Iraqi journal of civil engineering (IJCE)
P-ISSN: 1992-7428 ; E-ISSN: 2706-686X

Vol. 17 , No. 1 (2023) , pp. 19 ~ 29
DOI: 10.37650/ijce.2023.170102

Iraqi Journal of Civil Engineering

Journal homepage: https://ijce.uoanbar.edu.iq/

Some Properties of Self-Compacting Concrete with Optimum Percentages of Cement Replacement Materials

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PAPER INFO

Paper history
Received: 01 /01/2023
Revised: 26 /01/2023
Accepted: 31 /01/2023

Keywords:
fly ash
hardened properties
limestone powder
self-compacting concrete
silica fume

ABSTRACT

This paper presents and discuses some properties of self-compacting concrete SCC containing optimum contents of different types of cement replacement materials CRMs like fly ah, silica fume and limestone powder. The purpose is to evaluate the performance of SCC mixtures to choose the best one for strengthening purposes of corroded reinforcement concrete beams. In a preliminary work, the theoretical optimum contents of the above materials were specified using statistical program (Minitab) and they were verified experimentally. This verification based on checking fresh properties such as slump flow, T_{500}, L-box and segregation resistance as well as compressive strength. The optimum contents of CRMs: 14% fly ash, 19% limestone, 18% silica fume plus fly ash and 11% silica fume were selected and studied. Compressive, tensile, and flexural strengths were examined, as well as the modulus of elasticity, water absorption and porosity (which reflect the related durability properties) were examined. Test results show that the optimum verified theoretical percentage of a combination of fly ash and silica fume, at 18% by weight of cement with a fixed water-binder ratio of 0.33 showed the best overall performance. It was deduced that this SCC mix gave the highest mechanical properties and the lowest porosity and water absorption. For example, the compressive strength increased by 36.25% as compared to SCC mix containing limestone powder. Further, the porosity and water absorption decreased by 120.8% and 164% respectively as compared to the above same SCC mix. Thus, it could be used for strengthening purpose of corroded RC beams.

1. Introduction

Self-compacting concrete (SCC) is an innovative type of high-performance concrete that can be placed due to its own weight without the aid of vibration. It was firstly developed in Japan in 1980 (EFNARC, 2005). It can be considered as a sustainable material due to the ability of decreasing cement content using alternative materials which might increase its compressive strength (Puskas & Moga, 2015). It has many benefits compared to conventional concrete, such as eliminating vibration, high workability, and good pumpability. Thus, it easily placed in narrow spaces with limited access due to high congested steel reinforcement which is arduous matter in the case of using normal vibrating concrete (NVC). Further, SCC needs less labor for placing, compacting and

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finishing (Ma et al., 2017),(Kodeboyina, 2018).
NVC consists of combining conventional Portland cement in specified quantities with sand, gravel, water, and sometimes with chemical additives. As for sustainable self-compacting concrete, it is identical to NVC in the usage of components above, but with high content of chemical admixtures and a portion of cement replaced by a specified quantity of mineral and filler additives. Their presence in SCC can improve both the properties in the fresh and hardened states. The use of artificial pozzolans as additional or complementary cementitious materials in concrete has increased in recent years. The use of these materials also signifies special benefit in term of environment while also being cost-effective reductions. In addition, high-range water reducers (superplasticizers) added to SCC should achieve high flowability, which also contribute to decrease the water-to-binder ratio (w/b) and hens, increase the durability of the concrete product (Assié, S., G. Escadeillas, & V. Waller,2007), (Safiuddin, M., J. West, & K. Soudki, 2008).

The traditional approach to enhancing the stability of flowing SCC involves utilizing a significant amount of reactive or inert filler to raise the fines with decreasing the aggregate contents. Fine materials in larger quantities stabilize SCC and improve workability, so SCC is less susceptible to segregation and bleeding. The use of mineral additives in SCC as partial replacement of cement helps to save the environment and can minimize the cost of concrete production. By filling in the pores and increasing concrete density, they are also lowering the risk of bleeding, cracking and permeability (Who, 2020). The fly ash, silica fume, and other cementitious material could increase the strength of concrete, and improve cohesiveness and segregation resistance. Further, they made the concrete mixture of SCC with no change or increase in the strength characteristics (Kodeboyina, 2018).

Numerous researchers studied the addition of some materials that may improve the properties of SCC, such fresh, mechanicalness, and durability. (El-Chabib, H.& Sayed, A., 2013), prepared SCC mixtures using fly ash (FA) class F as cement replacement materials (CRMs) with different percentages while all other constituents are kept constant. Obviously, increasing the proportion of fly ash from (10% to 20%) by the weight of the cement increases the slump flow value from 555mm to 595mm in this study. However, at higher proportions from 20 to 50 %, the rate of increase in slump flow is significantly slower. Consequently, fly ash class F can be used to improve the flowability of SCC mixtures up to 20% cement replacement, next the effect becomes minor. Furthermore, (Beeralingegowda, B.& Gundakalle, V.D., 2013), demonstrated that the use of limestone powder LSP in self-compacting concrete is an effective way up to twenty percent of cement. Cement may be substituted by LSP without affecting the self-compatibility of SCC and even improving its workability. However, adding more than 20% powdered limestone makes the SCC denser and less self-compacting. However, there were no agreement in the literatures about the optimum contents of fillers in SCC as partial cement replacement. Therefore, these optimum contents of fillers should be clarified based on multi-tested properties (responses) in both fresh and hardened stages.

(Patel.J, 2014) concluded that replacing alternative cementitious materials instead of cement can change the workability and strength of SCC and modified the matrix's microstructure. The inclusion of various additional of cementitious materials, such as silica fume and fly ash, decreases both pore size and porosity. Furthermore, the fineness, chemistry, and dose of cement replacement materials CRMs influenced the early age strength development of SCC.

(Lisantono & Pratama, 2020) concluded that SCC workability and compressive strength are improved significantly by adding silica fume with an optimum percentage (10% to 15%). To achieve the optimal percentage substitution of silica fume, (0%, 5%, 10%, 15%, and 20%) via weight of cement has been used in self-compacting concrete in this investigation. The concrete test's workability shows that the results met the EFNARC requirement. The average compressive strength of cylinder specimens of self-compacting concrete with 10% and 15% silica fume was 50.93 MPa and 52.82 MPa, respectively. The optimum silica fume substitution in self-compacting high-strength concrete utilizing local sand was between 10% to 15% without specifying the exact percent.

The utilization of silica fume SF together with fly ash FA provides an interesting substitute. Much investigation has recently been conducted using a combination of these two by-products. (Arshad et al., 2021), used seven specimen series made with FA ranging from (17.5% to 25%) and SF varying from (1.25% to 7.5%) of the cement weight. The binder content of the control specimen is 80% OPC, 20% FA, and 0% SF. In the residual six series of samples, OPC is saved constant, while FA is reduced by 1% and SF is increased by 1%. The rheological behavior, mechanical properties, and microstructural features of produced high-performance mixtures were examined. The optimal powder content for high mechanical properties was discovered to be 80% OPC, 17.5% FA, and 2.5% SF.

It is clear from the above that the CRMs modify the properties of fresh or hardened SCC. Inert and pozzolanic/hydraulic additives are frequently employed to enhance and maintain the cohesiveness and segregation resistance due to the fresh property requirements of SCC. Also, the addition might control the cement content and heat of hydration(EFNARC, 2005). Although SCC has many positive features, it has some drawbacks such as low tensile strength and ductility and there is no standard method for its design mix (Kashani & Ngo, 2020).

This study was carried out after the control mixture, and the optimum proportions of LSP, FA, SF and FA+SF were obtained from preliminary work done by authors in a previous stage, including optimized mixtures in terms of best rheological properties such as slump flow, T_{500}, L- BOX and sieve segregation tests as well as the compressive strength as a main mechanical property. This was achieved using different proportions CRMs such as fly ash, silica fume, and limestone powder. The main aim of this work is to investigate different hardened properties for these optimized mixes verified from two methods: experimental and theoretical optimization to select the best SCC mix. Other researchers in the future can benefit from the results of this research to study other aspects such durability properties and their relationships with mechanical properties. It should be highlighted here that these optimum mixes were used to select the best one for strengthening purpose of corroded RC beams in a planned future publication.

2. Experimental program

2.1 Materials properties

Ordinary Portland Cement (Type I) was used. It has a specific gravity of 3.15, a specific surface area of 314 (m^2/kg). Initial and final setting of this type of cement were 126, 228 min, respectively. Cement's chemical and physical properties were tested and they were identical to Iraqi specification (IQS NO. 5, 2019) Fly ash (FA) with a specific gravity of 2.08 was used. It contains 47.7% silica and 28% alumina. This type's Blaine fineness was 380 m^2/kg, and according to (ASTM C 618, 2014), this mineral filler could be classified as class F. Silica fume (SF) SF-Type Mega Add MS(D) with a specific gravity of 2.2 was used. It meets the requirements for silica fume according to ASTM C1240 (ASTM C1240-15,2015). Limestone powder (LSP) is a by-product of the stone-crushing process. Its particle size was less than 75 microns with a specific gravity of 2.6 in the current study. Table 1 illustrates the chemical properties of these materials whereas Fig.1 shows photographs for the cement replacement materials used.
Superplasticizer SP used was a solution of polycarboxylate (Sika viscocrete 5930L) with a density1.1 kg/ liter and a PH of eight and it is a high range water reducing admixture which used to achieve desirable workability. It meets superplasticizer requirements according to ASTM-C-494 Types G and F (ASTM C494/C494M-08). Fine and coarse aggregate were: locally natural fine aggregate with a maximum size of 4.75 mm and a specific gravity of 2.62 and natural rounded coarse aggregate with a maximum size of 10 mm and a specific gravity of 2.6, respectively. Sieve analysis results, as shown in Fig.2 for these two types of aggregates were within the limits of the Iraqi specification IQ. S 45/1984 (IQS NO. 45, 1984).

Table 1- Chemical properties of Portland cement, fly ash, silica fume and limestone

Item %	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	CaO	$CaCO_3$	C3S	C2S	C3A	C4AF
Portland cement	16.25	3.42	-	2.38	3.75	67	-	51.9	31	8.96	7.98
Fly ash	47.67	27.73	18.43	2.65	0.34	5.11	-	-	-	-	-
Silica fume	94.4	0.3	0.81	0.14	0.87	0.26	-	-	-	-	-
Limestone	0.02	-	0.5	0.2	-	0.3	98.8	-	-	-	-

Fig.1 Cement replacement materials used

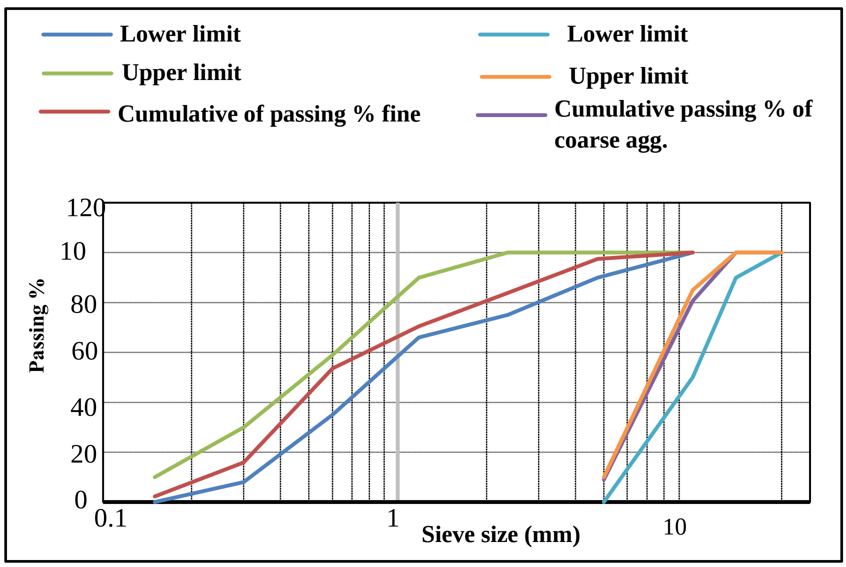


Fig. 2 Grading curves of fine and coarse aggregates

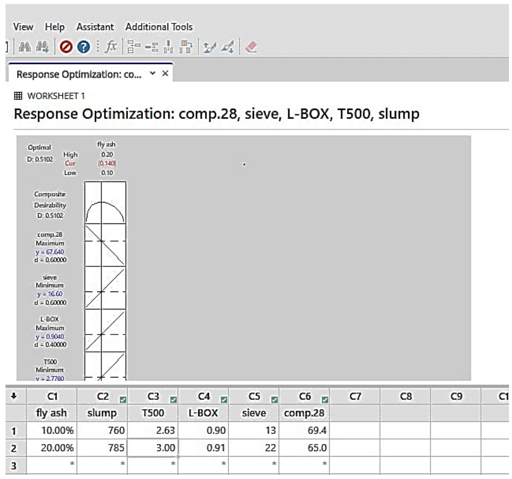
2.2 Mix proportions

There were two stages for preparing the SCC mixtures in the current study: stage 1 was to design the control mix that met the SCC limitations, and several laboratory trials were performed, based on trial and error method. The limitations of SCC mixes followed EFNARC guidelines(EFNARC, 2002). Following these limitations, a reference SCC mixture was designed. This is only in order to prepare four different mixes in stage 2 and to compare these mixes with each other's regardless to the reference one. Table 2 lists the weight of the ingredients per cubic meter, which were adopted for stage 2 which contain four SCC mixtures.

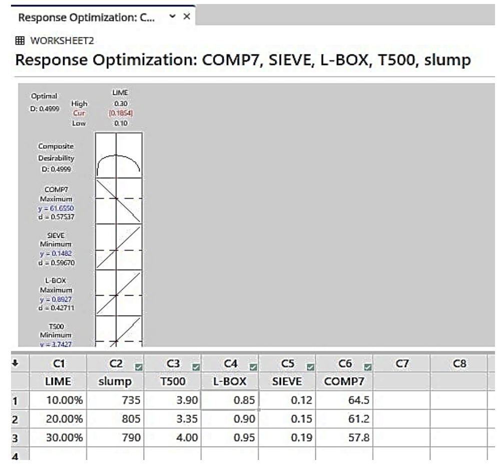
Different replacement materials were used in these four mixtures, representing fly ash, limestone powder, combination (fly ash and silica fume), and silica fume at optimum values, respectively. A theoretical statistical program was used in the second stage to choose the best design for these mixes. One mix was chosen from each group with different proportions using Minitab software, as shown in Fig.3, and all SCC mixtures with optimum proportions of CRMs are listed in Table 3.

Table 2- Ingredients weight per cubic meter

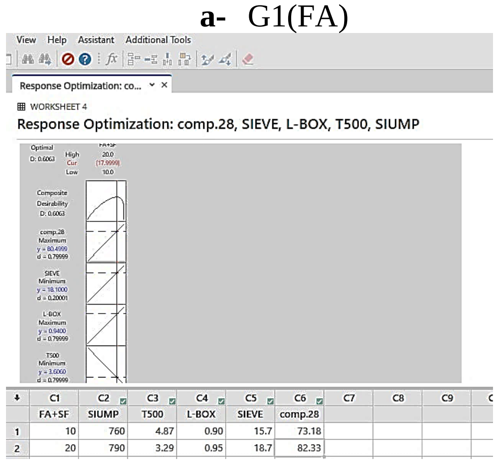
Binder	Coarse aggregate	Fine aggregate	Water
500	764	970	165



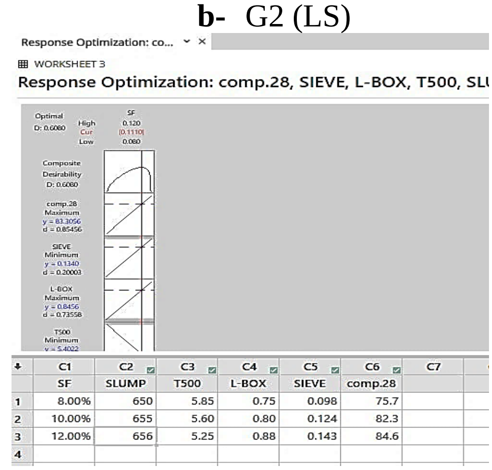
a- G1(FA)



b- G2 (LS)



c- G3 (FA+LSP)



d- G4 (SF)

Fig. 3 Output of statistical software (Minitab 2019)

Table 3- Optimization approach proportions for design mixes

Optimization mixes								
Mix	**Optimized CRM %**	**C kg/m³**	**CRM kg/m³**		**C.A kg/m³**	**F.A kg/m³**	**W kg/m³**	**SP kg/m³**
Mix -FA	14	430	70		764	970	165	8.6
Mix- LSP	19	405	95		764	970	165	8.1
Mix- FA+SF	18	410	FA	SF	764	970	165	8.2
			45	45				
Mix -SF	11	445	55		764	970	165	8.9

C: cement, C.A: coarse aggregate, F.A: fine aggregate, W: water, SP: superplasticizer

2.3 Mixing and casting processes

The required quantities of coarse and fine aggregate were blended in a rotary drum mixer with a capacity of 0.1 m^3 for one minute to produce the fresh SCC mixtures. Cement with cement replacement materials (CRMs) was manually pre-mixed for 2 min to ensure that the CRM granules were evenly distributed throughout the cement.

Then, cement and CRMs were added to the mixer. Through mixing, a small quantity of water was added to prevent volatilization of CRM granules. Following that, the remaining water as well as SP were added to the mixture, and two minutes of wet mixing were performed. Then, the slump-flow, T_{500}, L-box and sieve segregation resistance tests were conducted immediately. All casting molds were thoroughly cleaned and lubricated with an appropriate liquid prior to casting. After the concrete mixing was finalized, the samples were emptied into the prepared molds without vibration. Polyethylene sheets were placed over the molds for 24 hours. The samples were removed from the molds on the second day and placed in a water treatment tank until the test's age.

2.4 Fresh properties of optimum SCC mixes

Following the end of mixing, the states of the fresh concrete were checked. These states include tests to determine the rheological properties of the mixtures. All fresh properties of SCC are based on EFNARC guidelines (EFNARC, 2002). The optimum mixtures were formed in the laboratory with the same material conditions and with the exact level of materials as determined theoretically and they were verified experimentally. The obtained experimental results were very close to theoretical values. Table 4 lists the properties for assessing each optimum mix while Fig.4 shows photographs of slump flow and test results for the four optimum SCC mixes.

Table 4- Fresh properties for the optimum mixes

Mix	Slump Flow Test (mm)	T_{500} Test(sec)	L-BOX Test	% Sieve Segregation Test
Mix FA	800	2.28	1	19
Mix LSP	800	1.98	1	19
Mix FA+SF	745	4	1	15.6
Mix SF	651	6	0.8	14

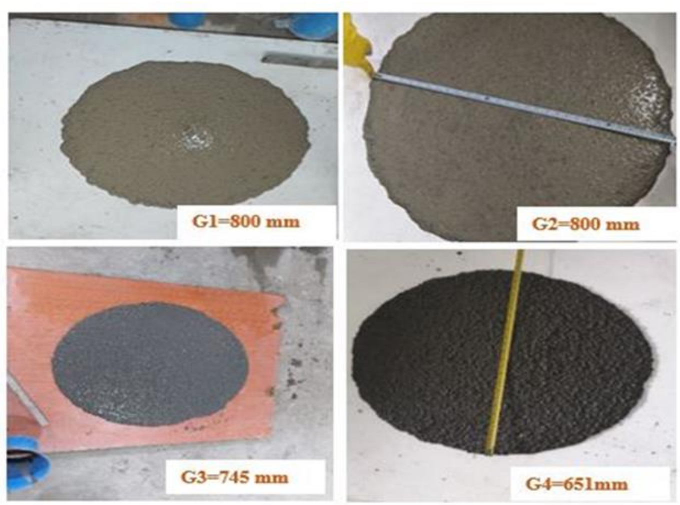


Fig. 4 Slump flow test

2.5 Testing program

The ELE-Digital testing compression machine with a maximum capacity of 2000 kN was used to assess the average compressive strength of 3 cubic specimens of 100 mm according to (BS,12390-3, 2009) at loading rate of 5.30 kN/s.

In the same compressive strength machine with a loading rate of 0.94 kN/s, splitting strength was tested following (ASTM C496/C496M-11, 2011)for three cylinders with dimensions (100×200) mm. Three prisms (100 ×100 ×500) mm tested based on the ASTM C78-15,2015) to determine the modulus of rupture. The flexural strength or modulus of rupture was measured using a hydraulic fracture machine with a capacity of 200 kN. Also, a cylinder with dimensions (150 ×300) mm, based on the (ASTM C469-02,2002) was used to determine Young's modulus of elasticity in a compressive test machine with a loading rate of 5.3 kN/s.

However, related durability properties tests were carried out due to their significant effect on concrete durability. Porosity and water absorption tests were done on three 100 mm cubic samples after 28 days curing period According to (ASTM C642,2013) and the results were calculated as the average of these samples. These mechanical and related durability properties' tests are shown in Fig.5.

Fig. 5 Mechanical and related durability properties' tests

3. Results and discussion

3.1 Mechanical properties

The test results at age 28-days of compressive strength, tensile strength, flexural strength, and static modulus of elasticity are shown in Fig.6, Fig.7, Fig.8, and Fig.9, respectively. It can be observed the highest strength in the case replacing 18% of cement weight by fly ash with silica fume together. A similar effect was noted at replacing 11% of cement weight with silica fume but with less values. It is widely accepted that the addition of SF and FA to concrete increases its compressive strength, particularly in binary mixes with OPC.

This might be due to combined actions of extremely fine particle size of silica fume (high surface area) and fly ash filling effect as well as silica fume pozzolanic activity (Arshad et al., 2021). However, the exact values of cement replacement by these two materials were identified in this study. If the excess calcium hydroxide produced during the cement hydration process reacts with enough pozzolans to form calcium silicate hydrate (CSH), this minimizes the amount of pozzolans is considered optimal. The interfacial transition zone formed by calcium hydroxide around aggregates which reduces the bond strength between aggregate and cement paste ITZ. As a result, the elimination of calcium hydroxide through the formation of additional CSH increases the amount of binder and thus the compressive strength.

Slight effects were recorded at replacing levels of 14% of cement by fly ash class F and 19% of cement weight by limestone powder. The possible reason for this behavior is attributed to a spherical form of FA particles with a very smooth surface(Kashani & Ngo, 2020) which can decrease the internal friction inside the mix and increase excess water. Thus, the formation of a non-homogeneous mixture leads to prevent the fly ash from increasing the mechanical resistance in a clear way. Limestone, which considered as a filler material and has no pozzolanic activity(Who, 2020), was not able to increase the mechanical properties clearly. However, LSP improved the fresh properties of SCC mixtures and can reduce the cost of SCC production without affecting its mechanical properties.

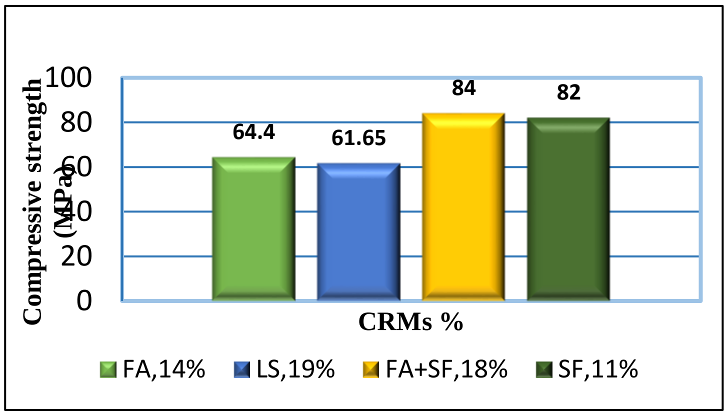


Fig. 6 Test results at age 28-days of compressive strength

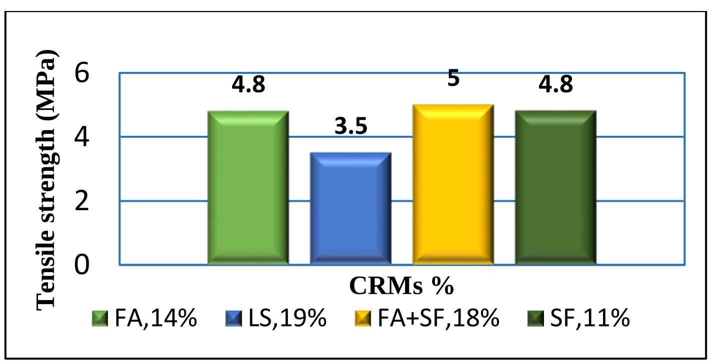


Fig.7 Test results at age 28-days of tensile strength

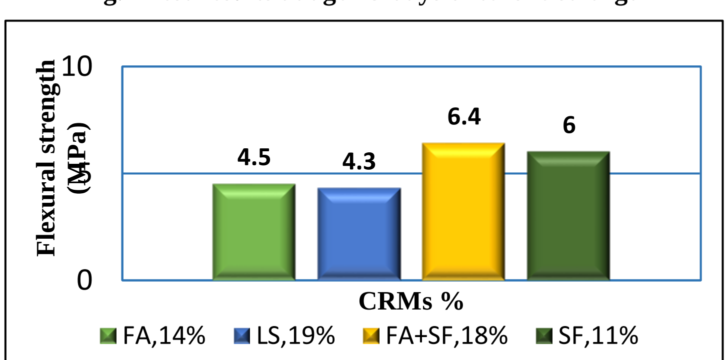


Fig. 8 Test results at age 28-days of flexural strength

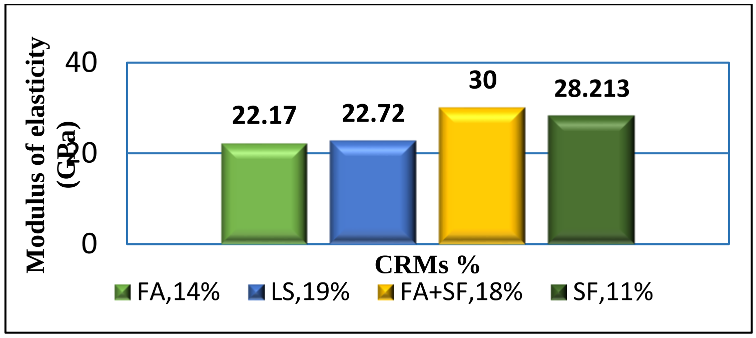


Fig. 9 Test results at age 28-days of modulus of elasticity

3.2 Related durability properties

The test results at age 28-days of water absorption, and porosity are shown in Fig.10 and Fig.11, respectively. Water absorption and porosity as an indicator for required concrete durability. It is noted from Figures 10 and 11 that the highest water absorption and porosity were for 19% of limestone powder and 14% of fly ash replacements, respectively as compared to fly ash and fly ash+silica fume mixes. It is noted that the use of silica fume and a binary mix of silica fume and fly ash as partial replacement materials reduced the water absorption ratio and porosity significantly. In particular, the combination of them at optimum values exhibited superior performance in this aspect. This might due to the increase in packing the microstructure of this SCC mix owing to improvement in particle size distribution of this combination. For SF replacement only, superior fines of SF particles which act as a filler, and their pozzolanic activity improves the homogeneity of the SCC structure, resulting decrease in absorption ratio and porosity. This was compatible with the results obtained by (Leung et al., 2016).

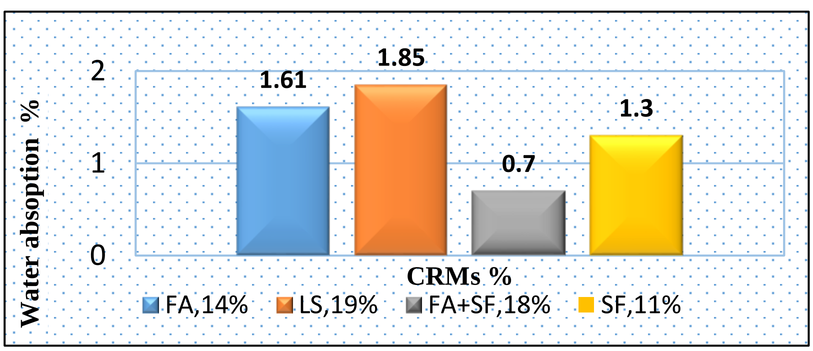


Fig.10 Test results at age 28-days of water absorption

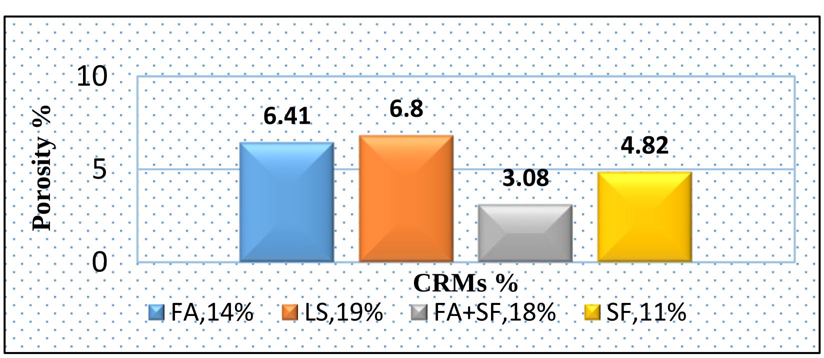


Fig.11 Test results at age 28-days of porosity

4. Conclusions

A series of tests on SCC mixes with varying levels of cement replacement by LSP, FA, and SF were conducted. The conclusions that can be drawn from the test results are:

1. The optimum verified theoretical percentages of a combination of fly ash and silica fume (18%), as well as the using silica fume alone (11%), showed the best mechanical and related durability properties of SCC.
2. The use of a combination of fly ash and silica fume by 18% as cement replacement materials gave the highest compressive strength of 84 MPa. In contrast, the lowest compressive strength was 61.65 MPa for 19% of limestone powder as cement replacement.
3. Once SF and FA are combined in SCC mixture at optimum content (18%), the reduction in water absorption and porosity is greater than other investigated SCC mixes including the SCC mix containing fly ash replacement alone. This indicates that the effect of this combination is significantly greater than that of FA only at optimum content (14%).
4. Limestone powder improves the fresh properties of the SCC mix. However, it had no significant impact on both mechanical and related durability properties.
5. The use of optimum content of fly ash (14%) with the fixed and specified dosage of superplasticizer (2% by weight of cement) produced an excessive amount of water, which led to a non-homogeneous SCC mixture. Therefore, there was no clear improvement in the tested properties of SCC in terms of mechanical and related durability properties.
6. In general, SCC mix containing FA+SF at optimum content showed superior overall performance. Thus, it was selected to be used for strengthening purpose to study the structural behavior of corroded RC beams in a future planed investigation.

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