Effects of silica nanopowder and silica fume on rheology and strength of high strength self compacting concrete

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Abstract: Strength and rheology of high strength self compacting concrete (SCC) containing silica nanopowders and silica fume have been addressed in the present paper. For this purpose, different mixtures were prepared with different amounts of nano silica and silica fume admixtures. In order to understand the influence of paste volume on SCC characteristics, three different binder contents as 400, 450 and 500 kg/m^3 were also investigated. For better comparison of rheological properties, a constant water to binder ratio (w/b= 0.38) was adopted. Rheological properties were investigated through slump flow time and diameter, V-Funnel flow time and L-box tests. Mechanical characteristics included compressive, splitting tensile and flexural strengths at the ages of 7, 28 and 90 days. The results showed that compressive and splitting tensile strengths increased in the mixtures containing both silica fume and nano silica admixtures. Strength enhancement could be due to the fact that the admixtures especially nanoparticles as a partial replacement of cement could accelerate C–S–H gel formation as a result of increased crystalline $Ca(OH)_2$ amount at the early ages and hence increase the mechanical properties of SCC specimens.
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1. Introduction

High strength concrete, according to American Concrete Institute Committee ACI 363 R [1], is the concrete which has specific compressive strength of 41 MPa or more at 28 days. The HPC offers significant economic and architectural advantages over NSC in similar situations, and is suited well for constructions that require high durability.

Self-compacting concrete (SCC) is also considered as a concrete which can be placed and compacted under its own weight with little or no vibration without segregation or bleeding. It is used to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members. It has gained significant importance in recent years because of the advantages it offers [2–5].

Many researchers have used SCC containing admixtures to satisfy the great demand for fines needed for this type of concrete, thereby improving its mechanical, rheological and durability properties in comparison with normal vibrated concrete (NVC). Siddique [6] investigated the properties of SCC made with different amounts of fly ash. El-Dieb [7] studied mechanical and durability properties of ultra high strength-fiber reinforced concrete (UHS-FRC) with self compacting characteristics. According to Fava et al. [8], in SCCs with ground granulated blast furnace slag (GGBFS), strength increase can be achieved. Kulakowski et al. [9] reviewed the silica fume influence on reinforcement corrosion in concrete and the effect of metakaolin on transport properties of concrete were also investigated by Shekarchi et al [10]. There are several few works on incorporating nano particles into concrete specimens to achieve improved physical and mechanical properties which most of them have focused on using SiO2 nano particles [11–15]. High strength SCC seems to be promising materials for many applications and structures. However, this would not be achieved without studying its performance before being widely adopted in construction. Also, the behavior of structural elements made with high strength SCC needs better understanding, together with design provisions.

The aim of this study is to investigate rheological and mechanical properties of high strength self compacting concrete incorporating nano silica and silica fume. The effect of different binder contents on the High strength SCC mixtures has also been investigated.

2. Materials

An ASTM Type II Portland cement (PC) was used to produce the various HPSCC mixtures. In addition, silica fume and nano silica were used as admixtures which are hereafter called Silica Fume (SF) and Nano Silica (NS) respectively. Table 1 summarizes physical properties and chemical composition of the cement and silica fume and table 2 shows the properties of Nano Silica used. The coarse aggregate used was limestone gravel with a nominal maximum size of 12.5 mm. As fine aggregate, a mixture of silica aggregate sand and crushed limestone (as filler) was used with a maximum size of 4.75 mm. The particle size gradation obtained through the sieve analysis and physical properties of the filler, fine and coarse aggregates are presented in Table 3. All aggregates in this research were used in dry form and the aggregates are a mixture of eight particle sizes of fine and coarse aggregates. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of between 1.06 and 1.08 was employed to achieve the desired workability in all concrete mixtures. Furthermore viscosity modifying agent (VMA) for better stability was used.

Table 1. Chemical composition and physical properties of cement and silica fume

Chemical analysis (%)	Cement	Silica fume
Sio_2	20<	93.6
Al_2O_3	6<	1.3
Fe_2O_3	6<	0.9
CaO	<50	0.5
MgO	<5	1
SO_3	<3	0.4
K_2O	<1	1.52
Na_2O	<1	0.45
Loss of ignition	<3	3.1
Specific gravity	3.15	2.2
Blaine fineness (cm^2/g)	3260	21090

Table 2. Properties of Nano Silica

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Purity (%)
15±3	165±17	<0.15	>99.9

Table 3. Sieve analysis and physical properties of the filler, fine and coarse aggregates

Sieve size (mm)	Filler (%passing)	Fine aggregate (%passing)	Coarse aggregate (%passing)
12.5	100	100	97.9
9.5	100	100	79.3
4.75	100	98.38	13.2
2.36	100	76.45	0
1.18	100	46.65	0
0.6	100	39.32	0
0.3	100	15.26	0
0.15	90.9	3.62	0
0.075	33.7	0	0
Bulk density (kg/m^3)		1460	1450
Specific gravity (g/m^3)		2.619	2.6
Absorption (%)	8	2.72	0.4

3. Grading

In fact, the packing theory of Fuller and Thompson[16] represents a special case of the more general packing equations derived by Andreasen and Andersen[17]. According to their theory, optimum packing can be achieved when the cumulative Particle Size Distribution (PSD) obeys Eq. (1) [18]:

$$P(D) = \left(\frac{D}{D_{\max}} \right)^q \qquad \text{Equation (1)}$$

where P is the fraction that can pass through a sieve with opening diameter D; D_{max} is maximum particle size of the mix. The parameter q has a value between *0* and *1*, Andreasen and Andersen [17] have found that optimum packing is obtained when $q = 0.37$. The grading by Fuller is obtained when $q = 0.5$ [18].

PSD curve of some of the mixtures used in this research has been compared with the Fuller and A&A optimized PSD curve, shown in Fig. 1.

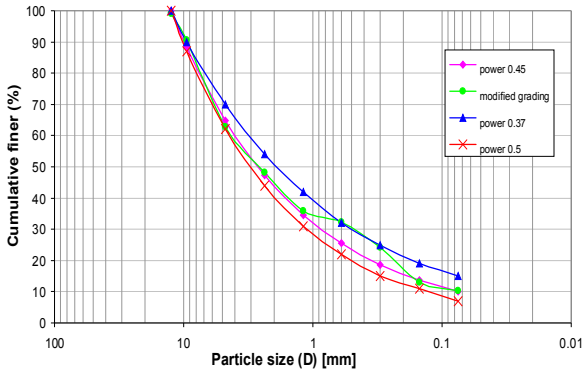

Fig. 1. Analysis of actual PSD of aggregates used with other models

As shown, the more the PSD curve of the mixtures approaches the Fuller curve ($q=0.5$), the more the results for the fresh HPSCC tests and segregation resistance of the mixes are improved. In this paper $q=0.45$ was used and the modified grading curve is shown in Fig. 1. The figure shows four grading curves with three different values of q. Though $q=0.37$ improves workability because of increase of finer grains, however it leads to strength and durability problems of the hardened concrete and hence it is not suitable to be used in high performance concrete mix design. Although strength improvement was expected by using Fuller grading curve, but it lead to decrease of finer grains compared to Andreasen and Andersen and resulted in segregation while making self-compacting concrete. In order to reach a more optimal gradation satisfying strength, durability and workability purposes, $q=0.45$ was considered as a base and according to the available aggregates, it was tried to prepare a modified grading curve which is plotted in Fig. 1.

4. Mix proportions

A total number of 12 concrete mixtures were designed with a constant water/binder (w/b) ratio of 0.38 and total binder content of 400, 450 and 500 kg/m^3. Concrete samples were prepared with 10% and 2% (by weight) replacement of Portland cement by Silica Fume and Nano Silica respectively. The mixture proportions of concrete and binder paste are given in Table 4. The abbreviations used in the study for labeling the mixtures were adopted in such a way that they clearly show the main parameters and their amount. SCC stands for high performance self compacting concrete which is followed by the binder content. SF and NS denote Silica Fume and Nano Silica respectively which are followed by their percentages.

Table 4. Mix proportions of the concrete specimens

No	Concrete ID	w/b	Cement	Silica fume	Nano silica	Filler	Fine aggregate	Coarse aggregate	Sp	VMA
			(kg/m^3)							
1	SCC400	0.38	400	-	-	177	1003	578	2.5	2
2	SCC450	0.38	450	-	-	177	1003	578	2.81	2.25
3	SCC500	0.38	500	-	-	177	1003	578	3.12	2.5
4	SCC400SF10%	0.38	360	40	-	177	1003	578	2.5	2
5	SCC450 SF 10%	0.38	405	45	-	177	1003	578	2.81	2.25
6	SCC500 SF 10%	0.38	450	50	-	177	1003	578	3.12	2.5
7	SCC400NS2%	0.38	392	-	8	177	1003	578	2.5	2
8	SCC450 NS 2%	0.38	441	-	9	177	1003	578	2.81	2.25
9	SCC500 NS 2%	0.38	490	-	10	177	1003	578	3.12	2.5
10	SCC400SF10NS2%	0.38	352	40	8	177	1003	578	2.5	2
11	SCC450SF10NS2%	0.38	396	45	9	177	1003	578	2.81	2.25
12	SCC500SF10NS2%	0.38	440	50	10	177	1003	578	3.12	2.5

5. Mixing procedure

Since the SP plays a very important role in the flowability of SCC mixes [19], a modified mixing procedure was adopted to take the benefit of action of adsorption of molecules of poly-carboxylic ether based SP on the cement particles for all the mixes. SCC mixtures were prepared by mixing the coarse aggregates, fine aggregates and powder materials (cement, silica fume and nano silica) in a laboratory drum mixer. The powder material and aggregates were mixed in dry form for 2 minutes. Then half of the water containing the whole amount of Super plasticizer was poured and mixed for 3 minutes. After that, about 1 minute rest was allowed and finally rest of the water containing VMA was added into the mixture and mixed for 1 minute.

6. Preparation of the specimens

Cubic moulds with dimensions of 150×150×150 mm and cylindrical moulds with dimension of 100×200 mm were made for compressive and splitting tensile tests respectively. The moulds for SCC were covered with polyethylene sheets and moistened for 48 h. Then the specimens were demoulded and cured in water at a temperature of 20ºC until the test time. The compressive and splitting tensile strengths of the concrete samples were determined at 3, 7, 28 and 90 days and the average of two trials was reported.

7. Testing of the specimens

When the mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow time and diameter, V-funnel flow time and L-box height ratio. Segregation was also visually checked during the slump flow test. From each concrete mixture, 150×150×150 mm, 100×100×100 mm cubic and 100×200 mm cylinder specimens were cast for the determination of compressive strength, split tensile strength and durability tests (absorption, capillary, specific electrical resistance and penetration Cl^- ion tests). All specimens were cast in one layer without any compaction. At the age of 48 h, the specimens were demolded and stored in water at 21 ± 2 ºC until the date of testing.

7.1. Tests on fresh concrete

The flow rate of a SCC mixture is influenced by its viscosity. When developing an SCC mixture in the laboratory, a relative measure of viscosity is useful. The time it takes for the outer edge of the concrete to spread and reach a diameter of 20 in. (500 mm) from the time the mold is first raised, based on the procedure described in the slump flow test, provides a relative measure of the unconfined flow rate of the concrete mixture. For similar materials, this time period, termed T_{50}, gives an indication of the viscosity of the SCC mixture [20]. According to Nagataki and Fujiwara [21], the slump flow represents the mean diameter of the mass of concrete after release of a standard slump cone; the diameter is measured in two perpendicular directions. Basic workability requirements for an acceptable SCC are summarized by Khayat [22] as; excellent deformability, good stability, and lower risk of blockage.

Workability properties of SCC mixtures in this study were evaluated through the measurement of slump flow time (T_{50}) to reach a concrete 50 cm spread circle, slump flow diameter (D), V-funnel flow time and L-box blocking ratio (ratio of heights at the two edges of L-box) according to the ‘‘Specification and Guidelines for SCC” prepared by EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) [23].

7.2. Tests on hardened concrete

Tests performed on hardened concrete aimed to determine the mechanical properties including the compressive and splitting tensile strengths of the concrete specimens. Compressive strength values were measured according to BS-1881 [24] on 150 × 150 × 150 mm cube specimens with two specimens for each concrete mix on 3, 7, 28 and 90 days of curing.

The splitting tensile strengths were determined on 3, 7, 28 and 90 days on cylinders measuring 100-mm diameter and 200 mm height and cured in water until the date of test according the ASTM C496 [25]. Flexural tests were performed conforming to the ASTM C293 standard on 50×50×200 mm cubes [26].

8. Results and discussion

8.1. Fresh concrete properties

In this experimental program, workability of SCC was measured by slump flow (D (mm) and T50 (sec)), V-funnel, and L-box tests. Table 5 lists the test results performed on fresh concrete. The slump flow diameters of all mixtures were in the range of 640–840 mm, slump flow times were less than 2.4 s, and the V-funnel flow times (sec) were in the range of 4–12 s. The lowest V-funnel flow time as 4 s was measured for the SCC500N2% while the SCC400NS2%SF10% mixture had the highest flow time as 12 s. Incorporating SF and NS in binary and ternary systems, generally made the concretes more viscous. In order to increase V-funnel flow time of the concretes, the mineral admixtures as SF were used in binary blends. The L-box height ratios were in the range of 0.73–0.98. Almost all workability test results were in the range established by EFNARC [23] except some T50 flow times. T50 measurements of some mixtures were less than the lower limit; however, all concrete mixtures filled the molds by its own weight without the need for vibration. In addition to the above properties, visual inspection of fresh concrete did not indicate any segregation or considerable bleeding in any of the mixtures containing SF and NS during the slump flow, V funnel and L box tests; however, a little bleeding was observed in the control specimens without any SF and NS.

Table 5. Fresh properties of SCC mixtures

Mix No	Concrete ID	Slump Flow		V funnel flow time (sec)	L box H_2/H_1
		D (mm)	T50 (sec)		
1	SCC400	750	2	9	0.73
2	SCC450	800	1.7	5	0.78
3	SCC500	840	1.5	4	0.84
4	SCC400SF10%	650	2.2	10	0.81
5	SCC450SF10%	700	2.1	7	0.9
6	SCC500SF10%	760	2.2	5	0.96
7	SCC400NS2%	740	2.1	10	0.75
8	SCC450NS2%	790	1.9	6	0.8
9	SCC500NS2%	820	1.7	4	0.85
10	SCC400SF10NS2%	640	2.4	12	0.84
11	SCC450SF10NS2%	700	2.3	8	0.93
12	SCC500SF10NS2%	740	2.1	6	0.98
Acceptance criteria of SCC suggested by ERNARC		Slump flow		V funnel flow time (sec)	L box H_2/H_1
		D (mm)	T50 (sec)		
	Min	650	2	6	0.8
	Max	800	5	12	1

The effect of including SF and NS with various volume fractions decreased flowability characteristics; however, they can improve the consistency of concrete mixtures. Less bleeding and segregation were also observed in the mixtures containing SF+NS. Variations of Slump Flow (mm) V funnel (sec) and L box are shown in Figs. 2, 3 and 4 respectively. Generally it can be inferred from the figures that rheological properties of the mixtures containing 2% NS were close to those of the mixtures without admixtures (SCC in the figures) and addition of 2% NS did not change the workability significantly. However, the rheological properties changed more in the mixtures containing 10% SF and 10% SF+2% NS and the concrete matrix gets more viscous and in other words, the consistency of the matrix increase which can result in less bleeding and segregation.

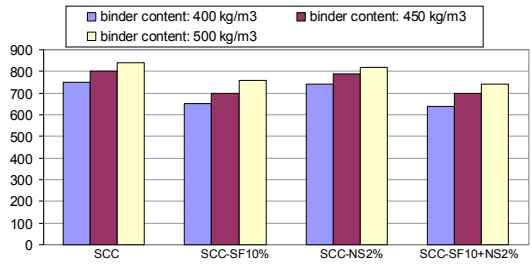

Fig. 2. Variations of slump flow diameter based on binder content

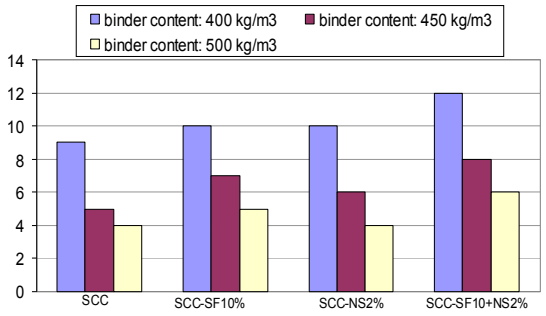

Fig. 3. Variations of V funnel (sec) based on binder content

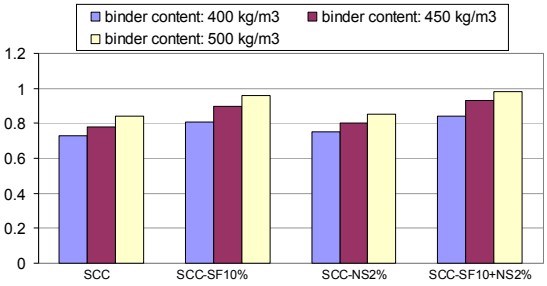

Fig. 4. Variations of L-box ratio based on binder content

8.2. Mechanical properties

The results of compressive, split tensile and flexural strengths are given in table 6. This table presents the average of the compressive strength as determined from two cubic specimens and splitting tensile strength as reported from two cylindrical specimens at each age. Increasing the SF content increased the compressive strength considerably, especially at older ages. Compared to control specimens, replacement by 10% SF in binary mixtures increased the compressive strength for binder content of 400, 450 and 500 by 34, 9 and 9%,

17.5, 12 and 11%, 9, 21 and 23% at 7, 28 and 90 days respectively. Replacement by 2% NS in binary mixtures increased the compressive strength for binder content of 400, 450 and 500 by 22, 38 and 43%, 21, 55 and 61%, 22, 56 and 62% at 7, 28 and 90 days respectively. Replacement by 10% SF and 2% NS in ternary mixtures increased the compressive strength for binder content of 400, 450 and 500 by 62, 52 and 55%, 38,61 and 70%, 30, 67 and 73% at 7, 28 and 90 days respectively. Generally in binary mixtures, the compressive strength improvement was higher in the mixtures containing 2% NS and the highest in ternary mixtures. Generally in all ages (7, 28 and 90 days) ascending trends were observed in compressive strength values by increasing the binder content.

Table 6. Compressive, splitting tensile and flexural strength results of SCC specimens

No	Concrete ID	Compressive strength (Mpa)			Splitting tensile strength (Mpa)			Flexural strength (Mpa)		
		7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
1	SCC400	36.4	51.8	53.1	2.9	3.6	3.9	3.4	3.9	5.3
2	SCC450	36.4	52	53	2.7	4.5	4.6	3.8	4.4	5.7
3	SCC500	40.2	52.5	53.2	3.7	4.7	4.8	4	4.8	5.9
4	SCC400NS2%	44.3	71.3	75.9	3	3.7	4.4	4.2	5.7	6.4
5	SCC450NS2%	44.1	80.4	85.3	3.1	4.5	4.8	4.4	5.9	6.9
6	SCC500NS2%	49.1	82.1	86.1	3.6	4.7	4.9	4.6	6.1	7.2
7	SCC400SF10%	48.7	56.5	58.1	3.1	3.7	4.3	3.8	4.6	5.9
8	SCC450SF10%	42.8	58.3	59.3	3.2	4.3	4.6	4.1	4.8	6.1
9	SCC500SF10%	43.9	63.4	65.1	3.7	4.7	4.8	4.3	5.2	6.3
10	SCC400SF10NS2%	59	78.8	82.4	3.4	4.8	4.9	4.2	6.2	7.8
11	SCC450SF10NS2%	50.1	83.5	89.9	3.8	4.9	5.1	4.5	6.8	8.6
12	SCC500SF10NS2%	52.3	87.9	92.1	3.7	4.8	5.3	4.8	7.3	9

Regarding splitting tensile strength, it can be inferred from the results that the highest values belong to the mixtures containing both silica fume and nano silica with binder content of 500 kg/m^3. Compared to control specimens, replacement by 10% SF and 2% NS in ternary mixtures increased the splitting tensile strength for binder content of 400, 450 and 500 by 17, 33 and 25%, 40,8 and 11%, 27, 2 and 11% at 7, 28 and 90 days respectively. In the same mixtures, binder content increase has also lead to average increase of splitting tensile strength by about 4%. In general, it may be seen from the results that the splitting tensile strength has increased significantly by addition of both silica fume and nano silica particles. It is also noted that the splitting tensile strength has increased rather significantly at more advanced ages.

Foe flexural strength results compared to control specimens, replacement by 10% SF + 2% NS in ternary mixtures increased the flexural strength for binder content of 400, 450 and 500 by 23.5, 18.4 and 20, 58.9, 54 and 52%, 47%, 50 and 52% at 7, 28 and 90 days respectively.

The higher flexural strength in the mixtures containing nanoparticles with respect to control specimens may be as a result of the rapid consumption of crystalline Ca(OH)2 which are quickly formed during hydration of Portland cement specially at the early ages as a result of high reactivity of TiO2 nanoparticles. As a consequence, the hydration of cement is accelerated and larger volumes of reaction products are formed. Also TiO2 nanoparticles recover the particle packing density of the blended cement, directing to a reduced volume of larger pores in the cement paste.

Several studies have also been conducted on flexural strength of cementitious composites reinforced by nanoparticles and some possible reasons have been represented to show the increment of flexural strength:

1) When a small amount of the nanoparticles is uniformly dispersed in the cement paste, the nanoparticles act as a nucleus to tightly bond with cement hydrate and further promote cement hydration due to their high activity, which is favorable for the strength of cement mortar [27,28].
2) The nanoparticles among the hydrate products will prevent crystals from growing which are positive for the strength of cement paste [28,29].
3) The nanoparticles fill the cement pores, thus increasing the strength. Nano-TiO2 can contribute in the hydration process to generate C–S–H through reaction with $Ca(OH)_2$ [30].

9. Conclusion

The results obtained in this study can be summarized as follows:

- Addition of silica fume and nano silica materials improved the consistency of the SCC and reduced the probability of bleeding and segregation.
- Increased in binder content from 400 kg/m^3 to 450 and 500 kg/m^3 improved all rheological properties which could be due to paste volume increase.
- Compressive and splitting tensile strengths improved rather significantly in the mixtures containing silica fume and nano silica which may be due to accelerated C–S–H gel formation as a result of increased crystalline $Ca(OH)_2$ amount at the early ages.
- Strength enhancement was achieved by increasing the binder content.

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