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EXPERIMENTAL INVESTIGATION OF SELF-COMPACTING CONCRETE BEAMS WITH NANO MATERIALS ADDITIVES

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Self-compacting concrete (SSC) is a concrete that flows and consolidates under its own weight without additional compaction; it has special mix design which provides high flow ability and high segregation resistance. This paper presents an experimental program that investigates the structural behavior of SCC beams with additives of Nano-silica (Nano-SiO_2) and Nano manganese ferrite (Nano-$MnFe_3O_4$). Ten SCC mixes were prepared containing Nano-SiO_2 additives with three percentages 1%, 2% and 3% of cement weight, and Nano-$MnFe_3O_4$ with percentages 0.3%, 0.5% and 0.7%. Laboratory tests were performed to determine the fresh properties (workability, passing ability and segregation resistance), mechanical properties (compressive strength, splitting tensile strength and flexural strength), and durability (water permeability and chloride penetration). The experimental results show that using Nano additives with 25% cement replacement by fly ash improved the mechanical and durability properties of SCC. Mixes with the optimum percentage were used to cast reinforced concrete beams which were tested in bending until failure in order to investigate the effect of Nano materials additives on the flexural performance.

Keywords: Self-compacting concrete; additives; Nano-silica; Nano-manganese ferrite; fresh properties; beams; flexure; durability.

Introduction

Self-Compacting Concrete (SCC) is a concrete with a special mix that compacts under self-weight without vibration; it can flow through dense reinforcement without segregation. It was first developed in Japan in 1988 and was applied widely starting from 1989 [1, 2]. Self-compatibility is accomplished through optimum flowing ability (filling ability and passing ability) and optimum segregation resistance. The perfect flowing ability and segregation resistance can be attained by utilizing high range water reducer (HRWR) such as poly carboxylates, limited coarse aggregates and increased amount of cementing materials at low w/b proportion [1]. To decrease the cost of SCC, it is possible to use mineral admixtures such as limestone powder, normal pozzolans, slag and fly ash [3]. Fly ash (FA) is an industrial waste material widely used as an additive or cement replacement in concrete; this provides advantages such as increasing concrete workability, enhancement of durability and mechanical strength in addition to reducing cement consumption.

Nanotechnology has managed to produce particles of Nano-scale that have been recently integrated in cement paste, mortar or in concrete to provide enhanced properties. Nanoparticles can accelerate hydration of cement due to their high activity, thereby improving the workability, compaction and microstructure and minimizing porosity [4, 5]. Most published works addressed using Nano-Silica (N-SiO_2) [6] and Nano-Titanum (N-TiO_2) [6-8] in cement-based materials. The effects of other nanoparticles, such as Nano-Al_2O_3, Nano-Fe_2O_3, Nano-ZnO_2 and Nano-CuO on the physical and mechanical properties of cement-based materials were also studied in some researches [9-11]. Researchers studied high performance SCC containing SiO_2 nanoparticles and investigated the effect of nanoparticles on durability, water absorption, chloride ion percentage, capillary absorption and strength [12, 13]. Durability of SCC mixtures containing Nano silica were measured in terms of porosity, water penetration under weight, freeze-thaw resistance and fast chloride relocation. Quercia et al. [14] and Beigi et al [15] examined the impact of Nano-silica on the mechanical, rheological, and strength properties of SCC.

This research aims to investigate the effect of addition of silica (SiO_2) and manganese ferrite ($MnFe_2O_4$) nanoparticles with different percentages on the fresh and hardened properties of SCC and on the structural performance of SCC beams. Details of the experimental program and the experimental results are described in the following sections.

Experimental Program

An experimental program is conducted consisting of two phases. In the first phase, ten mixes of self-compacting concrete are designed incorporating Nano silica (N-SiO_2) and Nano manganese ferrite (N-$MnFe_2O_4$) added with

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different percentages to the concrete mix; the fresh and hardened properties SCC are investigated. The SCC showing the best properties are used to cast reinforced concrete beams in the second phase; the beams were tested in bending until failure. All the experimental work was performed at the Materials Laboratory of the Construction Research Institute, National Water Research Center, Cairo, Egypt.

Materials and mix proportions

The mix proportions for the ten SCC mixes per cubic meter are given in Table 1. Two mixes have no Nano additives and act as control, one of them with 25% fly ash replacement of cement weight. Six mixes contain Nano additives: Nano silica (N-SiO_2) added as 1%, 2% and 3%, and Nano Manganese Ferrite (N-$MnFe_3O_4$) as 0.3%, 0.5% and 0.7% of the weight of cement. Two mixes have the highest Nano additive content as well as 25% cement replacement with fly ash. The w/c ratio for all mixes is 0.35. The SCC mixes for the beams are listed in Table 2.

Table 1. **Mix proportions for self-compacting concrete mixes per 1m^3**

Type	Nano-additive type and amount (%)	Water (kg)	Cement (kg)	Dolomite (kg)	Sand (kg)	Nano- (kg)	SP (kg)	FA (kg)
C	Control	157.5	450.0	893.28	893.28	-	8.55	-
NS1	N-SiO_2 1.0 %	157.5	450.0	890.31	890.31	4.50	9.36	-
NS2	N-SiO_2 2.0 %	157.5	450.0	887.83	887.83	9.00	9.76	-
NS3	N-SiO_2 3.0 %	157.5	450.0	885.36	885.36	13.50	10.17	-
C-FA	Control + FA	118.1	337.50	923.47	923.47	-	9.72	112.5
NS3-FA	N-SiO_2 3.0% + FA	118.1	337.5	918.60	918.60	10.12	10.05	112.5
NM3	N-$MnFe_3O_4$ 0.3%	157.5	450.0	892.68	892.68	1.35	8.55	-
NM5	N-$MnFe_3O_4$ 0.5%	157.5	450.0	892.29	892.29	2.25	8.55	-
NM7	N-$MnFe_3O_4$ 0.7%	157.5	450.0	891.09	891.09	3.15	8.55	-
NM5-FA	N-$MnFe_3O_4$ 0.5% + FA	118.1	337.5	923.02	923.02	1.013	9.72	112.5

Table 2. **Beams types and mixes**

Beam ID	Beam mix
B1	Control
B2	Nano silica 3%
B3	Control + 25% FA
B4	Nano silica 3% + 25% FA
B5	Nano manganese ferrite 0.5%
B6	Nano manganese ferrite 0.5% + 25% FA

The used materials are described as follows.

– *Cement:* Portland cement CEM 42.5N produced by Arabian Cement Company complying with the Egyptian standard specifications ES4756-1/2009 and EN 197-1/2000.

– *Coarse aggregate:* Dolomite from EMACOM with nominal maximum size of 4.75-12.5 mm, specific weight 2.80, volumetric weight 1.59 kg/m^3.

– *Fine aggregate:* clean sand with fineness modulus of 2.34 and specific gravity 2.64.

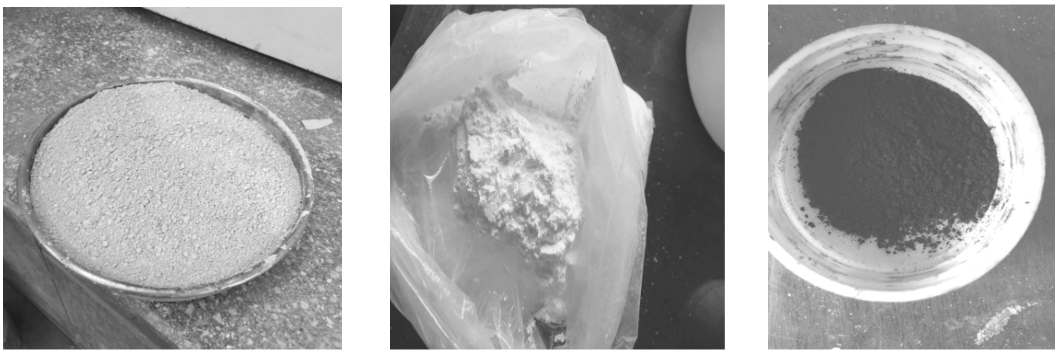
– *Fly ash:* Class F fly ash is used as finely divided powder of light grey color, with less than 10% retained on 45 μm sieve, bulk weight 0.9 t/m^2 , specific density 2.3.

– *Super plasticizer (SP):* Viscocrete-3425 produced by Sika with density 1.05 kg/lt.

– *Nano Silica* (SiO_2) of particle size 9.08-19.38 μm, bulk density 0.2 g/cm^3, surface area 560 m^2/g, used as additive as 1.0%, 2.0% and 3.0% of the weight of cement.

– *Nano Manganese Ferrite* ($MnFe_3O_4$) particle size (3.24 - 25.85 μm)

– The fly ash, silica and manganese ferrite Nano particles are shown in Fig. 1. Scanning electron microscopy (SEM) of the Nano silica and Nano manganese ferrite particles are shown in Fig. 2; Energy Dispersive X-ray analysis (EDX) results are shown in Fig. 3.



a *b* *c*

Fig. 1. Particles of (a) fly ash, (b) Nano silica and (c) Nano manganese ferrite

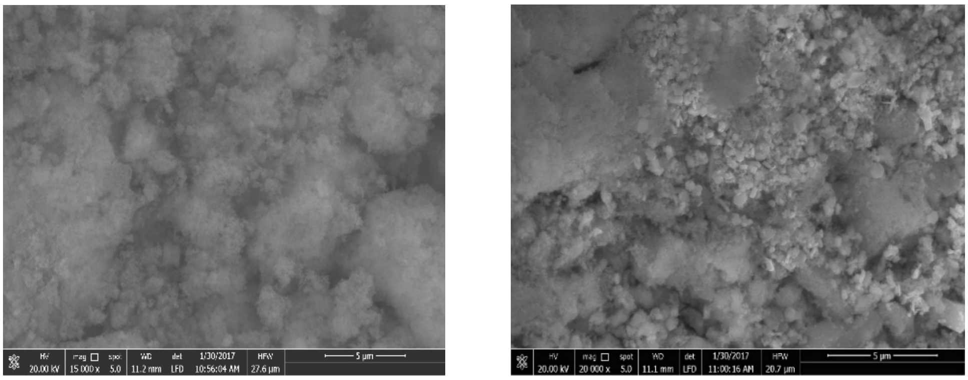


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Fig. 2. Scanning Electron Microscopy (SEM) of (a) Nano silica and (b) Nano manganese ferrite

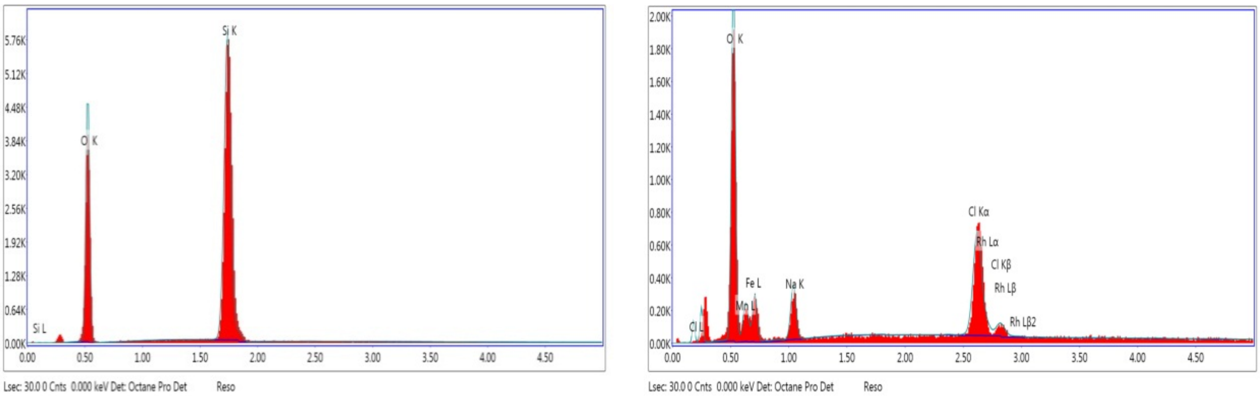

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Fig. 3. Energy Dispersive X-ray analysis (EDX) of (a) Nano silica and (b) Nano manganese ferrite

Preparation of test specimens

Specimens are cast from each mix for hardened concrete tests: cubes of side length 150mm, cylinders of diameter 100mm and height 200mm and prisms of size 100mm×100mm×500mm for flexure test, as shown in Fig. 4. Reinforced concrete beams with dimensions 100mm × 100mm × 900mm and 2ϕ10 main steel reinforcement are cast, as shown in Figs. 5 and 6. After casting, all specimens are covered with plastic sheet to reduce water evaporation and are stored in laboratory until demolding after 24 hours, and then all the specimens are continuously cured by water until the time of testing.

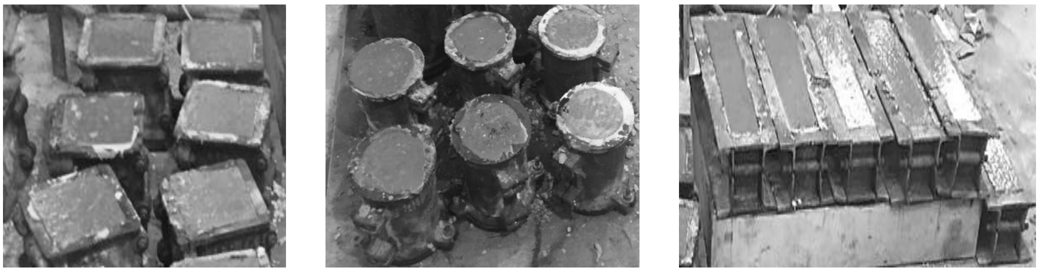

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Fig. 4. Casting of specimens for (a) compression, (b) splitting tensile and (c) flexure tests

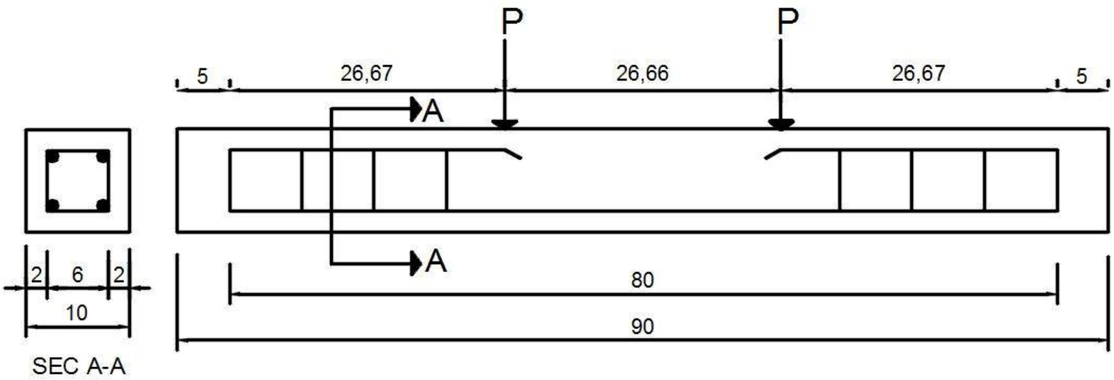


Fig. 5. Dimensions and reinforcement of beam specimens

Fig.6. Casting of beams

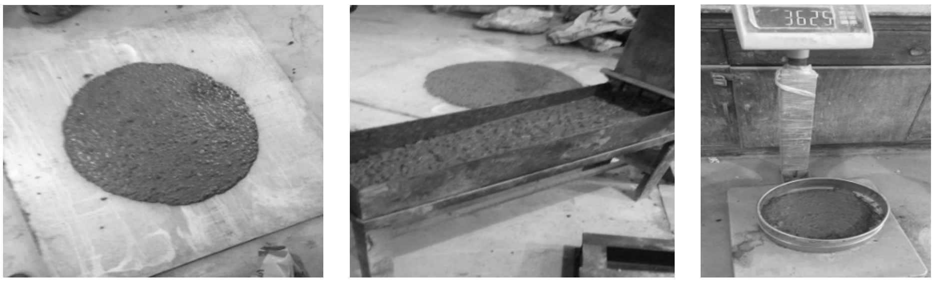
Testing procedures

***Fresh concrete tests**:* Slump test and L box test were conducted as per ASTM C143/C143M-09 to assess the workability parameters of the SCC mixes: filling ability, passing ability and segregation resistance, shown in Fig. 7.

Hardened concrete tests: **C**ompression test was carried out on cubes after 7, 28, and 56 days from casting according to ASTM E74; three cubes from each mix were tested in a compression testing machine of capacity 3000 kN and readability 5 kN to determine the failure load and compressive strength. Splitting tensile strength test was carried on 3 concrete cylinders of each mix using a 1000 kN capacity hydraulic testing machine after 7 and 28 days from casting, and the tensile strength calculated. Flexure test was made on plain concrete beams in four-point loading to determine the flexural strength. The performed tests are shown in Fig. 8.

Durability tests: Rapid Chloride Permeability Test was carried out by adapting a concrete slice, then monitoring the amount of current passing, according to ASTM C1202. Water permeability test was carried out on cylinders of 150mm diameter according to ASTM C432-04, as shown in Fig. 9.

Flexural testing of beams: The beams were tested in a hydraulic testing machine in four-point loading as shown in Fig. 10; the load is gradually increased until failure. Displacement at mid-span is measured by gauge connected to LVDT and is recorded at every load increment.



a *b* *c*

Fig. 7. Fresh concrete tests: (a) slump flow, (b) L-Box and (c) segregation resistance test

a *b* *c*

Fig. 8. Hardened concrete tests: (a) compression, (b) splitting tensile and (c) flexure tests

Fig. 9. Rapid chloride and water permeability tests

Fig. 10. Test set-up for beams in bending and the measuring instruments

Experimental Results

Fresh concrete properties

The results of fresh concrete tests are given in Table 3 and plotted in Figs. 11-13. The acceptable range for SCC for slump is 600-800mm, for T50 is 3-5 sec, and for passing ability with L-box test 0.8-1.0. For segregation resistance with sieve stability test, the acceptable values are 5-15%. The obtained results indicate that all the prepared SCC mixes have fresh properties within the acceptable range for SCC, and that addition of N-SiO2 and N-$MnFe_3O_4$ improved the workability (filling ability), passing ability and segregation resistance of SCC.

Table 3. **Results of fresh concrete tests**

Mix ID	Description	Slump		Passing ability			Segregation			
		T50 (sec)	D (cm)	h_1 (cm)	h_2 (cm)	%	Cont. wt. (gm.)	total wt. (gm.)	pass. wt. (gm.)	%
C	Control	3	710	72	66	0.92	0.91	3.72	1.11	5.38
NS1	N-SiO_2 1%	5	750	75	60	0.80	0.91	3.67	1.13	5.99
NS2	N-SiO_2 2%	4	690	77	68	0.88	0.91	3.75	1.12	5.60
NS3	N-SiO_2 3%	3	720	78	67	0.86	0.91	3.62	1.18	7.46
C-FA	Control+ FA	5	700	81	66	0.81	0.91	3.38	1.15	7.10
NS3-FA	N-SiO_2 3% + FA	4	630	80	65	0.81	0.91	3.33	1.24	9.76
NM3	N-$MnFe_3O_4$ 0.3%	3	650	76	69	0.91	0.91	3.38	1.16	7.25
NM5	N-$MnFe_3O_4$ 0.5%	4	670	78	66	0.85	0.91	3.28	1.10	5.76
NM7	N-$MnFe_3O_4$ 0.7%	3	750	79	64	0.81	0.91	2.94	1.07	5.28
NM5-FA	N-$MnFe_3O_4$ 0.5%+ FA	3	720	82	69	0.84	0.91	3.33	1.23	9.62

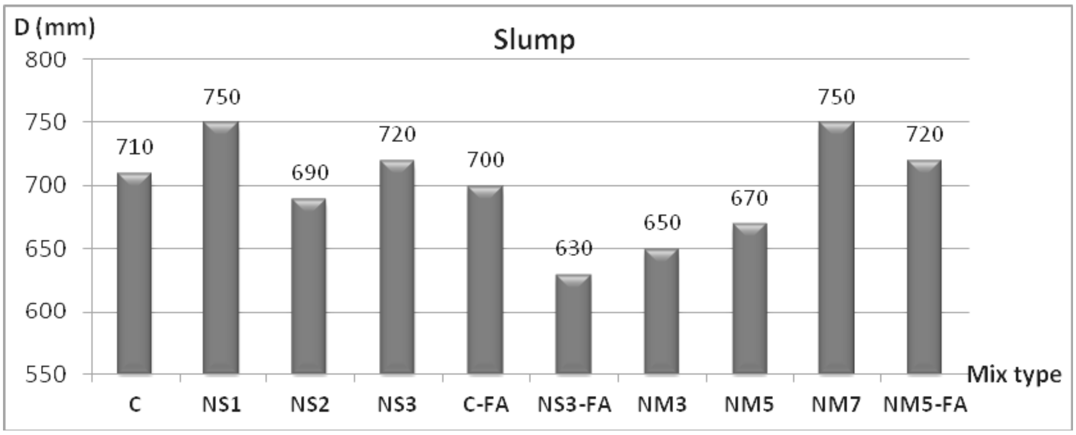


Fig. 11. Filling ability (slump) of all SCC mixes

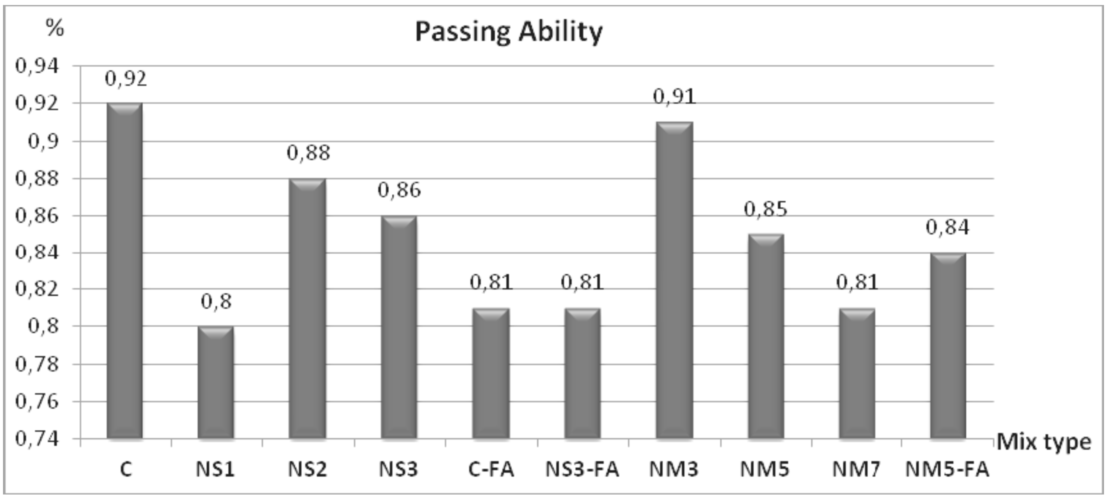


Fig. 12. Passing ability of all SCC mixes

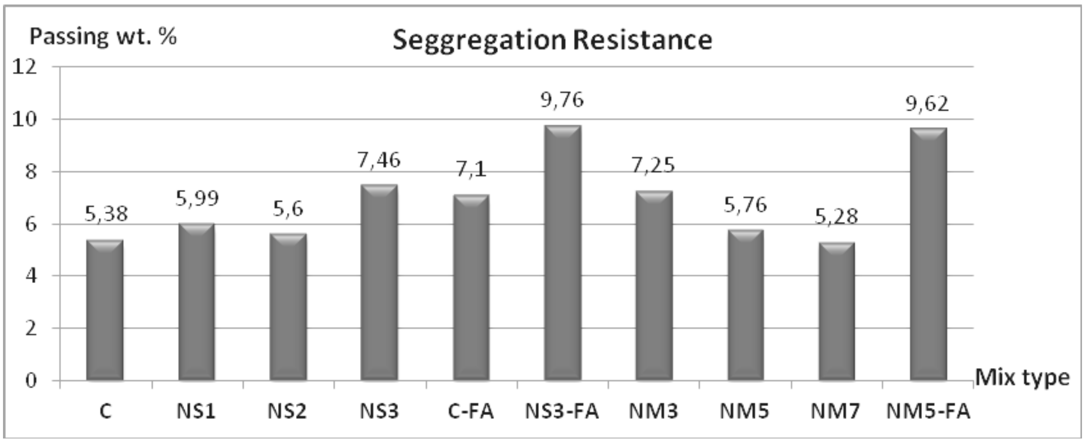


Fig. 13. Segregation resistance of all SCC mixes

Hardened concrete properties

The experimental results of the average compressive strength after 7, 28 and 56 days are given in Table 4 and are plotted in Fig. 14. The splitting tensile strength and flexural strength after 7 and 28 days are given in Table 5 as average of 3 tested specimens, and are plotted in Figs. 15 and 16. It is observed that addition of N-SiO_2 caused increase of the compressive strength, splitting tensile strength and flexural strengh; this improvement is more with increasing the percentage. The best dose of Nano silica addition is 3% of cement weight; which caused increase of the compressive strength after 7, 28 and 56 days by 30.8%, 31.4% and 59.8%, respectively, over that of the control mix with no additive. The combined mix with fly ash cement replacement in addition to 3% N-SiO_2 caused increase in compressive strength of 2%, 38% and 18% at 7 days, 28 days and 56 days, respectively, compared to the mix with fly ash and without Nano materials. The splitting tensile strength was not enhanced due to Nano additives; however when combined with fly ash, the tensile strength increase was more. The best percentage for addition of N-$MnFe_3O_4$ is therefore 0.5%, giving the highest compressive, tensile and flexural strengths.

Table 4. **Compressive strength results**

Mix ID	Mix description	Compressive strength					
		7 days		28 days		56 days	
		N/mm^2	% control	N/mm^2	% control	N/mm^2	% control
C	Control	36.57	100.00	46.42	100.00	45.06	100.00
NS1	N-SiO_2 1%	42.34	115.80	50.97	109.81	52.38	116.25
NS2	N-SiO_2 2%	45.97	125.70	53.14	114.47	69.07	153.28
NS3	N-SiO_2 3%	47.86	130.86	61.00	131.41	72.01	159.81
C-FA	Control + FA	40.99	112.08	47.10	101.46	53.44	118.60
NS3-FA	N-SiO_2 3%+ FA	42.12	115.18	65.07	140.18	63.10	140.04
NM3	N-$MnFe_3O_4$ 0.3 %	37.74	103.20	46.00	99.10	51.22	113.68
NM5	N-$MnFe_3O_4$ 0.5 %	40.75	111.43	50.43	108.64	52.24	115.94
NM7	N-$MnFe_3O_4$ 0.7 %	38.50	105.27	48.90	105.33	50.14	111.27
NM5-FA	N-$MnFe_3O_4$ 0.5 % +FA	41.57	113.68	51.35	110.61	58.99	130.91

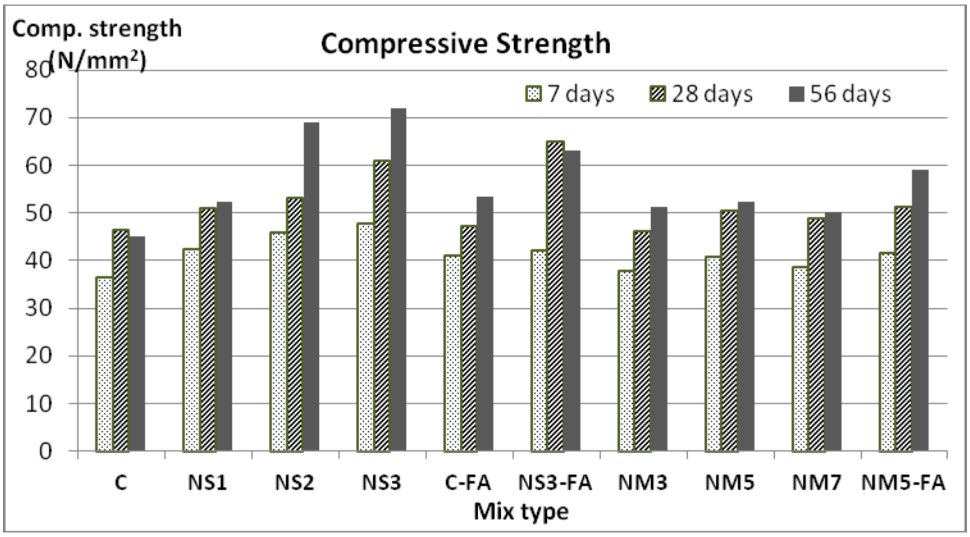


Fig. 14. Compressive strength of all tested SCC mixes

Table 5. **Splitting tensile and flexural strength results**

Mix ID	Description	Splitting tensile strength				Flexural strength			
		7 days		28 day		7 days		28 days	
		N/mm^2	% control	N/mm^2	% control	N/mm^2	% control	N/mm^2	% control
C	Control	4.13	100.00	4.64	100.00	7.30	100.00	9.17	100.00
NS1	N-SiO_2 1%	4.08	98.70	4.65	100.22	7.47	102.33	9.68	105.56
NS2	N-SiO_2 2%	4.06	98.16	4.76	102.56	9.00	123.25	10.70	116.66
NS3	N-SiO_2 3%	3.68	88.88	4.33	93.23	9.17	125.58	12.40	135.18
C-FA	Control + FA	3.71	89.54	4.787	103.15	8.92	122.09	10.70	116.68
NS3-FA	N-SiO_2 3%+ FA	3.84	92.80	4.89	105.34	9.68	132.56	12.54	136.77
NM3	N-$MnFe_3O_4$ 0.3 %	3.42	82.67	3.35	72.07	7.05	96.51	7.64	83.34
NM5	N-$MnFe_3O_4$ 0.5 %	3.73	90.07	4.38	94.40	8.24	112.79	9.51	103.71
NM7	N-$MnFe_3O_4$ 0.7 %	3.32	80.26	4.12	88.77	7.30	100.00	8.49	92.60
NM7-FA	N-$MnFe_3O_4$ 0.5% +FA	3.52	85.02	4.46	96.10	8.55	117.01	10.36	113.01

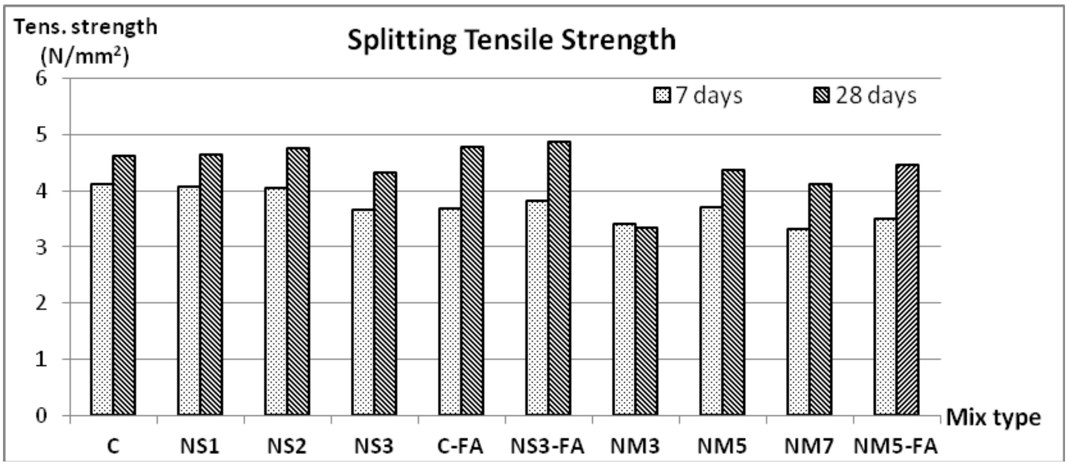


Fig. 15. Splitting tensile strength of all SCC mixes

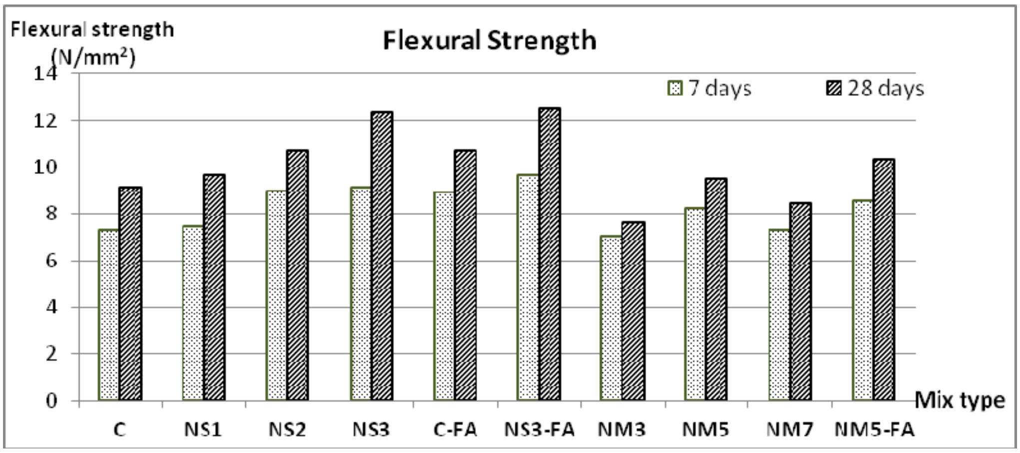


Fig. 16. Flexural strength of all SCC mixes

Table 6. **Water and rapid chloride permeability at 28 days**

Chloride permeability	Charge passed (coulombs)	Penetration (mm)	Description	Mix ID
Very low	145	27	Control	C
-	-	26	N-SiO_2 1%	NS1
-	-	20	N-SiO_2 2%	NS2
Negligible	44	17	N-SiO_2 3%	NS3
Low	1845	25	Control + FA	C-FA
Negligible	30	3	N-SiO_2 3%+ FA	NS3-FA
-	-	50	N-$MnFe_3O_4$ 0.3 %	NM3
Moderate	2132	31	N-$MnFe_3O_4$ 0.5 %	NM5
-	-	38	N-$MnFe_3O_4$ 0.7 %	NM7
Moderate	2132	15	N-$MnFe_3O_4$ 0.5 % +FA	NM5-FA

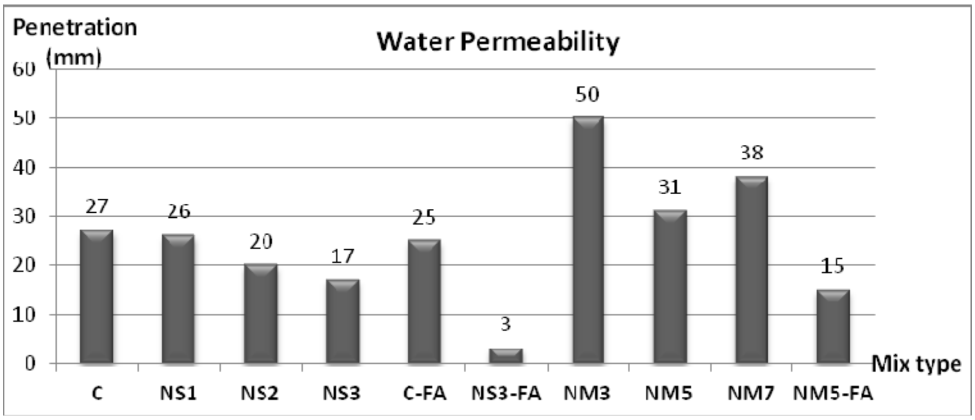


Fig. 17. Water permeability results for all mixes

Durability tests results

The results of water and rapid cloride permeability tests made after 28 days are given in Table 6; the water permeability results are plotted in Fig. 17. It is observed that adding 3% N-SiO_2 decreased the water permeability by 58%, thus improving durability. When using 3% N-SiO_2 with 25% fly ash cement replacement, there was almost no water penetration. Adding N-$MnFe_3O_4$ to SCC had little effect on water permeability, but caused slight improvement of durability (6%) when combined with fly ash replacement of cement. The best percentage for addition of N-SiO_2 is 3% as there was almost no chloride permeability with or without fly ash replacement. Addition of N-$MnFe_3O_4$ as 0.5% of cement weight had slight effect on chloride permeability, i.e. no improvement of the durability of SCC

Flexural behavior of RC beams

The load-displacement curve of each tested beam is shown in Fig. 18, and comparison of all curves is shown in Fig. 19. The failure mode and crack patterns for all the beams are shown in Fig. 20. The obtained failure loads and maximum recorded displacements of all beams are plotted in Fig. 21. The load-displacement curves show that addition of Nano silica caused increase of the flexural stiffness, compared to the control beam. Cement replacement by fly ash caused slight reduction of the beam failure load and the beam stiffness.

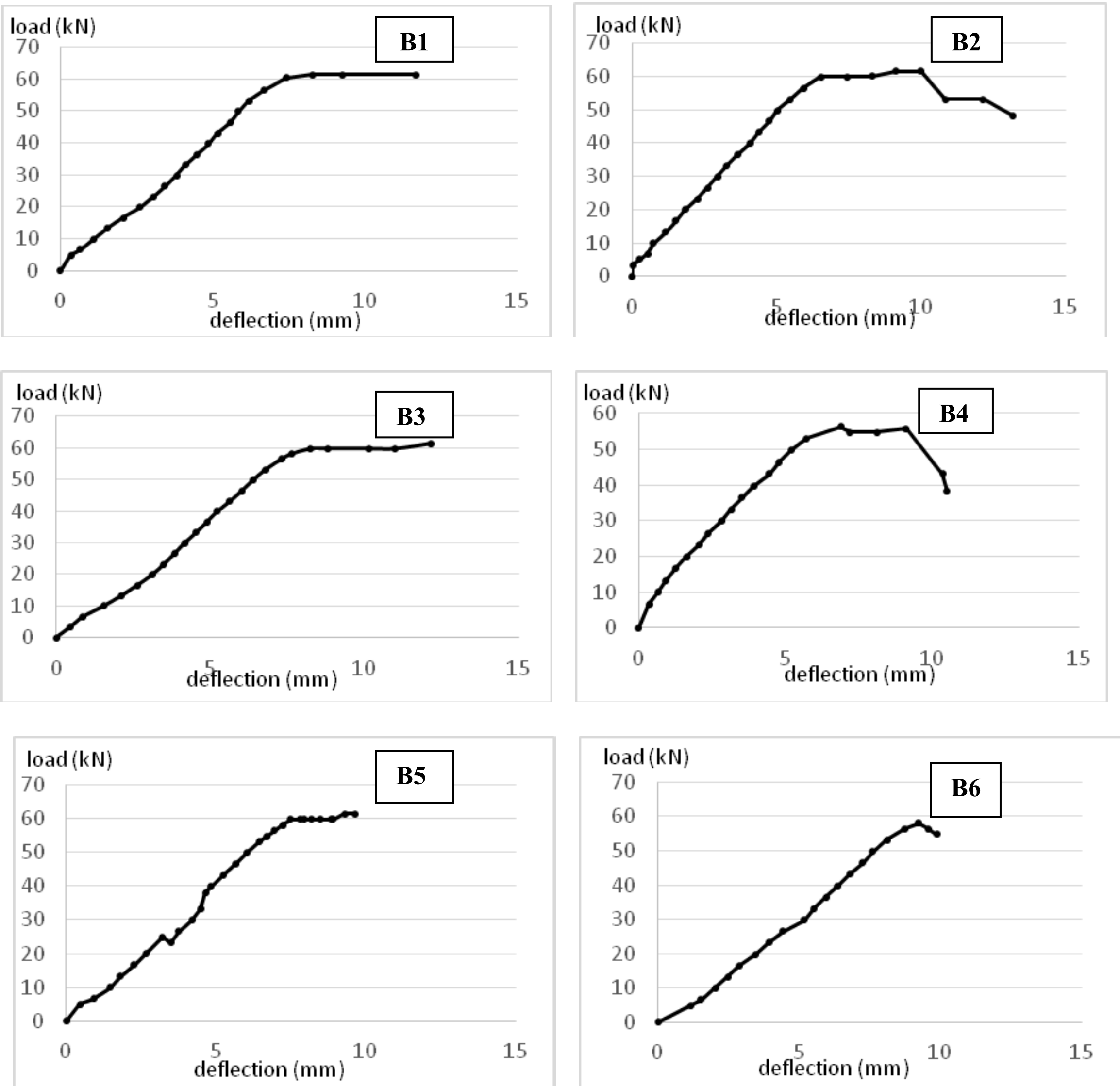


Fig. 18. Load-deflection curve for each tested beam

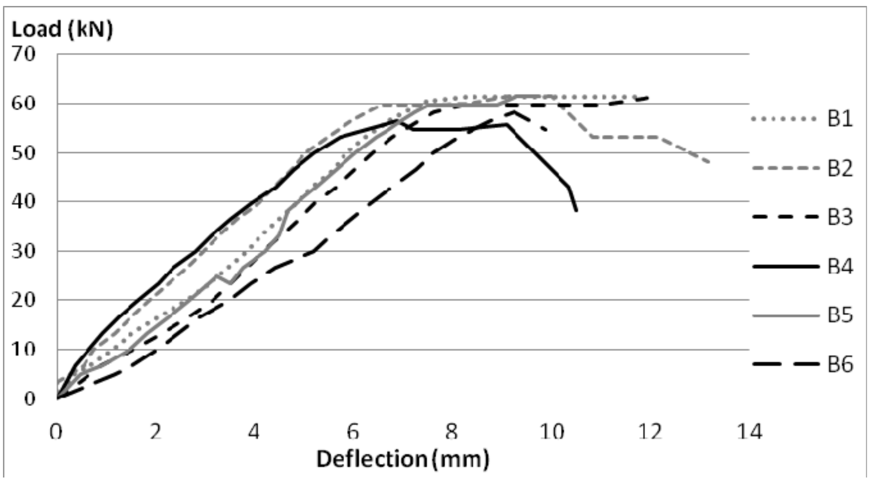


Fig. 19. Load-deflection curves of all tested SCC beams

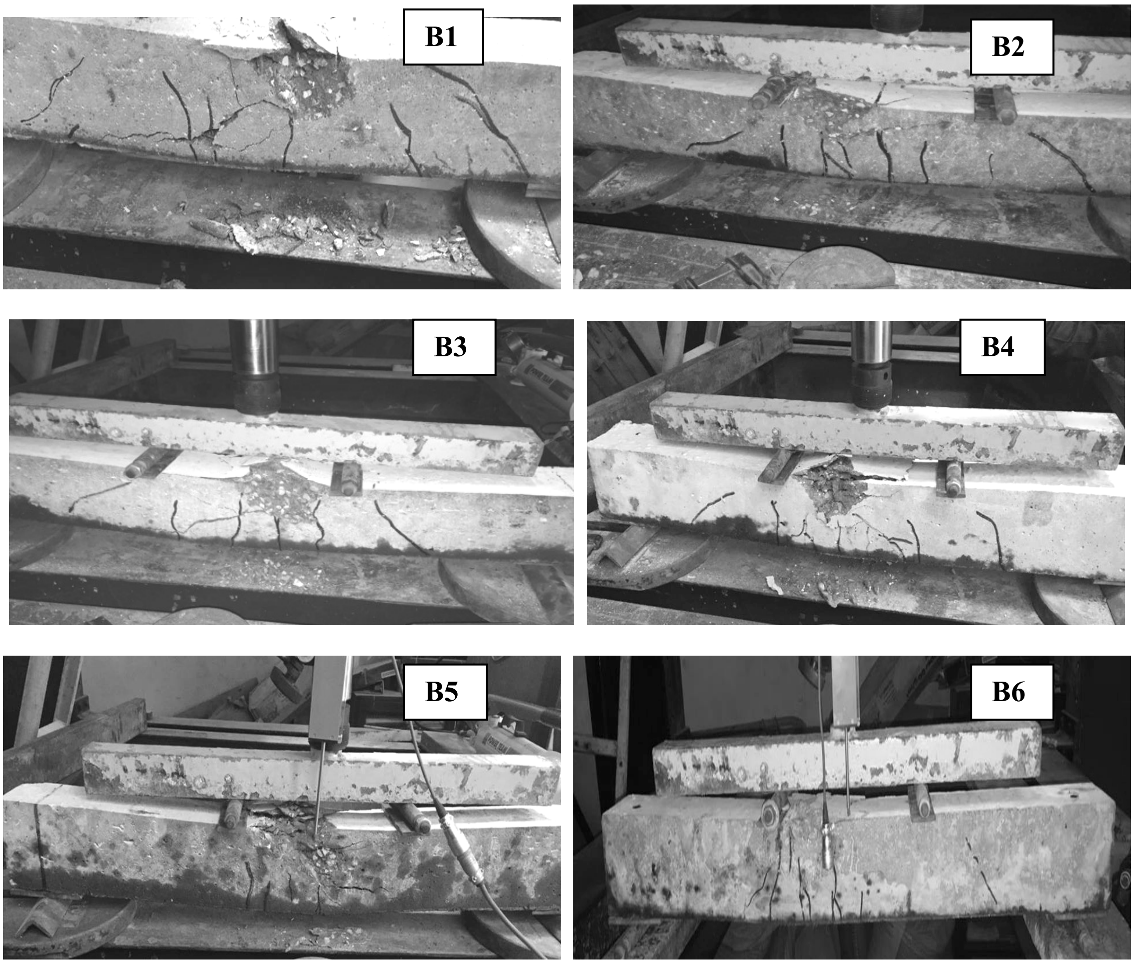
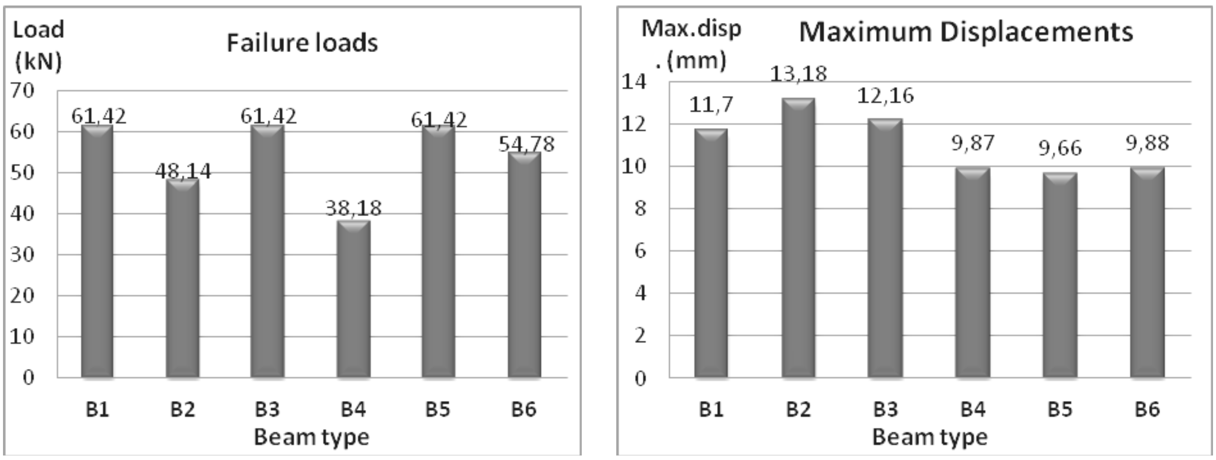


Fig. 20. Cracking patterns at failure for the tested beams



a *b*

Fig. 21. Experimental results of all beams: (a) failure loads and (b) maximum displacements

Conclusions

This paper presented a two-phase experimental program where self-compacting concrete (SCC) mixes were prepared containing additives of Nano silica and Nano manganese ferrite with several percentages. The fresh and hardened mechanical properties as well as the permeability and chloride penetration were evaluated and discussed. Further, beams were cast using the optimum percentage of Nano additives and were tested in flexure until failure. The main conclusions deduced from the experimental results can be summarized in the following points.

- The filling ability, passing ability and segregation resistance values for all the prepared SCC mixes are in the acceptable range.
- Addition of Nano silica to SCC cause increase of the compressive strength, splitting tensile strength and flexural strengh; this improvement is more with increasing the percentage of Nano silica addition.
- Addition of Nano silica and Nano manganese ferrite causes increase of compressive strength by 10-60% and 0-15%, respectively, compared to control mix.
- The best percentage for addition of Nano silica can be deduced to be 3% of cement weight, giving the highest compressive, tensile and flexural strengths. For Nano manganese ferrite additive, the optimum percentage is 0.5%.
- Addition of Nano manganese ferrite was shown to slightly improve the compressive strength, splitting tensile strength and flexural strength of SCC; adding 0.5 % of Nano-$MnFe_3O_4$ increased strength by 11.4%, 8.6% and 15% after 7, 28 and 56 days, respectively.
- The combined type with 0.5% Nano-$MnFe_3O_4$ improved the ompressive strength at 7, 28 and 56 days by 1%, 9% and 10%, respectively.
- Fly ash replacement of cement caused obvious increase in the compressive strength when used in combination with Nano additives.
- Addition of Nano silica significantly reduces the water permeability of SCC, which results in better durability.
- Adding Nano manganese ferrite to SCC had little effect on water permeability, but caused slight improvement of durability (6%) when combined with fly ash replacement of cement. .
- When adding Nano silica with 3% there was almost no chloride permeability, but addition of Nano-$MnFe_3O_4$ had no effect on improving chloride permeability of SCC.
- Nano additives combined with 25% fly ash replacement have extremely low water and chloride permeability values, indicating superior durability aspects.

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Экспериментальное исследование балок из самоуплотняющегося бетона с наноразмерными добавками

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Самоуплотняющийся бетон – это бетон, который течет и уплотняется под собственным весом без дополнительного воздействия; он имеет особый состав смеси, который обеспечивает высокую текучесть и устойчивость к расслоению. В данной статье представлены результаты исследования, направленного на изучение структурного поведения балок из самоуплотняющегося бетона с добавками нанокремнезема (Nano-SiO_2) и наномарганцевого феррита (Nano-$MnFe_3O_4$). Было приготовлено десять типов смесей, содержащих добавки нано-SiO_2 с тремя концентрациями: 1, 2 и 3 % от массы цемента и нано-$MnFe_3O_4$ с концентрациями 0,3, 0,5 и 0,7 %.

Лабораторные испытания проводились для определения свойств свежеприготовленной смеси (пластичности, проходимости и устойчивость к расслоению), механических свойств (прочности на сжатие, прочности на раскалывание и прочности на изгиб) и долговечности (водопроницаемости и проникновения хлоридов). Результаты эксперимента показывают, что использование нанодобавок и замена 25 % цемента летучей золой улучшило механические свойства и повысило долговечность самоуплотняющегося бетона. Смеси с оптимальным составом были использованы для изготовления железобетонных балок, которые затем испытывались на изгиб до разрушения с целью исследования влияния нанодобавок на характеристики при изгибе.

Ключевые слова: самоуплотняющийся бетон, добавки, нанокремнезем, наномарганцевый феррит, свойства свежеприготовленной смеси, балки; изгиб, долговечность.

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