Effect of Nano Particles on Self Compacting Concrete: An Experimental Study

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Abstract: Nanotechnology is a research area that has revolutionized mechanical and chemical properties of materials. Recently, focusing on concrete as a porous material with micro-scale and nano scale pores, researchers developed investigations to find microstructure and mechanical properties of concrete. This paper investigates the effect of nano-silica as an addition on new concrete generation called self consolidating concrete, (SCC) and high strength SCC. For the designed mixes, the fresh properties (Slump Flow, L-box, V-funnel and J-ring tests) as well as the hardened concrete properties such as compressive strength, flexural strength and modulus of elasticity were determined at different ages in order to establish the adequacy of nano SCC for structural applications. The results were compared with SCC specimens without nano-silica addition. In order to investigate the development on the microstructure of SCCs, the scanning electron microscopy (SEM) imaging on specimens were also performed. Results show that use of nano-silica with micro-silica can improve the engineering properties of hardened SCC.
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1.INTRODUCTION

Self-Compacting Concrete (SCC) is a new generation of concrete, which has generated tremendous interest since its initial development in Japan by Okamura in the late 1980s in order to reach durable concrete structures [1]. The SCC was developed first by Okamura and Ouchi [2]. It is a special kind concrete that can flow through and fill the gaps of reinforcement and corners of molds without any need for vibration and compaction during the placing process [1-3].SCC can flow into place under its own weight without any external or internal consolidation and with limited signs of segregation. Since that time, Japanese contractors have used SCC in different applications. In contrast with the Japan, research in Europe, America and Iran started only recently [4,5].

The advantages of SCC offers many benefits to the construction practice such as, achieving self consolidating, facilitate casting, and improve in-situ performance. These will results in reduced costs of placement, equipment needed on construction, shortening of the construction time and improved quality control [6,7]. Recently, applicable discussion in concrete technology is application of nanotechnology in concrete design. Nowadays the micro-level does not provide enough insights into building materials. Therefore, all around the world, increasing amounts of research funding are being diverted into the nano-level, which is claimed to have tremendous potential for the future [8]. The fundamental processes that govern the properties of concrete are affected by the performance of the material on a nanoscale. The main hydration product of cement-based materials, the C-S-H gel, is a natural nano-structured material [8,9]. The mechanical properties and the durability of concrete mainly depend on the gradual refining microstructure of the hardened cement paste and the gradually improving of the paste-aggregate interface zone (ITZ) [10].

One of the most referred to and used new cementitious nano-materials is amorphous silica with a particle size in the nano-range, even though its application and effect in concrete has not been fully understood yet. It has been reported that nano-silica addition increases the compressive strength and reduces the overall permeability of hardened concrete due to the pozzolanic properties, which are resulting in finer hydrated phases (C-S-H gel) and densified microstructure (nano-filler and anti-$Ca(OH)_2$ leaching effects) [10,11]. These effects may enhance the durability of concrete elements and structures. There are different commercial types of nano-silica additives available on the market, which are produced in different ways such as precipitation, pyrolisis, sol-gel and others [12]. The main characteristic of nano-silica, such as particle size distribution, specific density, specific surface area, pore structure, and reactivity (surface silanol groups), depends on the production method [13]. Despite the existence of several studies that describe the main properties and characteristics of concrete with nano-silica particles, most of them focus on the applications of nano-silica as an anti-bleeding [14,15] and as a compressive strength enhancement additive [16,17,18]. But in the literature only a few reports on the effects of nano-silica additions on mechanical properties of SCC are available [18,19].

Visual examination, optical microscopy, and scanning electron microscopy (SEM) have been extensively used in microstructure research of hardened cement paste and concrete, providing additional understanding of macroscopically properties. The addition of nanoscaled materials to the Portland cement system can also have an effect on the material. Nano-silica (nano-SiO2) is a synthetic product with spherical particles in the range of 1-50 nanometers. Nano silica has been successfully incorporated into Portland cement concrete materials in the laboratory [20].

It has been found that nano-silica additions improve the mechanical properties of SCC with respect to micro-silica [21]. Furthermore, it has been seen that this effect cannot stem from a pozzolanic reaction. In fact XRD studies have confirmed that, contrary to the case of micro silica, in the case of nano-silica, the consumption of Ca(OH)2 is completely negligible [22].

2. Materials

Type II and type V Portland cement complied with ASTM C150 was used in all concrete mixes. The coarse and fine aggregate were natural siliceous with a nominal maximum size of 20 and 10 mm. Aggregates were well-graded and conformed to ASTM C-33. The PCE superplasticiser was used in all mixtures to produce self compacting concrete. To enhance the stability of self compacting mixes Nano silica (in a form of colloidal silica solution) and lime stone powder with average particle size of 50 nm and 0.3 mm respectively were used in mixtures.

SiO2 nanoparticles with the average particle size of 15nm and 45m²/g Blaine fineness producing from a local manufacturer were used. The properties of SiO2 nanoparticles are shown in Table 1.

3. Experimental program

SCC has a very high flow and therefore there is a tendency to segregation. In this experiment SCC mixes were made using lime stone powder filler with/without nano-silica. Fresh properties of concrete mixes were measured using slump, L-box, J-ring and V-funnel tests and in hardened concrete phase, the compressive strength, flexural strength and modulus of elasticity were determined. The samples were cast in accordance to standard method [23]. After casting, samples were covered with two layers of plastic sheets and placed in temperature controlled room at 20±3 ºC for 24 hours. All samples were demoulded after 24 hours and cured for 28 days curing in saturated lime then curing in air (curing condition “W”). Based on the results of fresh mixes of SCC further investigation on harden concrete including compressive strength, flexural strength and modulus of elasticity were determined. Table 2(a) shows the mix proportions of mixes for two types of concrete (i.e., Type II and Type V). Mix SN has similar proportions to mixes S but contain nano-silica whereas, Table 2(b) is prepared for high strength self compacting concrete, HSSCC consisting of only Type II cement. Again, mix SH has similar proportions to mix SHN but contain nano-silica. Table 3(a) shows the summary of fresh properties of mixes S and SN and Table 3(b) shows the summary of fresh properties of mixes SH and SHN. The obtained results of fresh properties of all mixes are compared with the recommended values of EFNARC [23], indicated in the par antes, and it was concluded that the proposed design mixes can be considered as SCC. Also, a typical experimental fresh phase of HSSCC is shown in Figure 1.

Table 1. The properties of SiO2 nanoparticles

Diameter (nm)	Surface volume ratio (m²/g)	Density (g/cm³)	Purity (%)
15 ± 3	165 ± 17	<0.1	>99.9

Table 2(a). Mix design of SCC mixtures (mass per m³)

Group	Mix No.	Water (kg)	C (kg)	W/C**M**	Gravel (kg)	Sand (kg)	Filler (kg)	SP (L)	Micro Silica (Kg)	Nano silica (L)	Nano silica (wt%)
Cement Type II	S	168	360	0.42	750	870	100	2.8	40	-	-
Cement Type II	SN	168	360	0.42	750	870	100	2.8	40	2.4	5%
Cement Type V	S	210	360	0.525	750	850	300	3.675	40	-	-
Cement Type V	SN	210	360	0.525	750	850	300	3.675	40	2.4	5%

CM: cement+micro-silica Filler: lime stone powder

Table 2(b). Mix design of high strength SCC mixtures (mass per m³)

Group	Mix No.	Water (kg)	C (kg)	W/C **P**	Gravel (kg)	Sand (kg)	Filler (kg)	SP (L)	Mico Silica (Kg)	Nano silica (L)	Nano silica (wt%)
Cement Type II	SH	210	450	0.38	685	820	100	2.75	50	-	-
Cement Type II	SHN	210	450	0.38	685	820	100	2.75	50	3.0	5%

CP: cement+micro-silica+ filler   Filler: lime stone powder

Table 3(a). Fresh properties of SCC mixes

Group	Mix No.	Slump flow diameter (mm)	L-box h2/h1	V-funnel* 5 minute flow time **(s)**	J-ring (mm)
Cement Type II	S	620	0.79	7.2	590
Cement Type II	SN	630 (650-800)	0.82 (>0.8)	7.0 (6-10)	610 (Same as slump flow)
Cement Type V	S	670	0.9	6.85	650
Cement Type V	SN	690 (650-800)	0.9 (>0.8)	6.95 (6-10)	670

*V-funnel opening of 75*75mm

Table 3(b). Fresh properties of high strength SCC mixes

Group	Mix No.	Slump flow diameter (mm)	L-box h2/h1	V-funnel* 5 minute flow time **(s)**	J-ring (mm)
Cement Type II	SH	680	0.87	5.0	670.0
Cement Type II	SHN	650 (650-800)	0.83 (>0.8)	6.0 (6-10)	640.0 (Same as slump flow)

*V-funnel opening of 75*75mm

Figure 1(a): Slump flow test

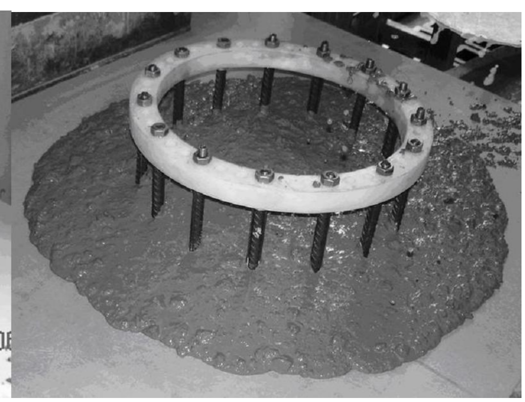

Figure 1(b): J-ring test

4. Compressive strength

Strength of SCC mixes of Table 2(a) and Table 2(b) was measured at different ages and the strength development of mixes based on average strength of three samples tested at each age are shown in Figures 1-3 respectively.

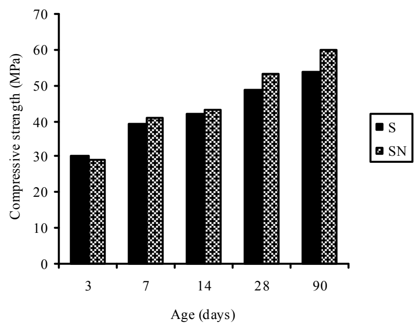

Figure 1. Compressive strength of SCC mixes at different ages (Type II)

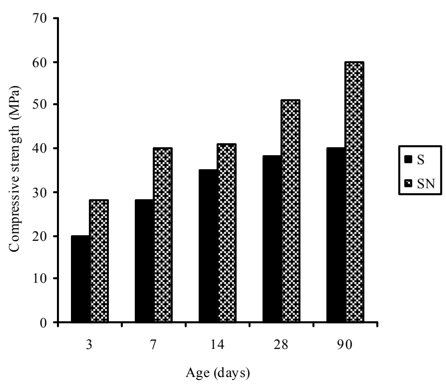

Figure 2. Compressive strength of SCC mixes at different ages (Type V)

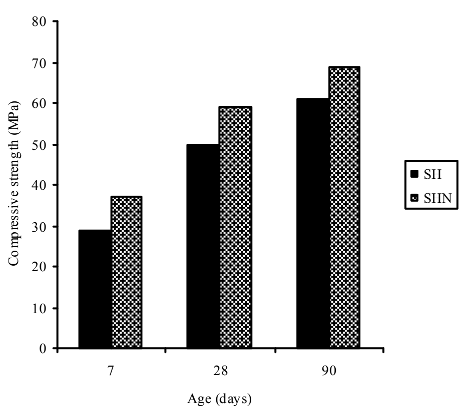

Figure 3. Compressive strength of high strength SCC mixes at different ages (Type II)

The higher rate of strength gain from 28 to 90 days at curing condition "W" may be due to rapid drying and crystallization of lime in the pore structure of concrete. The presence of nano-silica in the mixture appeared to introduce more reactive particles which can combine with lime and increase the strength.

It can be seen that irrespective of cement type, the compressive strength of SCC mixtures containing nano-silica are all higher than the control mixes with the same W/CM or W/CP.

The different of strength development in concretes can be attributed to pozzolanic reactions. The same conclusion is reported by recent research connected by Wangjo et al. on characteristics of cement mortar with nano-SiO2 particles. They also concluded that, nano particles are thought to be more effective in pozzolanic reaction than silica fume. Also, the nano-SiO2 would fill pores to increase the mortar strength, as silica fume does [24]. Therefore, it is confirmed that the addition of nano-SiO2 to cement mortars improves their strength characteristics.

5. Flexural strength

Figures 4-6 show the results of flexural strength of samples with/without nano-silica stored in conditions "W". A prism samples were tested at 28 and 90 days and average results of three samples are reported.

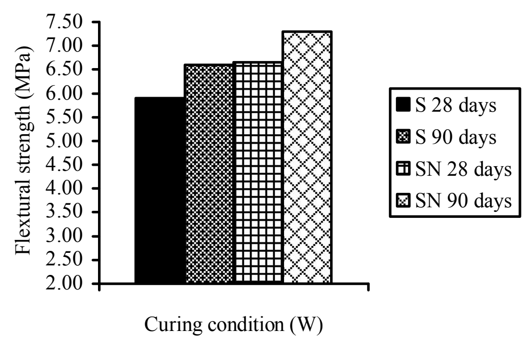

Figure 4. Flexural strength of SCC mixes at different ages (Type II)

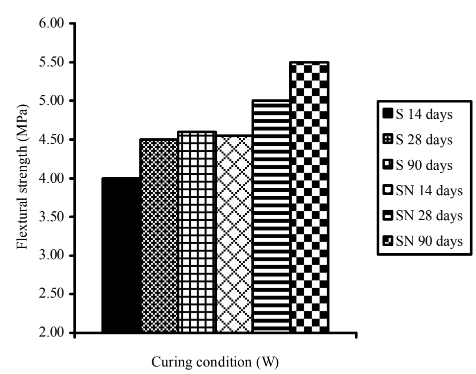

Figure 5. Flexural strength of SCC mixes at different ages (Type V)

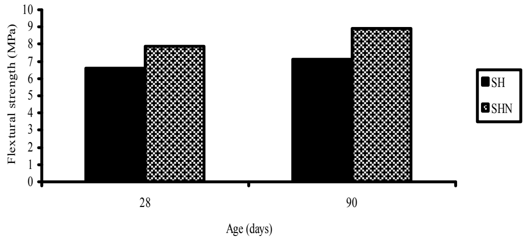

Figure 6. Flexural strength of high strength SCC mixes at different ages (Type II)

A similar trend which is normally observed for normal concrete i.e. the greater compressive strength, the higher flexural strength was observed for SCC. Overall, SCC mixes containing nano-silica showed better hardened properties than mixes without nano-silica. Irrespective of cement type, the flexural strength of SCC mixtures containing nano-silica is all higher than the control mixes with the same W/CM or W/CP.

6. Modulus of elasticity

There are several different definitions of the modulus of elasticity. However, here the slope of a tangent to the curve at 33.3% of the ultimate strength of the SCC mixes was considered as Ec. The obtained value of Ec for cement Type II (S and SN) and cement Type V (S and SN) of Table 2(a) were respectively as 34000, 30000 and 32000, 34600 MPa at 28 days, and 36000, 35000 and 35000, 36000 MPa at 90 days of age respectively. It is indicated a much closed values are obtained. The obtained value of Ec for cement Type II mixes of high strength SCC (SH and SHN) of Table 2(b) was respectively as 37000, 39000 MPa at 28 days of age. However, irrespective of cement type, the Ec values of SCC mixtures containing nano-silica are all higher than the control mixes with the same W/CM or W/CP.

7. Scanning electronic microscopy (SEM) imaging

Figure 7, has shown the cement paste, aggregate interface in SN consisting cement Type V. So, compositions of elements were determined with image processing software of captured image. Also, Figure 8, has shown its line diffraction from yellow line.

Figures 9(a) and 9(b), shown the SEM cement Type II the SEM cement Type II consisting micro silica respectively. Also Figures 10 and 11 shown the SEM image of SH (Type II) and SHN (Type II) respectively.

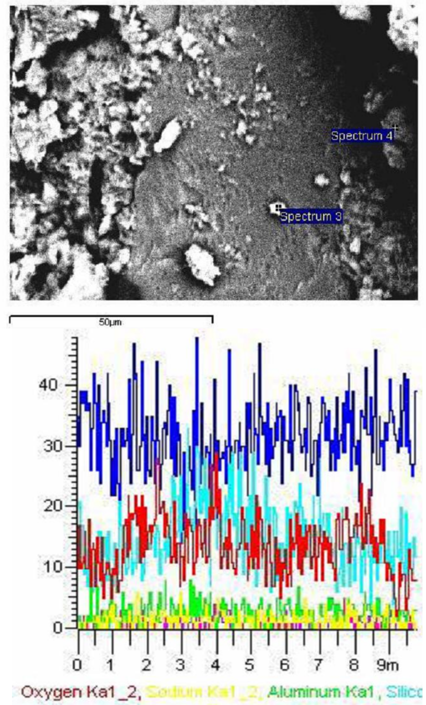

Figure 7. SEM image of SN (Type V)

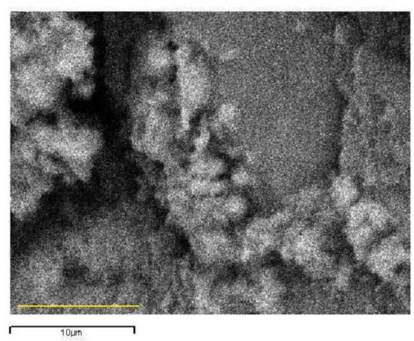

Figure 8. X-Ray analysis of cement paste (Type V)

The SCC with colloidal nano-silica presented a denser paste matrix and a better aggregates ITZ than the SCC without nano-silica. In addition, a refined microstructure was obtained (no Ettringite needles were found or identified). These refined were translated in better mechanical and durability properties of the SCC tested. Despite the lower reactivity at early ages of the nano-silica, the properties of the SCC were still significantly improved compared to the reference mix. However, the spherical shape and the lower reactivity of the nano-silica favoured to a better fresh behaviour of the SCC when it is compared with the SCC mix.

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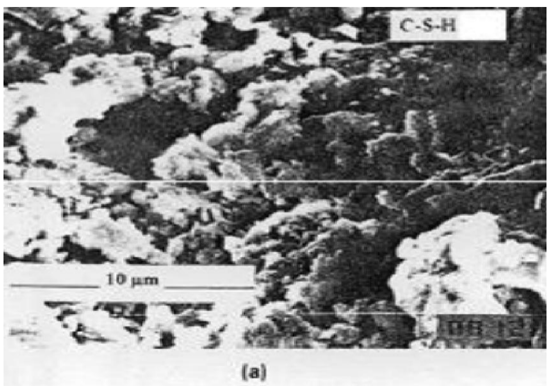

Figure 9(a). SEM image of cement II

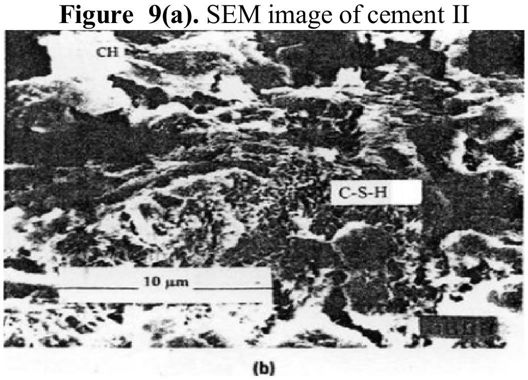

Figure 9(b). SEM image of cement II + microsilica

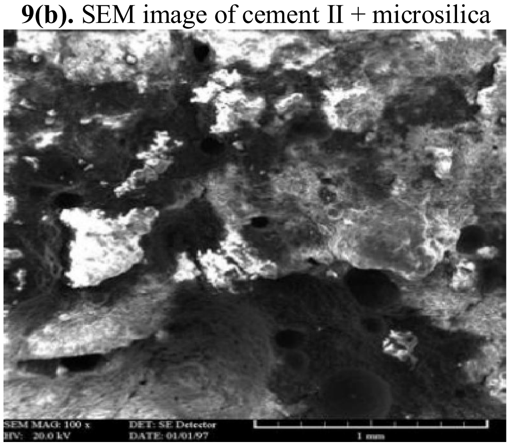

Figure 10. SEM image of SH (Type II)

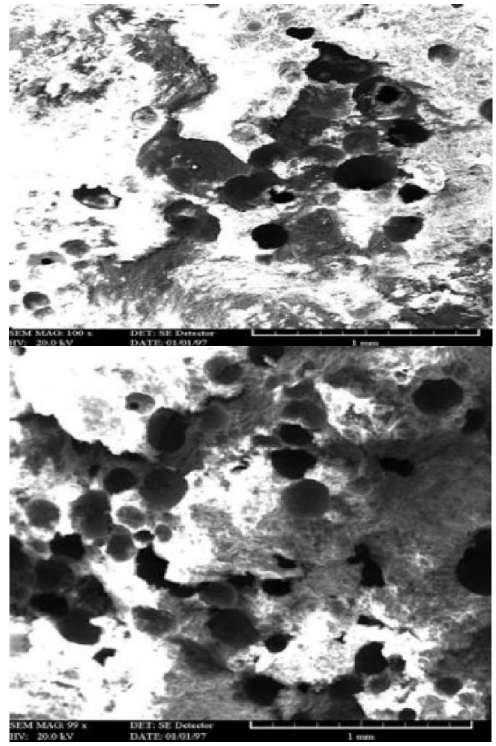

Figure 11. SEM image of SHN (Type II)

8. Conclusions

1- The higher rate of strength gain from 28 to 90 days at curing condition "W" may be due to rapid drying and crystallization of lime in the pore structure of concrete. The presence of nano-silica in the mixture appeared to introduce more reactive particles which can combine with lime and increase the strength.

2- Irrespective of cement type, the compressive strength of SCC mixtures containing nano-silica are all higher than the control mixes with the same W/CM or W/CP. The different of strength development in concretes can be attributed to pozzolanic reactions.

3- A similar trend which is normally observed for normal concrete i.e. the greater compressive strength, the higher flexural strength was observed for SCC. Overall, SCC mixes containing nano-silica showed better hardened properties than mixes without nano-silica.

4- The addition of nano-silica in SCC mixes, consisting of micro silica causes to increase the compressive, flexural strength and modulus of elasticity up to the age of 90 days, and therefore, a reasonably better serviceability conditions can be expected while used in structural concrete and also its durability is enhanced.

5- The mechanical properties of SCC were improved by the addition of nano-silica.

6- Compare those of micro-silica and nano-silica in SCC cause to reduce in pores size and the concrete structures will be more dense and durable.

7- SEM test shows that, the progress of hydration in the case of using nano-silica developed from 28 days age respect to using just micro-silica.

8- The microstructural analysis of the hardened SCC reveals that the additions of nanosilica particles produced a homogeneous microstructure, characterized by compact and small sized C-S-H gel. As a consequence, a denser ITZ was produced. The additions of nano-silica caused a refinement of the microstructures (less interconnected pore structure) and induced precipitation of small sizes C-S-H gel having high stiffness. The improvement of the microstructure was reflected by the mechanical properties due to the fact that the pozzolanic gel structure presents better mechanical properties than the C-S-H gel precipitated in standard OPC concrete.

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