 57.5 FA 30 SF 12.5	273	59.4	142.5	0.327	773	830	4.00	0.25
26	C 75 FA 10 SF 15	356	71.3	47.5	0.327	808	830	2.50	1.25
27	C 70 FA 15 SF 15	333	71.3	71.3	0.327	793	830	2.75	1.00
28	C 65 FA 20 SF 15	309	71.3	95.0	0.327	778	830	3.00	0.50

The nomenclature used "**C X FA Y SF Z**" in describing the test cases is explained as follows,

- **C** represents Portland Cement and **X** is the cement in %age used in SCC
- **FA** represents Fly Ash and **Y** is Fly Ash in %age used to replace the cement in SCC
- **SF** represents Silica Fume and **Z** is Silica Fume in %age used to replace the cement in SCC.

For example, in explaining "**C 100 FA 0 SF 0**" C is Portland cement used 100%, whereas, amount of both fly ash (FA) and silica fume (SF) used in preparation of SCC is 0%.

2.3.Mixing process

The mixing process was carried out as per the guidelines and provisions of ACI 304R 2009[31] in a mechanical mixture at a speed of 300rpm. In the first step, mixing of constituent materials was commenced with the preparation of paste i.e. mixing of 2/3rd of water, cement, and pozzolanic materials. The duration of paste mixing was limited to one minute. After preparing the paste, the coarse aggregates together with PCE, VMA, and 1/3rd of water were added and mixed for four (04) additional minutes. Hence, the total time consumed for mixing of SCC was five (05) minutes.

2.4. Fresh properties of self-compacting concrete

Slump flow tests, J-ring test, and L-box test, etc. have been performed to determine fresh properties of self-compacting concrete. A summarized procedure of performing these tests is given below:

2.4.1.Slump Flow Test

The test indicates flowability and gives a horizontal spread of SCC. The test is performed using a 900x900 mm flow table. The time when the SCC first touched 500 mm diameter circle, T500, and the final spread of concrete is measured. The spread diameter is measured in two perpendicular directions and visually examined to see if any bleeding or segregation took place.

2.4.2.J-Ring Test

This test characterizes the ability of SCC to pass through the bars. The higher the slumps flow, the farther the SCC can travel through the bars under gravity and faster it can fill. The parameter that can be used to indicate the degree of affection of the SCC flow through reinforcing bars is the difference between the unconfined slump flow and the J-ring slump flow. If the steel bars retain the coarse aggregate inside the ring, the SCC has an increased potential for blockage and the mix needs to be re-proportioned to ensure the stability of the mix.

2.4.3.L-Box Test

L-box test also determines the SCC's ability to pass. Concrete is poured into the filling hopper of the L-box and allowed to stand for 60±10 seconds. Segregation, if any, is recorded and then

Table 4

Fresh Properties of SCC as per EFNARC, 2005 and ACI 237R-07

Characteristic	Test method	Measured Value		
		EFNARC, 2005		ACI 237R-07
		Measure	Class	
1-Flowability/Filling ability Consistency & T_{500} time (s) to flow freely and fill all spaces in complicated formwork	Slump Flow Test	Total spread	Slump Flow SF-1, SF-2, SF-3	Flow distance Visual stability of the mixture
2-Viscosity/Flowability: Measure of the speed of flow of SCC	T_{500} V-Funnel	Flow time	VS1 & VS VF1& VF22	Rate of flow
3-Passing ability Ability to flow or pass through the tight and congested reinforcement without blockage	L-Box test J-Ring test	Passing ratio. Step height, total flow	PA1 & PA2	Flow rate and distance Flow rate
4-Segregation Resistance Ability to remain homogeneous, no bleeding, no segregation	V-Funnel test after 5 min-segregation resistance	Percent laitance	SR1 & SR2	Segregation of aggregates

the gate is raised to start the flow of SCC into the horizontal section of the box. Three similarly spaced points are marked across the width of the box. These points are later used to measure the vertical distance at the end of the horizontal section as soon as the movement of the mix stops.H2 (mm) or the mean depth of the mix is calculated using these three measurements. A similar procedure is used for the calculation of the depth of SCC immediately behind the gate as H1 mm. The ratio of heights H2/H1gives the blocking ratio. Both ACI 237R 2019[25] and EFNARC 2005 [11] recommend this test with similar procedures and limitations. The minimum value of the blocking ratio is considered to be 0.8. The blocking ratio can be used to indicate the passing ability of the SCC or how much the passage of the SCC is restricted due to the reinforcing bars. Visual detection can only be done to spot segregation or blocking being caused due to the presence of course aggregates behind the bars.

The properties of freshly prepared SCC prescribed by EFNARC 2005; ACI 237R 2019 [11,25] are given in Table 4.

2.5.Tests on hardened concrete

Cylinders were casted and tested in the hardened state to determine the compressive strength and prisms were tested for flexural strength. Determination of the compressive strength of concrete was done following the provisions and procedure as per the ASTM C39 2018 [32], at the age of 7, 14, 28, 56, and 90 days to evaluate the effect of additions of FA and SF on strength development. For this purpose, 448 cylinders (100 mm dia and 200 mm high) were casted. Three cylinders and two prisms were casted for each age of testing except for 28 days, for which four cylinders were casted for each mix type. Flexural strength was determined at the age of 28, 56, and 90 days for all the mix proportions. Six (06) prisms (500×100×100 mm) were casted from each mix type for determination of the Modulus of Rupture.

2.6.Methodology

Following methodology/procedure was adopted for preparation & testing of Self Compacting Concrete.

1. Preparation of mix design of SCC with FA and SF as a partial replacement of cement
2. Preparation of samples
3. Following tests were performed on the fresh concrete
   i. Slump Flow Test (to determine flowability),
   ii. J-Ring Test (to access the passing ability),
   iii. L-Box Test (to indicate passing-ability),
   iv. Column Segregation Test (to determine segregation resistance)
   v. Funnel Test (to measure the difference in flow times at 0 seconds and after 5 minutes and to find out segregation resistance)
4. Following tests were performed on hardened concrete
   i. Compressive strength tests were performed on cylinders at the age of 7, 14, 28, 56, and 90 days. For determining the compressive strength, 448 cylinders were casted using 28 variations of FA and SF. Testing was performed following the procedure outlined in ASTM C39 2018 [32]. For performing tests, sixteen (16) cylinders were casted for each SCC mix. Four (04) cylinders of each mix were tested for 28 days compressive strength while three (03) cylinders were tested for each of 7, 14, 56, and 90 days strength, and the average of results was taken.
   ii. Similarly, flexural strength tests were performed on prisms at an age of 28, 56, and 90 days. For performing flexural strength tests, six (06) prisms were casted for each mix design, i.e., two prisms each for 28, 56, and 90days prism strength. Hence, in total, 168 prims were casted and tested by applying one-point loading.

Finally, analysis and comparison of results were carried out.

3.Experimental results

3.1.Test results of fresh concrete

Tests were performed on freshly prepared SCC to determine flowability, passing ability, viscosity, and segregation resistance. The results of the above-mentioned tests are discussed below,

3.1.1.Slump Flow Test

The test indicates flowability and gives a horizontal spread of SCC. According to EFNARC 2005 [11], slump flow for Class SF1 falls between 550 mm and 650 mm. This flow is easily achieved. However, with a higher dose of FA, the SCC became more cohesive and showed resistance to flow. 26 out of 28 mixes gave slump flow ≥ 550 mm. The mixes prepared by using 20% FA and 15% SF gave slump flow spread of 540 mm and 525 mm respectively which is somewhat less than the ACI 237R 2019 [25] requirement of 550 mm but falls within the prescribed conformity criteria. Thus, using FA and SF individually and in combination, have produced satisfactory results for all the remaining 26 SCC mixes. T_{500} is an indicator of the flowability of SCC. According to EFNARC 2005 [11], T_{500} is < 3.5 seconds for slump flow < 600 mm and T_{500} is 3.5 to 6.0 seconds for slump flow ranging from 600 to 750 mm. According to ACI 237R 2019 [25], the examination of the SCC slump flow spread is involved in the Visual Stability Index (VSI), which determines the stability of SCC mixes. A VSI No. 0, 1, 2, or 3 is assigned to the spread for characterization of the stability of the mix. In terms of VSI, all the SCC mixes showed satisfactory results. There was no evidence of any bleeding in the slump flow spread or any signs of segregation in either of the mixes for which a VSI value of 0 (zero) indicating high stability was assigned. Figure 3(a) shows the slump flow test results.

3.1.2.J-Ring test

This test characterizes the ability of SCC to pass through the bars. The higher the slumps flow, the farther the SCC can travel through the bars under gravity and faster it can fill. For the current mix designs, FA & SF replacement of cement showed satisfactory performance in terms of passing ability. Following EFNARC 2005 [11], the height of the SCC mixture just inside and outside the J-ring was measured. The results were found satisfactory. SCC having a difference <10 mm, shows good passing ability. Combined results of Slump Flow and J-Ring tests are shown in Figure 3(a).

3.1.3.L-Box Test

L-box test also determines the SCC's ability to pass. Both ACI 237R 2019[25] and EFNARC 2005 [11] recommend this test with similar procedures and limitations. The minimum value of the blocking ratio is considered to be 0.8. The blocking ratio can be used to indicate the passing ability of the SCC or how much the passage of SCC is restructured due to the reinforcing bars. Visual detection can only be done to spot segregation or blocking being caused due to the presence of course aggregates behind the bars. To make sure that the mix is stable enough, re-proportioning is done for the SCC mix showing either of these two characteristics. The mixes showing a blocking ratio less than 0.8 is due to the higher cohesiveness. Figure 3(b) shows that all specimens have a blocking ratio greater than 0.8.

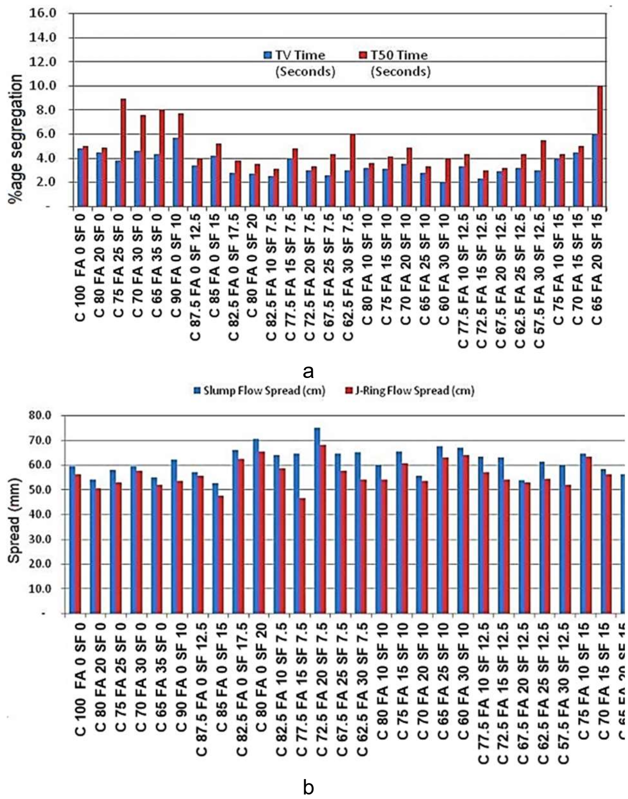


Fig. 3 - Combined Results of Slump Flow & J-Ring Tests (a) and L-Box Test Results (b)

3.1.4.Column segregation /Sieve segregation test

Column segregation test assesses the segregation resistance of SCC. Weight of the coarse aggregates from the bottom and top molds are recorded and segregation value in percentage is worked out. According to ACI 237R 2019 and ASTM C1610 2017 [25,33], the percentage static segregation should be less than 10% in SCC. However, a less segregating mix may not easily flow. The mix having less than 5% static segregation may require some vibration for complete filling. Whereas according to EFNARC 2005 [11], segregation resistance is an important parameter with higher slump flow classes and/or the lower viscosity class, or if placing conditions cause segregation. If none of these apply, it is usually not necessary to specify a segregation resistance class. In this research, a lower slump flow class i.e., SF1 was used because viscosity class T_{500} was more than 2 seconds in 23 out of 28 mixes which fall in category VS2 i.e., the higher viscosity class. Besides, placing conditions did not show segregation, hence, it is not necessary to specify a segregation resistance class in this study program. However, 6 mixes were prepared and tested for static stability and all the mixes had a percentage static segregation of lesser than 10%. It is noteworthy that with an increase in the contents of FA, the paste fraction became very cohesive and caused resistance to flow. Similarly, when using SF in conjunction with FA, their high level of fineness and spherical particle shape resulted in better cohesion and improved segregation resistance. However, for 10%FA and 15%SF mix, percentage segregation was found to be 3.77 %. As per ACI 237R 2019 [25], SCC is generally considered acceptable if segregation is lesser than 10%. All the results fall within the acceptable limit. Static segregation test results are shown in Figure 4(a).

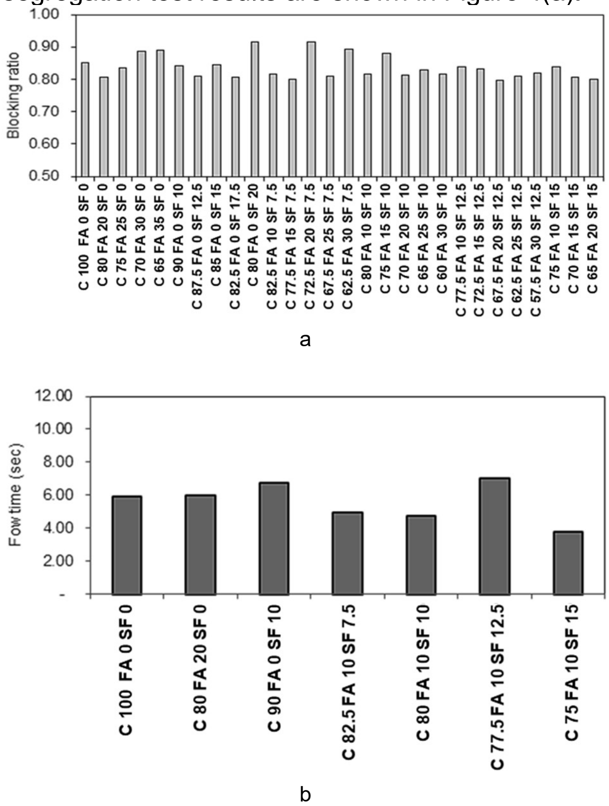


Fig. 4. - Segregation for Combinations of Fly Ash and Silica Fume (a) and V-Funnel Test (b) Results

3.1.5. V-Funnel Test

The V-funnel test is used to assess the viscosity and filling ability of SCC. V-funnel flow time, tv, and t5 minutes are noted in the test. The range of V-funnel flow time is from 3 to 15 seconds ($3 \leq tv \leq 15$). A value of tv< 8 seconds indicates low viscosity whereas tv> 12 seconds shows high viscosity and the mix is likely to experience segregation. t5 minutes should not exceed 3 seconds from the tv. This test gives an indication of segregation resistance. A longer t5 value may be due to rapid loss of workability. According to EFNARC 2005 [11], the V-funnel test is not suitable when the maximum size of the aggregate exceeds 20 mm. The SCC mixes tested for V-funnel flow time in this research program, showed tv values varying from a minimum of 2.0 to a maximum of 6.0 seconds. Eight (08) values ranged from 2.0 to 2.9 seconds and the remaining twenty (20) values ranged from 3.0 to 6.0 seconds. Regarding V-funnel time t5 minutes, twenty-five (25) test results out of twenty-eight (28) gave satisfactory results where the increase in flow time was less than 3 seconds. V-Funnel t_v& t_{50} time results are shown in Figure 4(b).

3.1.6. Analysis of effects of FA & SF on fresh properties

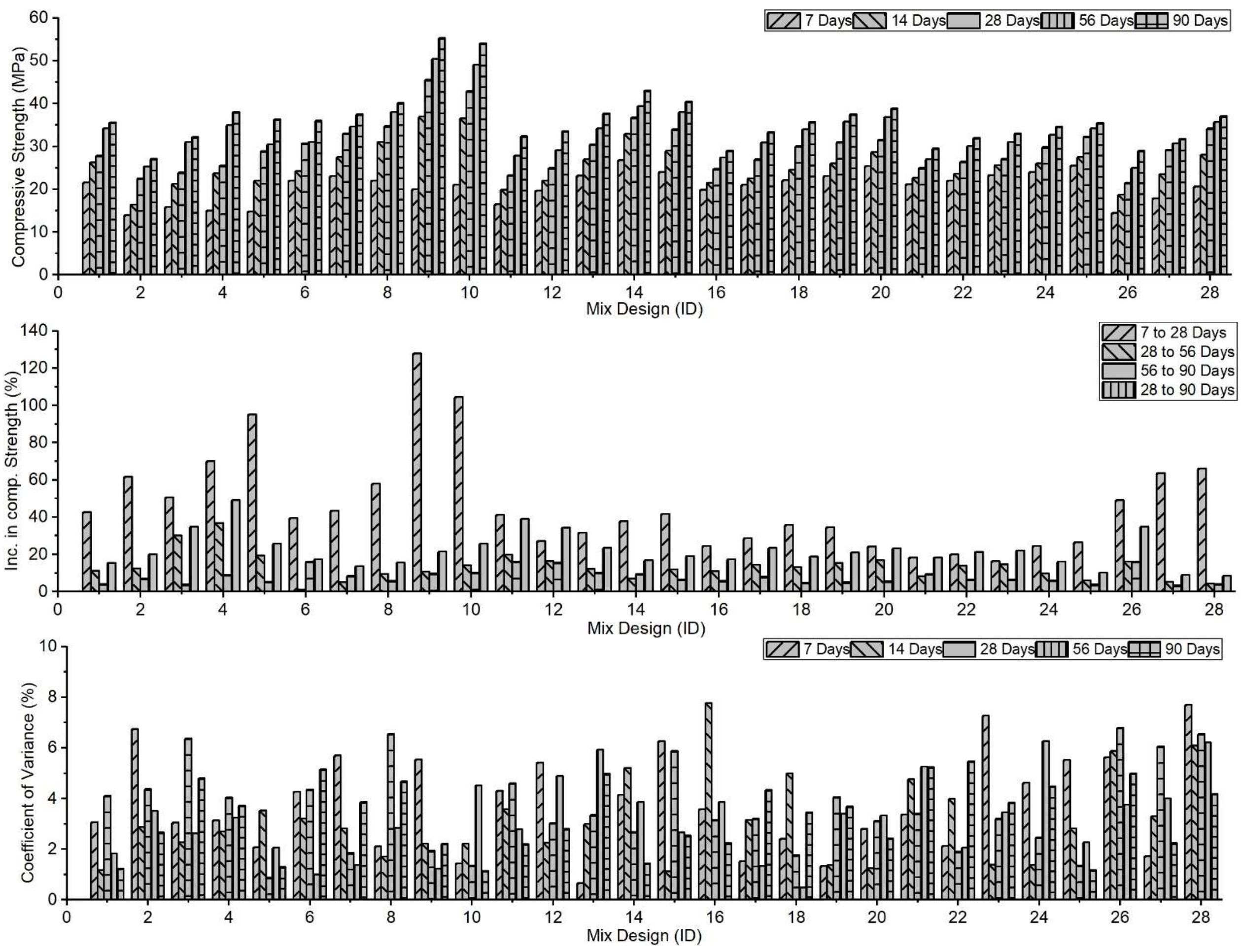
Test results show that in almost all the SCC mixes up to mix design id 28 (i.e., 15%SF and 20%FA), the fresh properties of SCC were not affected. Afterward, using a combination of 15%SF and 25%, 30%FA, there was a sudden decrease in flowing and passing abilities with an abrupt loss of workability. Even by increasing the dose of HRWR super-plasticizer (PCE) to 4% and reducing the dose of viscosity modifying agent to 0.25%, the flow properties i.e., flow-ability and the passing ability could not be improved and therefore, further research work has been stopped. However, filling the interstitial pores in the concrete matrix improves the arrangement of particles ensuring a better contribution of the mixing water to achieve adequate fluidity of the mix up to a certain critical dose beyond which a considerable increase in viscosity is expected [34].

3.2. Test results of hardened concrete

3.2.1. Compressive strength of hardened SCC

Results of compressive strength tests are shown in Figure 5(a).The control mix (i.e., mix design without the incorporation of FA or SF) showed the compressive strength of 21.59, 26.20, 27.78, 34.22, and 35.57MPa at 7, 14, 28, 56, and 90 days respectively. The percentage increase or decrease in compressive strength versus age is shown in Figure 5(b). The strength of the control mix achieved was 27.78 MPa and 35.57 MPa for 28 days and 90 days respectively. With the addition of 17.5%SF (Mix Design 09), 28 and 90days compressive strength was increased to 45.55 and 55.31MPa respectively. The addition of 17.5%SF, therefore, showed a 64% and 55% increase in strength for 28 and 90 days respectively.

The coefficient of variance for compressive tests is shown in Figure 5(c). ASTM C39 2018 [32]gives the limiting value of the coefficient of variance for an average of three test results as 7.80% and it can be seen from the figure that all the tests have a coefficient of variation less than the acceptable limit of 7.80%.



(a)

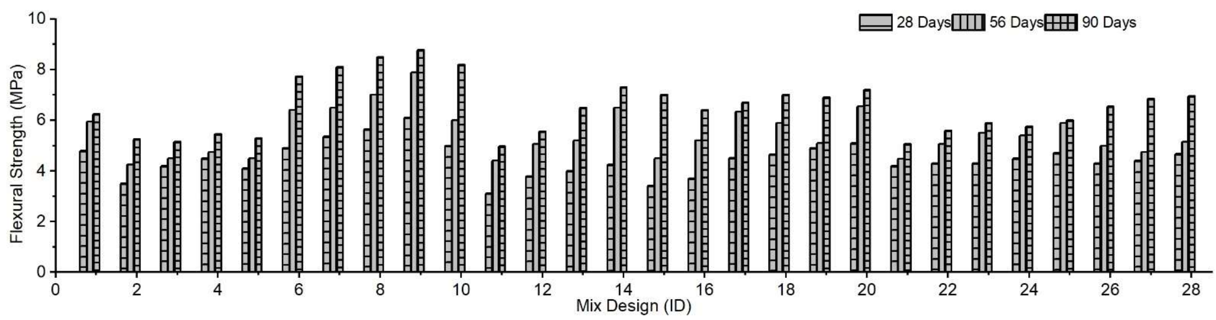
(b)

(c)

Fig.5 - Compressive strength (a), percentage increase in compressive strength (b) and Coefficient of variance for compressive strength of all twenty-eight (28) concrete mixes (c)

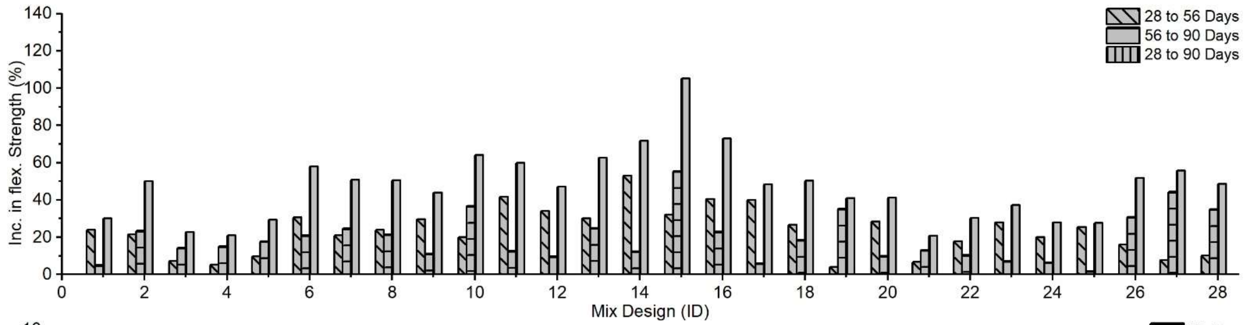
3.2.2. Flexural Strength of Hardened SCC

Results of flexural strength tests are shown in Figure 6(a). The control mix (i.e. mix design without FA or SF) showed the flexural strength of 4.80, 5.95, and 6.24MPa at 28, 56, and 90 days respectively. The percentage increase in flexural strength versus age is shown in Figure 6(b). The maximum increase was found with an addition of 30%FA and 7.5%SF (Mix Design 15).The coefficient of variation of test results has been observed to be dependent on the strength level of the prisms/beams. The coefficient of variance for tests is shown in Figure 6(c). ASTM C39 gives the limiting value of the coefficient of variance for an average of three test results as 15% and it can be seen from the figure that all the tests have a coefficient of variation less than the acceptable limit of 15%.

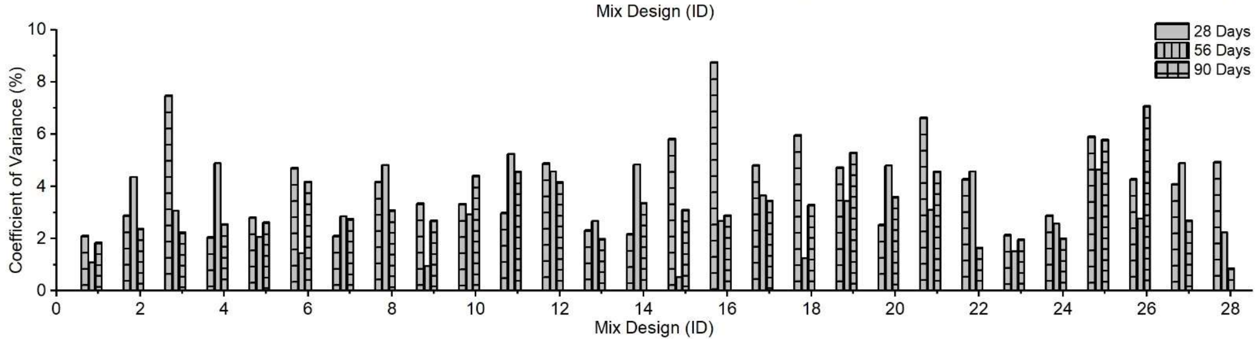


(a)

Fig. 6 continues on next page



(b)



(c)

Fig. 6 - Flexural strength (a), percentage increase in Flexural strength (b) and coefficient of variance for Flexural strength for all twenty-eight (28) concrete mixes (c).

3.2.3. Analysis of effects of FA and SF on hardened concrete properties

The results of the test performed on cylinders and prisms of hardened concrete are summarized as followed:

- **Mix proportions: C 80 FA 20 SF 0, C 75 FA 25 SF 0, C 70 FA 30 SF 0, C 65 FA 35 SF 0**

Using replacement of cement by varying quantity of FA by 20%, 25%, 30% & 35%, the samples showed a trend of lesser rate of increase in strength than that of the control mix at early ages due to reduction of cement quantity and also, due to reduction in the rate of Alite (C_3S) hydration by FA. Nevertheless, at later ages beyond 28 days, the strength increased due to pozzolana reactivity; CH resulted by cement hydration reacts with FA, and hydrates as CSH are formed. A maximum increase in strength was achieved by 30% replacement of cement by FA. The strength showed a decreasing trend for 35% FA. The CV for testing of cylinders for 90 days was 3.72%.

- **Mix proportions: C 90 FA 0 SF 10, C 87.5 FA 0 SF 12.5, C 85 FA 0 SF 15, C 82.5 FA 0 SF 17.5, C 80 FA 0 SF 20**

Using 10%, 12.5%, 15%, 17.5% & 20% replacement of cement by SF, the strength increased for all mixes for all ages due to the SiO_2 reaction of highly active pozzolans with CH accompanied by the formation of hydrates as CSH. A maximum increase in strength was achieved by 17.5% replacement of cement by SF. The increase in compressive strength at later ages was mainly attributed to the reaction of highly active SF with CH, by which an increased quantity of CSH is forming. In another research, Mahalakshmi and Khed 2020 [37] used the replacement of cement with SF (0%, 10%, 15%, and 20%) and observed better results with 15% SF. In the present research, the increment was refined to 2.5% so that results could be observed more closely between the ranges of 10 to 20%. Better results were observed with the use of 17.5% SF.

- **Mix proportions: C 82.5 FA 10 SF 7.5, C 77.5 FA 15 SF 7.5, C 72.5 FA 20 SF 7.5, C 67.5 FA 25 SF 7.5, C 62.5 FA 30 SF 7.5**

Using replacement of cement by a combination of SF 7.5% and varying quantity of FA (10%, 15%, 20%, 25% & 30%), the samples showed a trend of increase in strength at later ages due to CH reaction with pozzolans. Maximum strength was achieved by a combination of 7.5% SF and 25% FA. The strength development up to 28 days was mainly due to the hydration process of cement compounds. The FA slows down the hydration of Alite (C3S) at an early stage and offsets the activity of SF within the first week. The increase in compressive strength, however, continued till later age. The increase in strength at later ages beyond 28 days, observed for 56 days and 90 days, was mainly attributed to the pozzolanic activity and partially to the hydration of cement compounds.

- **Mix proportions: C 80 FA 10 SF 10, C 75 FA 15 SF 10, C 70 FA 20 SF 10, C 65 FA 25 SF 10, C 60 FA 30 SF 10**

Using replacement of cement by a combination of SF 10% and varying quantity of FA (10%, 15%, 20%, 25% & 30%), the rate of increase of strength at early ages slowed down due to delaying of hydration of Alite by FA but increased at later ages due to slow reaction of FA with CH resulted by cement hydration. The maximum increase in strength was given by a combination of 10%SF and 15%FA. The strength development up to 28 days was due to both SF active reaction with CH and the hydration process of cement compounds. The progression of compressive strength increase continued at a later age. The increase in compressive strength at later ages beyond 28 days, observed for 56 days and 90 days, was mainly attributed to the pozzolanic activity of SF and FA.

- **Mix proportions: C 77.5 FA 10 SF 12.5, C 72.5 FA 15 SF 12.5, C 67.5 FA 20 SF 12.5, C 62.5 FA 25 SF 12.5, C 57.5 FA 30 SF 12.5**

Using replacement of cement by a combination of 12.5%SF and FA by 10%, 15%, 20%, 25% & 30%, the rate of strength gain increased due to pozzolanic activity of higher content of SF (12.5%). The maximum strength was achieved by a combination of 12.5% SF and 15% FA. Nevertheless, at later ages beyond 28 days, the strength increased due to pozzolana reactivity; CH resulted by cement hydration reacts with FA, and hydrates as CSH are formed.

- **Mix proportions: C 75 FA 10 SF 15, C 70 FA 15 SF 15, C 65 FA 20 SF 15**

Using replacement of cement by a combination of SF 15% and FA (10%, 15% & 20%), strength increased due to pozzolanic activity of SF in higher content (15%). Maximum strength was achieved using a combination of 15% SF and 20% FA. The progression of compressive strength thus continued at a later age. The increase in compressive strength at later ages beyond 28 days, observed for 56 days and 90 days, was mainly attributed to the hydration reaction of pozzolans.

For a combination of 25 %, and 30 % SF, flow properties could not be achieved and therefore, SCC could not be prepared. Out of all the aforesaid six (06) types of mixes' compressive strength results, the maximum strength for 28 days and 90 days of 45.55 MPa and 55.31 MPa respectively was achieved using 17.5% of SF.

- **Mix proportions: All concrete mixes/mix designs**

The rates of development of strength on prisms were identical to that of the previously mentioned results of compressive strengths on cylinders. A combination of 30% FA and 7.5% SF gave maximum flexural strength at 28 and 90 days. On the other hand, coefficients of variation (CV) for all the 448 cylinders and 168 prisms were found within the acceptable limit prescribed by ASTM C39 2018 [32].

4.Conclusions

An experimental series with the main objective of finding the best mix design of SCC reaching the highest compressive and flexural strength while maintaining the flowability, passing ability, and segregation resistance has been performed in this research. The following conclusions can be drawn from the study

1. SF, FA, Poly Carboxylic Ether (HRWR admixture) and Modified Lignosulphonate based retarder (VMA) are all compatible. Thus, both SF and FA could be effectively used without any processing as filler in SCC, thereby reducing the burden of solid waste on the environment.
2. When the fresh properties such as flowability, passing ability, and segregation resistance are considered, all concrete mixes were found with an acceptable range as prescribed by code/standard.
3. Some combinations as 30% FA + 17.5% SF, 25% FA + 7.5% SF were found to be the most favorable in producing of good quality SCC.
4. With the use of FA 25% and beyond, and SF 15% and beyond as replacements of cement, SCC could not be prepared. The mixture could not qualify for any of the prescribed fresh properties criteria prescribed by the code.

ACKNOWLEDGMENTS

Department of Civil Engineering, University of Engineering and Technology, Lahore, Pakistan, is greatly acknowledged for providing research, financial, and experimental facilities. Whereas, experts from National Engineering Services Pakistan (NESPAK), and Sohar University, Oman are greatly acknowledged for providing technical assistance. The authors would like to thank Sohar University for supporting the publication of the manuscript.

REFERENCES

[1] A. Campens, The sociological dimension of concrete interiors during the 1960s, Palgrave Commun, 2017, 17035. https://doi.org/10.1057/palcomms.2017.35

[2] P. Kumar, R. Kumar, Y. Gupta, A. Rawat, Comparison of NVC to Different Mixed Design Method of Self-Compacting Concrete, J. Struct. Eng. Manag, 2016, 37–45.

[3] H. Okamura, M. Ouchi, Self-Compacting Concrete, J. Adv. Concr. Technol, 2003, **5**(15). https://doi.org/10.3151/jact.1.5

[4] B.M. Aïssoun, S.D. Hwang, K.H. Khayat, Influence of aggregate characteristics on workability of superworkable concrete, Mater. Struct. Constr, 2016. https://doi.org/10.1617/s11527-015-0522-9

[5] S. Mohamed, B. Tayeb, Effect of coarse aggregates and sand contents on workability and static stability of self-compacting concrete, Adv. Concr. Constr, 2019

[6] Z. Ding, X. An, Deep Learning Approach for Estimating Workability of Self-Compacting Concrete from Mixing Image Sequences, Adv. Mater. Sci. Eng., 2018, 6387930. https://doi.org/10.1155/2018/6387930

[7] M. Moravvej, M. Rashidi, Structural performance of self-compacting concrete, in: R.B.T.-S.-C.C.M. Siddique Properties and Applications (Ed.), Woodhead Publ. Ser. Civ. Struct. Eng., Woodhead Publishing, 2020, 371–387. https://doi.org/https://doi.org/10.1016/B978-0-12-817369-5.00013-1

[8] I. Liana, C. Bob, The Future Concrete: Self-Compacting Concrete, Bull. Polytech. Inst. Jassy, Constr. Arch. Sect., 2010, **56**(60).

[9] D.K. Ashish, S.K. Verma, An overview on mixture design of self-compacting concrete, Struct. Concr., 2019, **20**, 371–395. https://doi.org/https://doi.org/10.1002/suco.201700279

[10] M. Benaicha, A. Hafidi Alaoui, O. Jalbaud, Y. Burtschell, Dosage effect of superplasticizer on self-compacting concrete: correlation between rheology and strength, J. Mater. Res. Technol., 2019, 2063–2069. https://doi.org/https://doi.org/10.1016/j.jmrt.2019.01.015

[11] EFNARC, The European Guidelines for Self-Compacting Concrete: Specification, Production and Use, 2005.

[12] P. Ramanathan, I. Baskar, P. Muthupriya, R. Venkatasubramani, Performance of self-compacting concrete containing different mineral admixtures, KSCE J. Civ. Eng., 2013. https://doi.org/10.1007/s12205-013-1882-8

[13] M. Uysal, K. Yilmaz, Effect of mineral admixtures on properties of self-compacting concrete, Cem. Concr. Compos, 2011. https://doi.org/10.1016/j.cemconcomp.2011.04.005

[14] K. Kapoor, S.P. Singh, B. Singh, Durability of self-compacting concrete made with Recycled Concrete Aggregates and mineral admixtures, Constr. Build. Mater., 2016. https://doi.org/10.1016/j.conbuildmat.2016.10.026

[15] H.R. Tavakoli, O.L. Omran, M.F. Shiade, S.S. Kutanaei, Prediction of combined effects of fibers and nanosilica on the mechanical properties of self-compacting concrete using artificial neural network, Lat. Am. J. Solids Struct., 2014. https://doi.org/10.1590/S1679-78252014001100002

[16] A. Kanellopoulos, M.F. Petrou, I. Ioannou, Durability performance of self-compacting concrete, Constr. Build. Mater, 2012. https://doi.org/10.1016/j.conbuildmat.2012.07.049

[17] S. Dhiyaneshwaran, P. Ramanathan, I. Baskar, R. Venkatasubramani, Study on durability characteristics of self-compacting concrete with fly ash, Jordan J. Civ. Eng., 2013, 342–353.

[18] M. U. Qureshi, A. Al-Hilly, O. Al-Zeidi, A. Al-Barrami, A. Al-Jabri, A Vane shear strength of bio-improved sand reinforced with natural fibre, In E3S Web of Conferences (Vol. 92, p. 12004). EDP Sciences, 2019. https://doi.org/10.1051/e3sconf/20199212004

[19] M. U. Qureshi, M. Alsaidi, M. Aziz, I. Chang, A. M. Rasool, Z. A. Kazmi, Use of Reservoir Sediments to Improve Engineering Properties of Dune Sand in Oman, Appl. Sci., 2021, **11**. https://doi.org/10.3390/app11041620

[20] Z. Guo, J. Zhang, T. Jiang, T. Jiang, C. Chen, R. Bo, Y. Sun, Development of sustainable self-compacting concrete using recycled concrete aggregate and fly ash, slag, silica fume, Eur. J. Environ. Civ. Eng., 2020, 1–22. https://doi.org/10.1080/19648189.2020.1715847

[21] M.H. Mussa, A.A. Mutalib, R. Hamid, S.N. Raman, Dynamic Properties of High Volume Fly Ash Nanosilica (HVFANS) Concrete Subjected to Combined Effect of High Strain Rate and Temperature, Lat. Am. J. Solids Struct., 2018. https://doi.org/10.1590/1679-78254900.

[22] A. Adesina, P. Awoyera, Overview of trends in the application of waste materials in self-compacting concrete production, SN Appl. Sci., 2019, **1**. https://doi.org/10.1007/s42452-019-1012-4

[23] A.M. Falmata, A. Sulaiman, R.N. Mohamed, A.U. Shettima, Mechanical properties of self-compacting high-performance concrete with fly ash and silica fume, SN Appl. Sci., 2019, **2**(33). https://doi.org/10.1007/s42452-019-1746-z

[24] S.. Ehikhuenmen, U.. Igba, O.. Balogun, S.. Oyebisi, The influence of cement fineness on the structural characteristics of normal concrete, in: IOP Conf. Ser. Mater. Sci. Eng, 2019. https://doi.org/10.1088/1757-899X/640/1/012043

[25] ACI 237R, Self-Consolidating Concrete, in: Am. Concr. Inst., 2019.

[26] ASTM C33, Standard Specification for Concrete Aggregates, ASTM Int. West Conshohocken, 2018.

[27] ASTM C150, Standard specification for portland cement, ASTM Int. West Conshohocken, PA, 2020.

[28] ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use, Annu. B. ASTM Stand., 2019.

[29] ASTM C494, Standard Specification for Chemical Admixtures for Concrete, ASTM Int., 2019.

[30] K.H. Khayat, Viscosity-enhancing admixtures for cement-based materials - An overview, Cem. Concr. Compos., 1998. https://doi.org/10.1016/s0958-9465(98)80006-1

[31] ACI 304R, Measuring , Mixing , Transporting , and Placing Concrete, ACI Comm. 304, 2009.

[32] ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens: C39/C39M-18, Am. Soc. Test. Mater., 2018.

[33] ASTM C1610, Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique, Annu. B. ASTM Stand., 2017.

[34] I.B. Topçu, T. Bilir, Experimental investigation of some fresh and hardened properties of rubberized self-compacting concrete, Mater. Des., 2009. https://doi.org/10.1016/j.matdes.2008.12.011

[35] S.H.V. Mahalakshmi, V.C. Khed, Experimental study on M-sand in self-compacting concrete with and without silica fume, Mater. Today Proc., 2020, 1061–1065. https://doi.org/https://doi.org/10.1016/j.matpr.2020.01.432

****