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ENHANCEMENT OF PROPERTIES OF SELF-COMPACTING CONCRETE BY ADDITION OF NANO SILICA

Asmaa Y. Barakat, Construction Research Institute, National Water Research Center, Cairo, Egypt,
Mostafa A. Mostafa, Construction Research Institute, National Water Research Center, Cairo, Egypt,
Gehan A. Hamdy, Faculty of Engineering at Shoubra, Benha University, Egypt, gehamdyl@gmail.com
Hossameldin H. Ahmed, Faculty of Engineering at Shoubra, Benha University

Significant interest is recently shown in the use of materials with Nano dimensions in the construction industry. Research studies attempt to improve the properties of concrete by addition of Nano-sized materials. Self-compacting concrete (SCC) is a concrete with special mix designed to flow and consolidate under its own weight without additional compaction energy due to its properties of flowability and high segregation resistance. This paper presents an experimental program conducted to explore the influence of Nano silica additives on the physical and mechanical properties of self-compacting concrete. The research investigates the fresh properties (workability, passing ability and segregation resistance) and mechanical properties (compressive strength, splitting strength and flexural strength) of self-compacting concrete by incorporation of Nano silica with three different percentages (1%, 2% and 3%) of cement weight. Fresh properties of SCC were determined by slump, L-Box and segregation resistance tests. The mechanical characteristics were determined by compression, splitting tensile and flexural tests at different ages. The experimental results showed that using Nano silica as additive managed to improve the mechanical properties of SCC specimens.

Keywords: Self-compacting concrete; additives; Nanoparticles; Nano-silica; physical properties; mechanical properties.

Introduction

Self-compacting concrete (SCC) is a fluid concrete that spreads through congested reinforcement, fills every corner of the formwork, and is consolidated under its weight. SCC should possess the properties of excellent filling ability, good passing ability and adequate segregation resistance [1]. To achieve these properties, a high volume of Portland cement, a very high dosage of chemical admixtures such as super plasticizers (SP) and viscosity modifying admixtures, and reactive mineral admixtures such as silica fume (SF), are usually used [2]. Industrial wastes such as mineral admixtures (limestone, natural pozzolans and fly ash) can be used to reduce the cost of SCC. Le et al. used common mineral admixtures (limestone powder and fly ash) in combination with rice husk ash, in the range of 5–20 % by weight cement replacement, to produce self-compacting concrete with good self-compactability and very high compressive strength [3]. Nehdi et al. found that SCC with 50% replacement of Portland cement with FA and granulated furnace slag can improve the workability and durability [4].

Recently, increasing amounts of funding are being directed all around the world to research dealing with material properties on the Nano-level, which is claimed to have a tremendous potential for the future [5]. The fundamental processes that govern the properties of concrete are affected by the performance of the material on Nano-scale level. The main hydration product of cement-based materials, the C–S–H gel, is a Nano-structured material.

The mechanical properties and the durability of concrete mainly depend on the refinement of the microstructure of the hardened cement paste and the improvement of the paste aggregate interface zone [6]. Recently, research works attempted incorporating nanoparticles into concrete specimens to achieve improved physical and mechanical properties; most of them have focused on using Nano silica (SiO₂). According to Nazari and Riahi [7], it was possible to increase the compressive strength by 70% with the addition of 4% of nano-SiO₂ in cement mass. The SiO₂ nanoparticles not only behaved as filler to improve the microstructure but also as an activator to accelerate pozzolanic reactions. Shih et al. demonstrated that addition of 0.6% of colloidal nano-SiO₂ can increase the compressive strength of cement pastes by 43.8%. By addition of 3% and 5% of nano-SiO₂ in cement-based mortars, the 28-day compressive strength increases by 13.8% and 17.5%, respectively [8]. Nili et al. [9] used mechanical dispersion techniques or ultrasounds to mix Nano silica with third generation superplasticizer before mixing it with concrete. It was observed that increase in percentage replacement of nano-silica had negative effect on workability of concrete and demand of water also increased [10]. In high volume fly ash concrete with nano-silica, cement was replaced 2% and 4% by nano-silica, and in high volume slag concrete nano-silica dosage from 0.5% to 2% by mass of cement was observed to increase the compressive strength of concrete [11, 12]. It was concluded that early

strength results with nano-silica are better than late strength results [12].

Some researchers investigated the use of nano-materials to produce SCC. Subramanian et al. used Nano silica and micro silica as admixtures and observed that mechanical properties of compressive strength, split tensile strength and flexural strength increased, also satisfactory workability and rheological properties were achieved by using viscosity modifying agent [13]. Another research investigated SCC concrete modified with different amounts of SiO₂, TiO₂ and Al₂O₃ nanoparticle additives, and studied the influence on the physical and mechanical characteristics of hardened self-compacting concrete (SCC) [14]. Rheological properties, microstructure and compressive strength were determined. All studied nano materials densified the microstructure of the hydrated binder matrix and worsened the workability while compressive strength was increased by SiO₂ addition [15]. It was observed that cement replacement with nano-silica up to 4%, shows positive impact on compressive, flexural and tensile strength. Workability of self-compacting concrete was observed to decrease with addition of nano silica due to high effective surface area [16].

This research aims to investigate the effect of addition of SiO₂ nanoparticles with different percentages on the physical and mechanical properties of SCC. The following sections present the details of the experimental program and the experimental results.

Experimental program

An experimental program was conducted to investigate the fresh and hardened properties of self-compacting concrete (SCC) incorporating Nano silica (Nano-SiO₂) added with different percentages to the concrete mix. Six mixes for self-compacting

concrete were designed and cast. The fresh properties were studied by slump test to investigate filling ability, L- Box test for passing ability and sieve test for segregation resistance. The hardened properties were investigated in terms of compressive strength, splitting strength for cylinders and flexural strength. All the experimental work was performed at the Materials Laboratory of the Construction Research Institute, National Water Research Center, Cairo, Egypt.

Materials Properties and Mix Proportions

Six self-compacting concrete mixes were prepared, designated with the symbols S1 to S6. Two mixes are control mixes with no Nano-silica additive: S1 with no additives and S5 with fly ash added as cement replacement in the ratio 25% of cement weight. The w/c ratio for all the designed concrete mixes was equal to 0.35. To obtain proper workability, the amount of superplasticizer needed was sequentially increased with increase the percentage of Nano silica. The composition and mix proportions for 1m³ of concrete are listed in Table 1. Analogous symbols are used for the samples made from these mixes. Constituents for each of the six mixes were weighed according to the mix proportions listed in Table 1. Mixing of each mix was made in a pan-type mechanical mixer at room temperature.

The constituent materials used in the mixes are as follows.

Egyptian ordinary *Portland cement* CEM 42.5N produced by Arabian Cement Company complying with the Egyptian standard specifications was used. Its composition is 95 to 100% clinker and minor components between 0 and 5%. Calcium sulfate added to adjust the setting time, cement properties are given in Table 2.

Table 1. Mix proportions for self-compacting concrete mixes per cubic meter

Mix No.	Mix Type	Water (kg)	Cement (kg)	Coarse aggreg. (kg)	Fine aggreg. (kg)	Nano-addit. (kg)	SP (kg)	FA (kg)
S1	Control	157.5	450.0	893.28	893.28	-	8.55	-
S2	NSi 1%	157.5	450.0	890.31	890.31	4.50	9.36	-
S3	NSi 2%	157.5	450.0	887.83	887.83	9.00	9.76	-
S4	NSi 3%	157.5	450.0	885.36	885.36	13.50	10.17	-
S5	Control + FA	118.13	337.5	923.47	923.47	-	9.72	112.5
S6	NSi 3% + FA	118.13	337.5	918.60	918.60	10.12	10.05	112.5

Table 2. Physical, chemical and mechanical properties of cement

Property	ES 4756-1/2009 EN 197-1/2000	ACC Results 2013
Loss on ignition, %	5.0	3.2
Insoluble residue, %	5.0	0.8
Sulfate content (as SO ₃), %	3.5	3.0
Initial setting time, min	60	155
Soundness (expansion), mm	10.0	1
Chloride content, %	0.10	0.04
Early strength-2 days, MPa	10.0	20.5
Standard strength-28 days, MPa	42.5-62.5	51.9

The coarse aggregate used was Dolomite delivered from EMACOM for concrete products, having nominal maximum size of 4.75-12.5 mm, specific weight 2.80 and volumetric weight 1.59 kg/m³. The fine aggregate was clean sand provided from local quarries around Cairo, having fineness modulus 2.34 and specific gravity 2.64. The grain size distribution of fine and coarse aggregates is shown in Fig.1, compared with upper and lower limits of Egyptian code.

Tap water was used for mixing and curing. Superplasticizer Sika Viscocrete-3425 produced by Sika Company (third generation superplasticizer for homogenous concrete and mortar) with a density of 1.05 kg/lt.

Class F fly ash was used in this study with physical and chemical properties as shown in Table 3.

Table 3. Properties of fly ash

Property	Description
Presentation	Finely divided dry powder
Color	Light grey
Bulk Weight	0.9 t/m ²
Specific density	2.3
Fineness	< 10% retained on 45 micron sieve
Loss-on-Ignition	< 2.5%
Particle Shape	Spherical
Packaging	30 kg bags, 1t bags and bulk tankers

Nano additive: The used additive was Nano Silica (SiO₂) with a particle size of 9.08-19.38 nm, bulk density 0.2 g/cm³. Scanning electron microscopy (SEM) of the Nano silica particles is shown in Fig. 2, and the Energy Dispersive X-ray

analysis (EDX) is shown in Fig. 3. Nano Silica (SiO₂) was used in three percentages of 1.0%, 2.0% and 3.0% of the weight of cement, as given in Table 1.

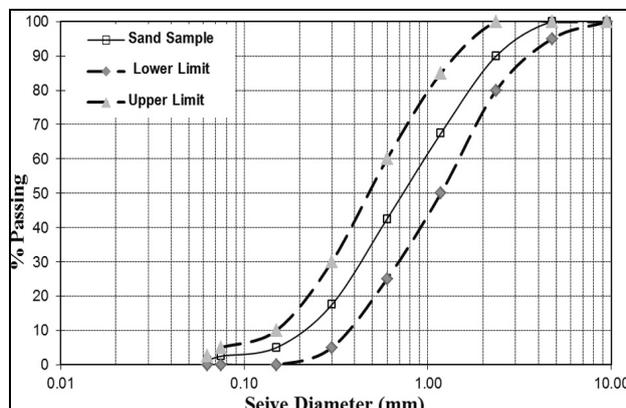
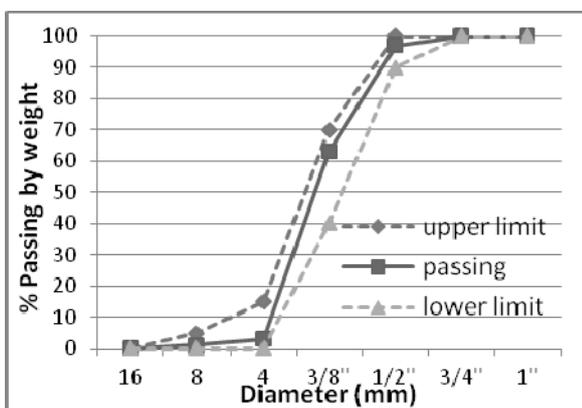


Fig. 1. Grain size distribution for coarse and fine aggregates

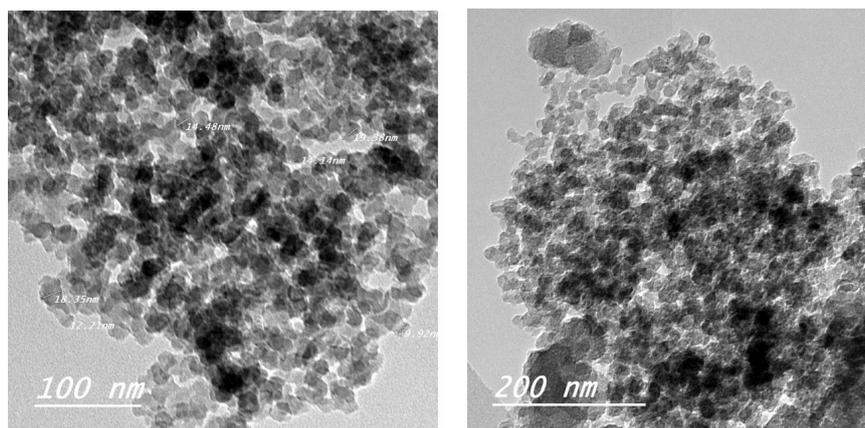


Fig. 2. Scanning Electron Microscopy (SEM) of the Nano silica particles

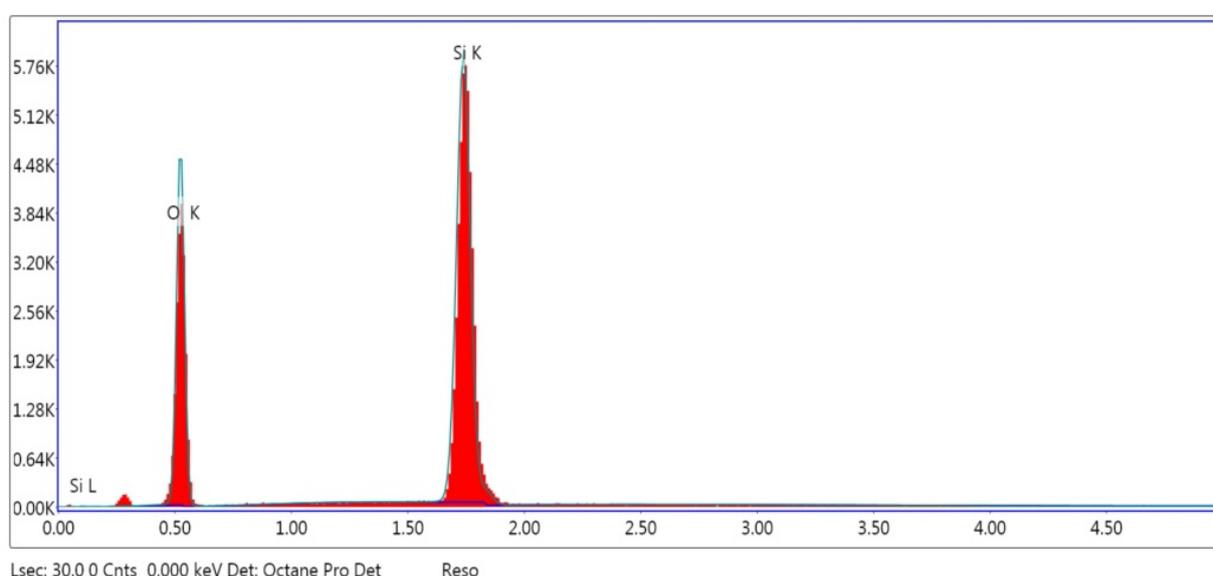


Fig. 3. Energy Dispersive X-ray analysis (EDX) of the Nano silica particles

Fresh Concrete Tests

Slump flow test: The slump flow test was conducted as per ASTM C143/C143M-09 standards to investigate the filling ability of SCC by measuring two parameters: flow spread diameter (60-80) cm and flow time T_{50} which is the time recorded to nearest 0.1 sec for the concrete to reach the 50 cm circle, as shown in Fig. 4(a).

L-Box Test: The L-Box test was used to evaluate the passing ability of SCC to flow through tight openings between reinforcing bars and other obstructions without segregation and blocking as shown in Fig. 4(b). The passing ability is calculated

as H_2/H_1 , where H_1 is the mean depth of concrete in the vertical section of the L-box behind the gate, and H_2 is the mean depth of concrete at the end of the horizontal section of the L-box

Sieve segregation resistance test: Segregation resistance test was conducted to investigate the resistance of SCC to segregation by measuring the portion of the fresh concrete sample passing through a 5mm sieve, according to the EN 12350-11, as shown in Fig. 4 (c). If the SCC has poor resistance to segregation the paste can easily pass the sieve, therefore the sieved portion indicates whether the SCC is stable or not.



Fig. 4. Fresh concrete tests: slump flow, L-Box and segregation resistance tests

Hardened Concrete Tests

For the hardened concrete tests, test specimens were prepared as follows: standard cubes with 150 mm side length for compressive strength tests, cylinders for splitting tensile strength with diameter 100 mm and height 200 mm, and standard beams for flexure test having dimensions 100x100x500 mm. For each test, three samples were cast from every mix. The specimens were cast in clean standard steel molds moistened with oil for easy removal. The molds were filled with freshly mixed concrete in three layers of approximately equal height, each tapped 25 times by standard hammer. The specimens were removed from the molds and kept submerged under water until testing age. Some of the cast specimens are shown in Figure 5.

Compressive strength test was carried out on cubes 150x150x150 mm according to according to ASTM C 39 ASTM E74, using 2000 kN capacity hydraulic compression testing machine shown in Fig. 6 (a). For all mixes, compressive tests were made at 7, 28 and 56 days after casting. At any given testing age three specimens were tested and

the value of maximum compression load was recorded. The compressive strength was calculated as P/A , where P is the failure load and A is the area of the face of cube.

Splitting tensile strength test was carried out for cylinders of 100mm diameter and 200 mm height in accordance with ASTM C 496, using 1000 kN hydraulic testing machine shown in Fig. 6(b). For each mix, three samples were tested after 7 days and three samples after 28 days of casting. The splitting tensile strength is equal to $2P/\pi D L$, where P is the maximum recorded load, D and L are the cylinder diameter and length, respectively.

The flexural strength test was carried out on concrete prisms having dimensions 100x100x500 mm, in accordance with ASTM C 78, using the universal automatic testing machine 1000 kN capacity 7 and 28 days after casting. The vertical load was gradually increased and the failure load recorded for each tested specimen, as shown in Fig. 6 (c). The flexural strength is calculated as PL/bd^2 , where P is the maximum recorded load, b , d and L are the beam width, height and length, respectively.

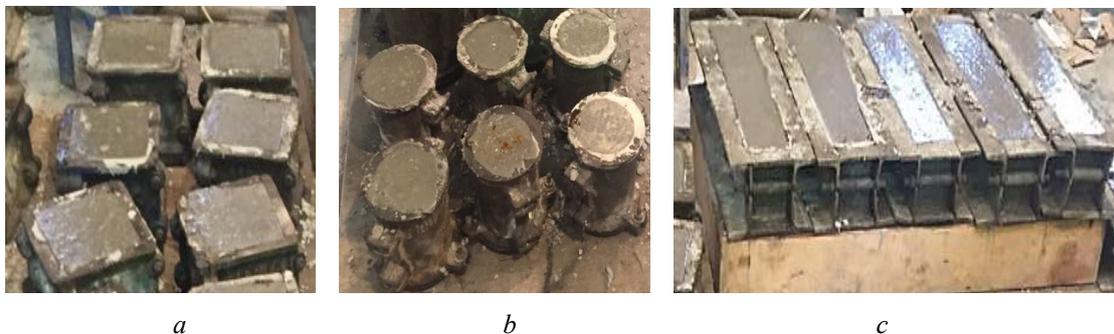


Fig. 5. Test specimens cast in molds for a) compression, b) splitting tensile and c) flexural tests

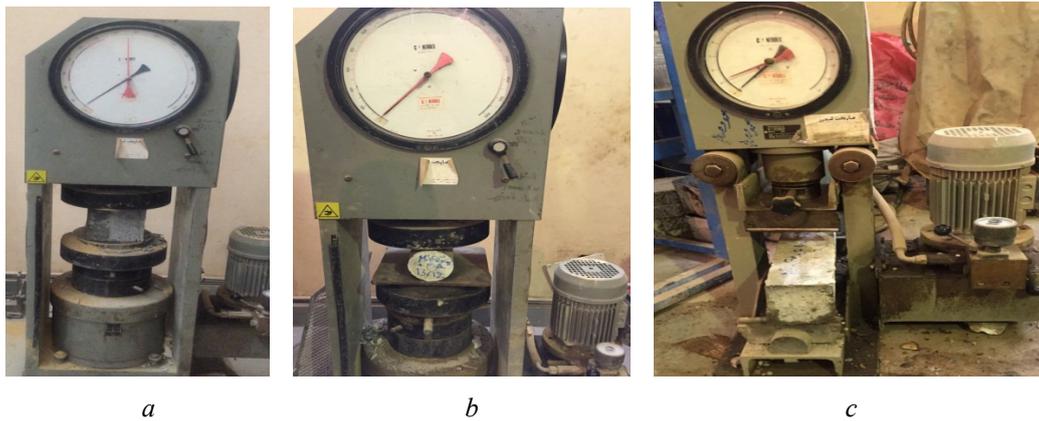


Fig. 6. Hardened concrete tests: a) compression, b) splitting tensile and c) flexural tests



Fig. 7. Concrete cubes, cylinders and prisms after testing

Experimental results and discussion

Fresh Concrete Properties

Results of the tests carried out on fresh concrete to evaluate its workability are given in Table 4 for all the studied concrete mixes. The results are plotted in Figs. 8 - 10. The results show that the slump flow of all mixes was in the range of 630 to 720 mm, and the passing ability value ranged from 0.73 to 0.92. The results of sieve segregation test show that all mixes showed higher value than the control mix, with the highest value for mix S6 with Nano-silica 3% and Fly ash. Fly ash replacement of ce-

ment by 25% of cement weight had nearly no effect on slump of the SCC mix, but results of L-Box test and sieve segregation showed change by 12% and 30%, respectively. SCC incorporated with Nano silica has large effective surface, it absorbs too much water and thus reduces concrete workability. This would increase the concrete shear strength against followability and viscosity of SCC. Mixes with small dosage of Nano silica has greater workability compared with the mixes with higher dosage of Nano silica. Reduction in bleeding was found in SCC mixes with Nano silica.

Table 4. Results of fresh concrete tests

Test	Mix						Range of acceptable values
	Control	NSi 1%	NSi 2%	NSi 3%	Control +FA	NSi 3% +FA	
Slump test (mm)	710	750	640	720	700	630	600-800
T ₅₀ Slump (sec)	3	5	4	3	5	5	3-5
L-box	0.92	0.80	0.88	0.86	0.81	0.80	0.8-1.0
Segregation (%)	5.38	5.99	5.60	7.46	7.10	9.76	≤ 15

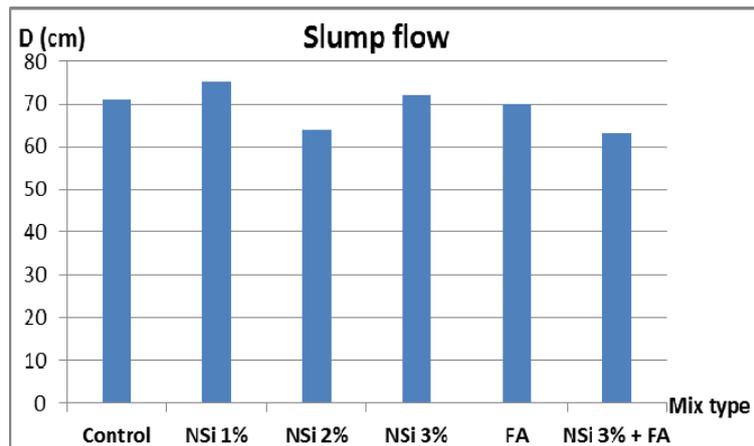


Fig. 8. Slump flow test results for all mix types

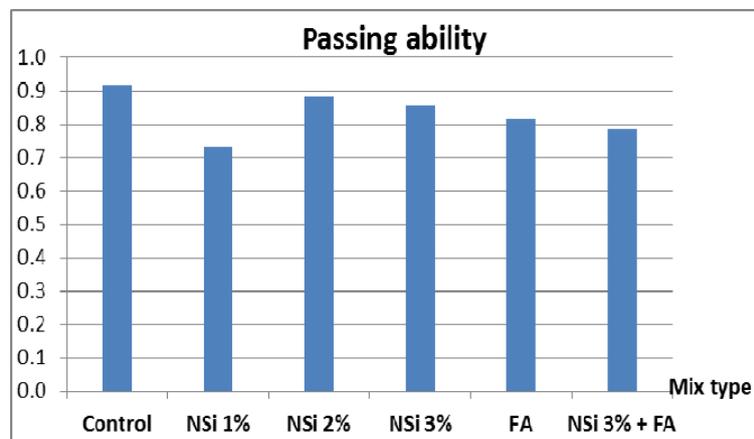


Fig. 9. Passing ability results for all mix types

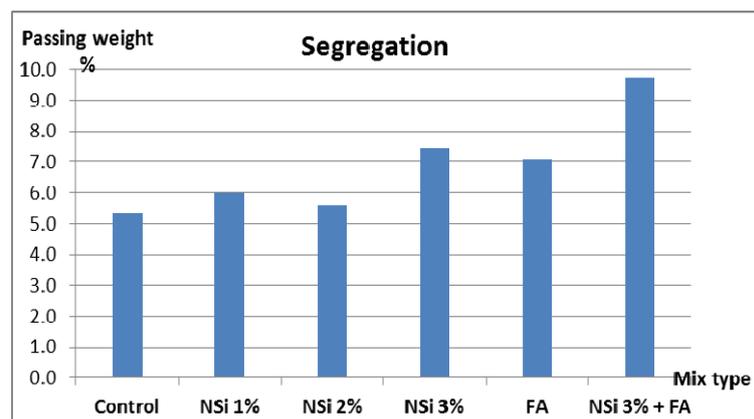


Fig. 10. Segregation test results for all mix types

Hardened Concrete Properties

The results of cubes compression test performed after 7, 28 and 56 days of casting are given in Table 5 as the average of the three tested cubes. For all mixes, the compressive strength is also given as percentage of that of the control mix.

The results are plotted in Fig. 11 for all concrete mixes. Addition of Nano-silica with percentage 1%,

2% and 3% of cement weight increased the 7 days compressive strength by 15%, 25% and 30%, the 28 days compressive strength by 9%, 14% and 31% and the 56 days compressive strength by 0, 31.4% and 36.7%, respectively, compared to the control mix. Increase in compressive strength with the addition of nanosilica is due to its high pozzolanic activity. Nanosilica, due to its high surface area, is

so reactive. High strength dense gel C-S-H, a product of pozzolanic reaction, increases the density of transition area by filling empty spaces and thus increases the strength. The dispersion of nanoparticles within the cement paste is a significant factor. When nanoparticles are added in excess to the mixture, these are not uniformly dispersed in the cement paste, and as a consequence weak areas appear in the cement mortar due to

agglomeration. Additionally, the amounts of nanosilica exceeding the quantity required for consuming the Ca(OH)_2 did not contribute to enhance the compressive strength. Nanosilica mitigated the strength loss due to fly ash due to its high pozzolanic activity; its filler effect improved the interfacial transition zone between the cement paste.

Table 5. Compressive strength test results

Mix No.	Mix type	Compressive strength					
		7 days		28 days		56 days	
		kg/cm ²	% of control	kg/cm ²	% of control	kg/cm ²	% of control
S1	Control	365.69	100.00	464.21	100.00	526.48	100.00
S2	NSi 1%	423.45	115.79	509.73	109.81	523.84	99.50
S3	NSi 2%	459.68	125.70	531.39	114.47	690.66	131.18
S4	NSi 3%	478.55	130.86	610.00	131.41	720.09	136.77
S5	FA	409.86	112.08	471.00	101.46	534.40	101.50
S6	NSi 3% + FA	421.19	115.18	650.74	140.18	631.03	119.86

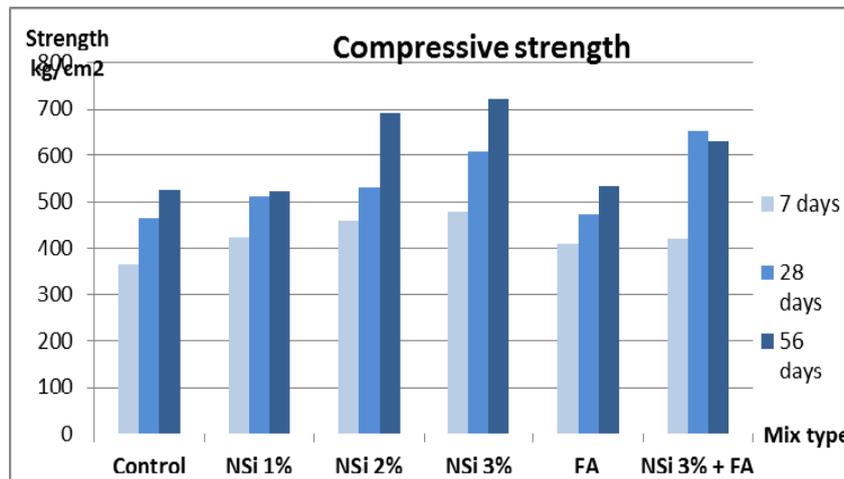


Fig. 11. Compressive strength of all mix types after 7, 28 and 56 days

The experimental results for splitting tensile tests conducted after 7 and 28 days of casting the cylinders are presented in Table 6, as average value of the three conducted tests for each mix, and compared to the control mix. The results are plotted in Fig. 12 for all concrete mixes. The higher splitting tensile strength for mixes with nanosilica observed in later age may be due to the additional binding property of finely divided nanosilica because of high pozzolanic reaction and cement paste aggregate interfacial refinement leading to higher bond strength. The mix with nanosilica 2% shows greater splitting strength. Higher dosage of nanosilica 3% shows a reduction in splitting tensile strength.

Experimental results of flexural tests conducted on prisms 7 and 28 days after casting are given in Table 7 as average value of the three conducted tests for every mixes, and are compared to the control mix. The results for flexural test are plotted in Fig. 13. Variation in the flexural strength of SCC mixes shows similar trend like that of compressive strength. With increase in nanosilica content flexural strength increases, indicating that nanosilica addition improves the structural properties and adhesion of cement matrix mortar-aggregates interfaces area.

Table 6. Splitting tensile strength test results

Mix No.	Mix type	Tensile strength			
		7 Days		28 Days	
		kg/cm ²	% of control	kg/cm ²	% of control
S1	Control	41.38	100.00	46.41	100.00
S2	NSi 1%	40.84	98.70	46.51	100.22
S3	NSi 2%	40.62	98.16	47.60	102.56
S4	NSi 3%	36.78	88.88	43.27	93.23
S5	FA	37.05	89.54	47.87	103.15
S6	NSi 3% + FA	38.40	92.80	48.89	105.34

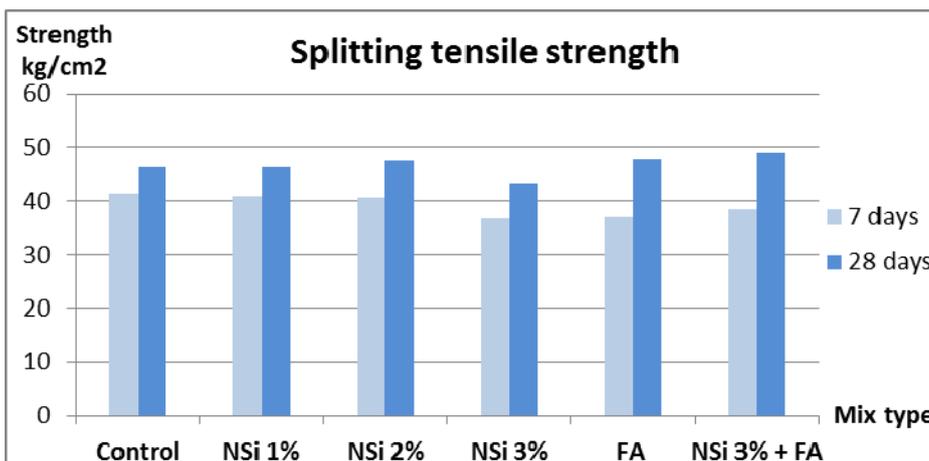


Fig. 12. Splitting tensile strength of all mix types after 7 and 28 days

Table 7. Flexural strength test results

Mix No.	Mix type	Flexural strength			
		7 Days		28 Days	
		kg/cm ²	% of control	kg/cm ²	% of control
S1	Control	73.03	100.00	91.71	100.00
S2	NSi 1%	74.73	102.33	104.77	114.24
S3	NSi 2%	86.62	118.61	107.00	116.67
S4	NSi 3%	84.92	116.28	109.74	119.66
S5	FA	89.16	122.09	101.41	110.58
S6	NSi 3% + FA	96.81	132.56	107.00	116.67

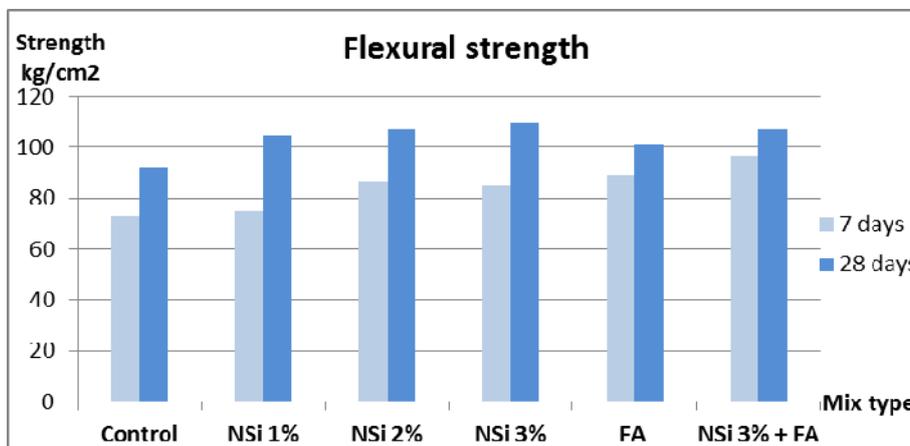


Fig. 13. Flexural strength of all mix types after 7 and 28 days

Conclusions

In this research work an experimental program was conducted aiming to enhance the properties of self-compacting concrete (SCC) through addition of Nano materials. Six self-compacting concrete mixes were prepared with addition of Nano-silica with percentages 1, 2 and 3% of cement weight, as well as partial replacement of cement with fly ash. Laboratory tests were made on fresh and hardened concrete to investigate the effect of the studied variables on the physical and mechanical properties.

Based on the obtained experimental results, the following conclusions can be drawn.

- The studied mixes of self-compacting concrete satisfy the performance requirements for fresh concrete as well as the strength requirement for hardened concrete.

- The slump flow, L-box and sieve test results were found satisfactory, showing that the passing ability, filling ability and segregation resistance are within the acceptable limits.

- Due to observed workability and high flowability of SCC, it can be used in highly congested reinforcement structural elements as compared to conventional concrete.

- Addition of nano-silica affected negatively the flowability of self-compacting concrete. Mixes with small dosage of Nano silica has greater workability compared with mixes with higher dosage of Nano silica.

- Fly ash replacement of cement by 25% of cement weight had nearly no effect on slump of the SCC mix, but results of L-Box test and sieve segregation showed change by 12% and 30%, respectively.

- All mixes yielded compressive strength exceeding 45 MPa at 28-days, with the highest value of 65 MPa for the mix with Nano-silica 3% and fly ash.

- Addition of nano silica 1%, 2%, 3% of cement weight caused increase of the compressive strength compared to the control mix. Nano-silica addition with percentage 3% of cement weight increased the compressive strength of SCC after 7, 28 and 56 days of casting by 30.86%, 31.41% and 36.77%, respectively, and increased the 28 days flexural strength by 20%, compared to the control mix. The 28 day compressive strength of SCC containing 25% of fly ash replacement of cement and 3% addition of nano-silica was improved by 40 %.

- Addition of fly ash did not contribute to the compressive or tensile strength of SCC, however it caused increase of flexural strength after 28 days by 11%.

- This experimental study demonstrates that Nano silica (N-SiO₂) can be successfully used as an admixture in the preparation of self-compacting concrete

- It is recommended to investigate other Nano materials as additives. Also, other engineering properties of SCC such as saturated water absorption, permeability, sulphate resistance, acid resistance, and others.

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Улучшение свойств самоуплотняющихся бетонов путем введения нанокремнезема

Асмаа Ю. Баракат, Исследовательский институт строительства, Национальный центр исследования водных ресурсов, Каир, Египет

Мостафа А. Мостафа, Исследовательский институт строительства, Национальный центр исследования водных ресурсов, Каир, Египет

Гехан А. Хамди, инженерный факультет, Университет Бенха, Шубра, Египет,

Хоссамельдин Х. Ахмед, инженерный факультет, Университет Бенха, Шубра, Египет

Сегодня в строительной отрасли наблюдается значительный интерес к использованию наноразмерных материалов. Исследования направлены на улучшение свойств бетона путем введения наноразмерных добавок. Самоуплотняющийся бетон – это бетон особого состава, уплотнение которого происходит за счет собственного веса без затрат дополнительной энергии благодаря свойствам текучести и высокой стойкости к сегрегации. В этой статье представлена экспериментальная работа, проведенная для изучения влияния добавок на основе нанокремнезема на физико-механические свойства самоуплотняющегося бетона. Были исследованы свойства бетонной смеси (удобоукладываемость, проницаемость и сопротивление сегрегации) и механические свойства (прочность на сжатие, прочность на разрыв и прочность на изгиб) самоуплотняющегося бетона при введении нанокремнезема в трех пропорциях (1, 2 и 3 % от веса цемента). Свойства самоуплотняющегося бетона определяли испытанием на осадку конуса и на сегрегацию. Механические характеристики были определены испытаниями на сжатие, растяжение и изгиб на разных этапах твердения. Результаты эксперимента показали, что использование нанокремнезема в качестве добавки способствует улучшению механических характеристик образцов самоуплотняющегося бетона.

Ключевые слова: самоуплотняющийся бетон, добавки, наночастицы, нанокремнезем, физические свойства, механические свойства.

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