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Coupled Effect of Nano Silica and Steel Fiber on Fresh and Hardened Concrete Properties

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ABSTRACT : *The aim of this experimental study is to assess the combined effects of using nano silica (NS) and steel fibers (SF) on the workability of fresh concrete and mechanical properties of hardened concrete. NS is used as partial cement replacement by 1, 1.5, 2, and 4 wt. %, and SF is used as volume substitution by 0.45, 0.9, and 1.35 %. Slump, compressive strength at 7 and 28 days of age, modulus of elasticity and flexural strength are evaluated using different combinations between NS and SF. Thermo-gravimetric analysis (TGA) is provided for detecting changes in hydration material due to the addition of NS. Significant improvement in the mechanical properties of concrete on using NS and SF, addition of NS not only act as pozzolanic additive, but also as pore filling leading to reduces the pore size structure of concrete. Optimum content of NS is (1.5 – 2) wt. % improves compressive strength for samples with various SF content. On the other hand, it can be stated that more than 2 wt. % NS leads to decrease compressive strength as unreacted agglomerated nanoparticles are existed when large amount of NS are used. Utilizing 2 wt. % NS with 0.9 % SF leads to doubling the modulus of elasticity compared to samples without either NS or SF. Finally, Flexural strength is improved 87.7 % for samples of 2 wt. % NS and 1.35 % SF compared to samples without NS and SF.*

Keywords: *Nano silica; Steel fiber; Mechanical properties; Thermal analysis*

I. INTRODUCTION

The Concrete is the most widely used material in construction, researchers aim to improve concrete properties by applying different kinds of micro and nanoparticles. Calcium Silicate Hydrate (C–S–H) gel is the main component formed from cement hydration and it has a natural nano-structure.

Additional calcium silicate hydrate gel are formed by using NS during treatment, hence compressive strength of concrete paste are significantly increased [1]. High pozzolanic reactivity of colloidal nano silica causes less formation of calcium hydroxide (CH) at early ages, and at later ages the hydration hindrance effect of colloidal nano silica on cement can be the main reasons as well as NS can improve the filler effect of concrete [2 to 4]. Calcium hydroxide reacts with NS due to its amorphous shape forming more calcium silicate hydrate. The amount of surface area available for reaction is responsible of rate of the pozzolanic reaction. Examining the residual CH and the rate of heat evolution showing the continuous hydration progress of CH and is observed by scanning electron micrograph (SEM) [5].

Thicker cement paste, and accelerating cement hydration process are observed due to NS addition. Bond strengths of paste–aggregate interface and compressive strengths of cement paste of silica fume concrete are lower than those incorporating NS, at early ages. [6].

C–S–H gel formation is accelerated by using NS up to 3.0 wt% as a result of increased crystalline CH amount and hence the resistance to water permeability of concrete is improved. Using NS over 3.0 wt% decrease the amount of C–S–H gel formation causes the reduced strength [7]. Decreasing harmful pores is found by using NS which can acts as nano fillers by [8]. Moreover, acceleration of cement dissolution causing accelerating effect of NS on hydration [9].

Concrete specimens containing 15 nm average diameters NS gives higher strength than those containing 80 nm of SiO_2 particles at early age [10]. Water penetration resistance of concrete is decreased by using NS [11]. This improvement mainly because using NS, which has pozzolanic and filler effects on the cementitious paste [12]. Nanoparticles lead to more compacted microstructure, hence frost resistance of concrete significantly improved [13].

SF can improve compressive strength of concrete at optimum value of 1.5% volume fraction [14]. The mechanical properties and durability of self-compacting concrete are improved using both NS and reinforcing SF in optimum ratios [15].

The objective of this study is to evaluate the combined effect of using nano silica as cement substitution and steel fibers on mechanical properties of concrete.

II. EXPERIMENTAL PROGRAM

2.1. Materials

Ordinary Portland cement (OPC) is used as the main cementing material. It meets the requirements of ASTM C 150 [16]. The general chemical composition of the OPC is illustrated in Table 1. Nano SiO_2 (NS) with average particle size around (9 to 20) nm is used as received from physical laboratory at housing and building national research center (HBNRC). The utilized NS particles are expected to have high pozzolanic reactivity due to their amorphous structure. XRD test indicates the amorphous structure of NS as shown in Fig. 1.

Two types of aggregates are used in the concrete mix: fine aggregates and coarse aggregates. Fine aggregates used for the study are locally available natural sand. Fine aggregates pass the 4.75 mm (No. 4) sieve and retain on the 75 lm (No. 200) sieve [17]. Dolomite is used as coarse aggregates with particle size not exceed 14 mm. Super-plasticizer of polycarboxylate base (Glenium C315, BASF Co.) with 1.08 g/cm^3 specific gravity is used. Hooked end steel fibers (SF) made of low carbon steel wire with average length of 30 mm and average diameter of 0.8 mm is used. SF tensile strength is between 800 N/mm^2 to 1100 N/mm^2 and meeting the requirements of ASTM A820.

2.2. Mixture proportioning

A total of twenty mixes are performed in the laboratory. The control mixture is prepared without using NS or SF, other mixtures are prepared using NS as partial cement replacement by 1, 1.5, 2, and 4 wt%, and SF is used as volume substitution by 0.45, 0.9, and 1.35%. The mixes are divided into four groups and the mixtures proportions are illustrated in Table 2. Constant binder content of 450 kg/m^3 is used for all mixtures with 0.40 water to binder ratio (w/b) is set. The amount of SP is set at 0.8% of the binder (cement + NS) weight.

2.3. Mixing procedure and curing

Colloidal NS is applied for 10 minutes to ultra-sonication probe to be vibrated at very high speed to avoid agglomeration and to be more efficient in dispersing NS. In the performing of concrete, the dry materials are first mixed without fibers to avoid fiber balling for 1 min at low speed to obtain a homogenous mixture, then wet mixed at low speed for another minute, after that colloidal NS is added to prevent any agglomeration which may occurred and finally SF and SP are added and mixed at medium speed for 3 minutes, hence good workability concrete with uniform material is produced [14 and 18 to 21]. Samples were removed from the molds and kept in 22–25 ºC water until the suitable age for each experiment. Each mixing design includes six 150 mm cubic molds for compressive strength and modulus of elasticity and three beams of 600 x 150 x 150 mm for flexural strength test.

2.4. Test methods

Standard slump tests conforming to ASTM C143/C 143 M [22] are performed to evaluate workability of fresh concretes. Compressive strength of concrete cubes is performed as per ASTM C 39 [23] after 7 and 28 days of moisture curing. Tests are carried out using a universal testing machine SHIMADZU 1000 kN on triplicate specimens and average compressive strength values are obtained.

The static modulus of elasticity is determined according to ASTM C 469 [24]. Tested specimens are exposed to uniaxial compression load using universal testing machine. The stress-strain characteristics are determined after 28 days of curing. The modulus of elasticity is measured as a tangent modulus in the elastic range.

Flexural tests are performed in accordance with the ASTM C293 [25] Standard. Tested specimens are exposed to one point load at mid-span. Again, flexural tests are carried out on triplicate specimens and average flexural strength values are obtained.

For TGA, the simultaneous thermal analyzer equipment, model STA 409 with a Data Acquisition System 414/1 programmer is used. Samples are heated in an inert N2 atmosphere from 100 to 1000 ºC with a heating rate of 20 ºC/min.

III. RESULTS AND DISCUSSION

3.1. Workability

Figure 2 indicates that addition of SF leads to decrease in slump values of concrete mixtures as the SF content increases. Increasing NS content lead to slight decrease in slump, it is observed that water needed for wetting the binder particles is increased as surface area of powder materials increased after adding nanoparticles due to their ultra-fine size [1, 26 and 28]. This behavior confirms ‘‘ball bearing’’ effect that appeared by using NS as cement substitution causes the need for higher amounts of water in order to maintain a suitable workability of the mixture [4], the coupled effects of NS and SF on workability showing that SP should be added to obtain the advantageous of workable concrete.

3.2. Compressive strength

The average test results of compressive strength of SF and SiO_2 nanoparticles concretes are presented. The effect of SF on compressive strength at 7 days and 28 days of curing age is presented in Fig. 3.a to Fig. 3.f. Nano silica due to its high special surface with amorphous shape is significantly reactive [29], and produces huge amounts of C-S-H condensed gel. It is suggested that the CH crystals reacts with NS lead to increasing strength [30].

The compressive strengths of all concretes increase with the increase of NS and SF content at all ages of curing (7 and 28 days) higher than control mix, this confirms the formation of higher amount of C–S–H gel in the presence of nanoparticles.

It can be noted that considerable improvement in concrete strength by addition NS as a part of cementitious materials. The 28 day compressive strength of concrete is improveded by 33.6% in comparison to the control mix using NS silica as cement substitution by 1.5wt% with 0.45% of SF. As well as, Observed improvement of 39%, 25.4% and 29.8% by using 2wt% of NS with 0%, 0.9% and 1.35% SF respectively. It is observed that SF improves compressive strength at 7 days of age to be more than compressive strength at 28 days of age for mixes without SF at the same NS content.

In all mixes, when SF content increase to the value of 0.9% in the sample, optimum compressive strength is reached of the sample. This improvement occurred as SF controls and bridges the cracks in the cement matrix that retarding failure of the sample.

Using 0.45% SF without NS increased compressive strength in all mixes compared to that containing NS alone. The optimum ratios of NS and SF are concluded to be 2 wt% and 0.9% respectively; hence leading to improvement in compressive strength compared to samples without either NS or SF is as much as 124%.

Using 4 wt% NS leads to reduction in compressive strength of the specimens at all ages of curing, this may be due to the agglomeration which reduce the amount of crystalline CH.

3.3. Modulus of elasticity

The results of modulus of elasticity are presented in Table 3. It is found that by adding SF significantly increase modulus of elasticity. Noticed, increase also is observed by addition of NS into concrete, this is in good agreement with [31, 32].

When SF content increases to the value of 0.9% optimum modulus of elasticity is reached for the samples with all NS content. Observed improvement of about 15.7%, 21.4%, and 22.4 by using 0% of SF with 1 wt%, 1.5 wt%, and 2 wt% NS respectively compared to samples without NS.

Improvement is about 14.5%, 18.4% and 21.4% by using 0.45% of SF with 1 wt%, 1.5 wt%, and 2 wt% NS respectively compared to samples without NS. With high content of SF (0.9% and 1.35%) the enhancement in modulus of elasticity due to addition of NS is around 1.5% to 9.7% compared to samples without NS.

Adding NS by 2 wt% improves modulus of elasticity about 5.4% compared to samples without NS at 0.9% SF. The optimum ratios of NS and SF are concluded to be 2 wt% and 0.9% respectively; hence leading to improvement in modulus of elasticity compared to samples without either NS or SF is as much as 93.6%.

3.4. Flexural strength

The average test results of flexure strength of SF and SiO_2 nanoparticles concretes for each mix are presented for each group in Fig. 4.a to Fig. 4.d It is found that increase in the amount of SF increased the flexural strength. It can be concluded that flexural strength increase by increasing either NS or SF, observed improvement about 16.3%, 13.9%, 20.6 and 24.3% by using 2wt% of NS with 0%, 0.45%, 0.9% and 1.35% SF respectively compared to samples without NS.

The improvement in flexural strength for samples utilizing 2 wt% NS and 1.35% SF compared to samples without NS and SF reaches 87.7%.

3.5. Thermo-gravimetric analysis (TGA)

The results of TGA/DSC on cement pastes without nano silica and with 1.5 wt% nano silica are given in Fig. 5.a and Fig. 5.b. DSC curves show three endothermic peaks, the first peak is at 30 ºC - 150 ºC resulted from loss of physically absorbed water from the pastes. The second peak is formed due to weight loss step at 400 ºC - 500 ºC is due to the dehydration of CH. The third weight loss step at 700 ºC - 800 ºC is due to the de-carbonation of $CaCO_3$.

CH content in the cementitious pastes can be estimated from the loss water in the second weight loss step due to heating. Mass loss of calcium hydroxide can be calculated as [34, 35]:

MCH= [(74.09/18.01)/ (M400-M500)/MC] …... Eqn. 1

Where

MCH = mass fraction of calcium hydroxide
M400= mass of the paste specimen at 400 ºC
M500= mass of the paste specimen at 500 ºC
MC= initial mass of the specimen

The calculated %CH for specimens without nano silica and containing NS of 1.5 wt% is 30.11 and 19.74 respectively; hence CH is decreased by using NS that indicate increasing in C-S-H which give good agreement with mechanical properties results.

IV. FIGURES AND TABLES

4.1. Figures

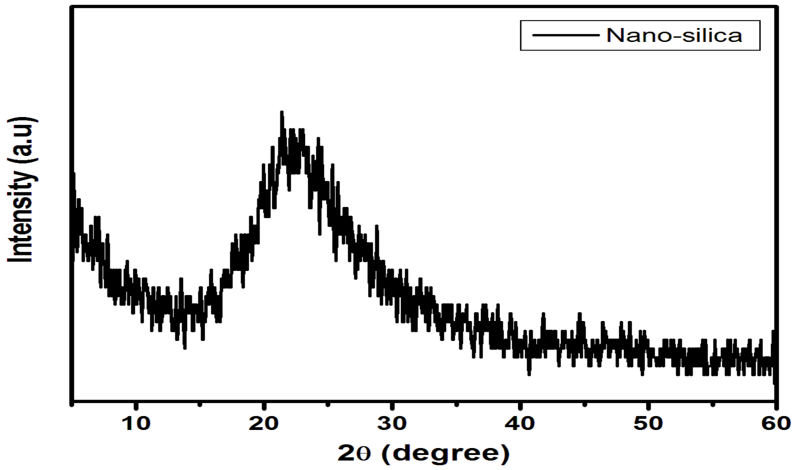

Fig. 1. XRD of SiO_2 nanoparticles with average particle size of (9-20) nm.

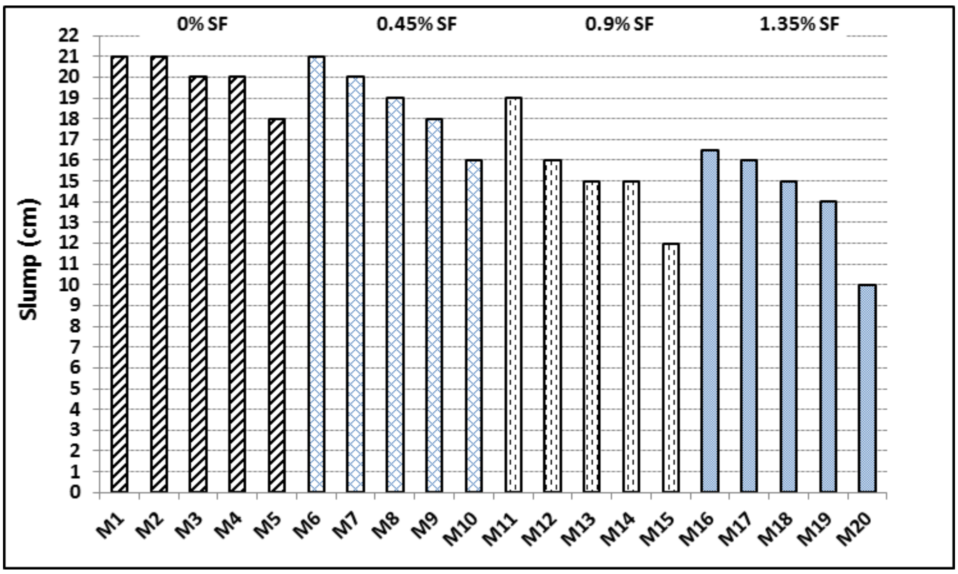

Fig. 2 Slump test results.

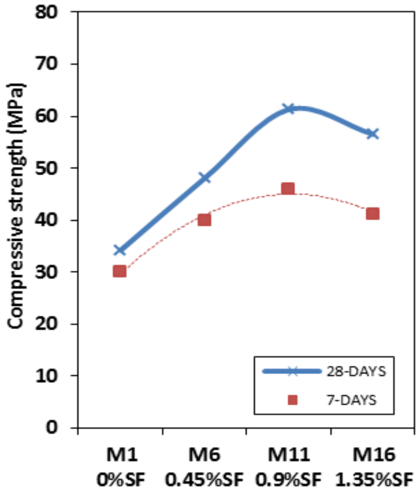

Fig. 3.a Compressive strength for mixes with 0 wt% NS.

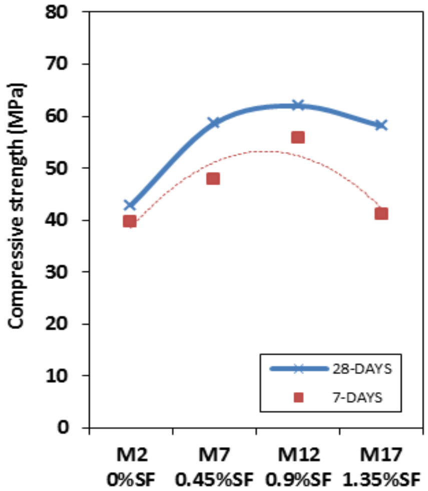

Fig. 3.b Compressive strength for mixes with 1 wt% NS.

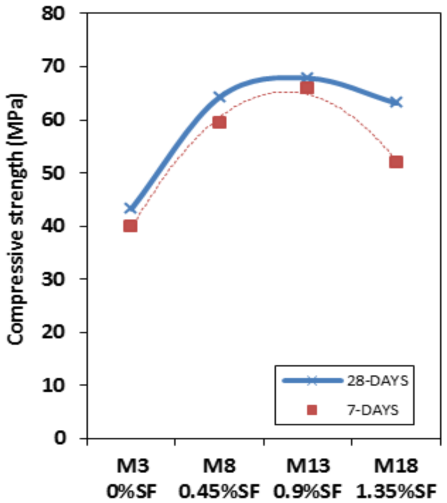

Fig. 3.c Compressive strength for mixes with 1.5 wt% NS.

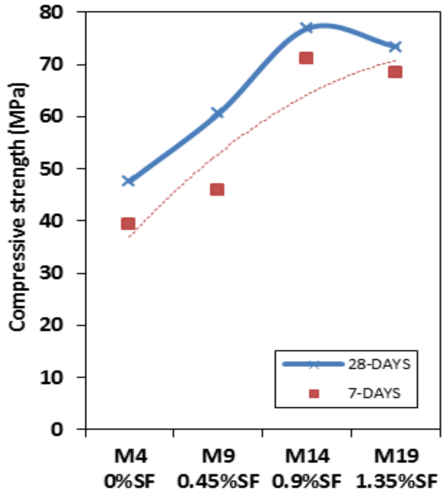

Fig. 3.d Compressive strength for mixes with 2 wt% NS.

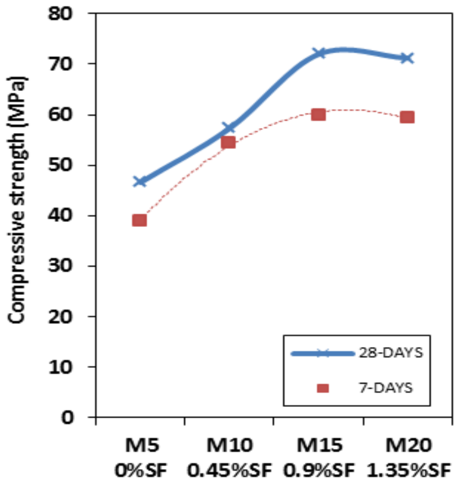

Fig. 3.e Compressive strength for mixes with 4 wt% NS.

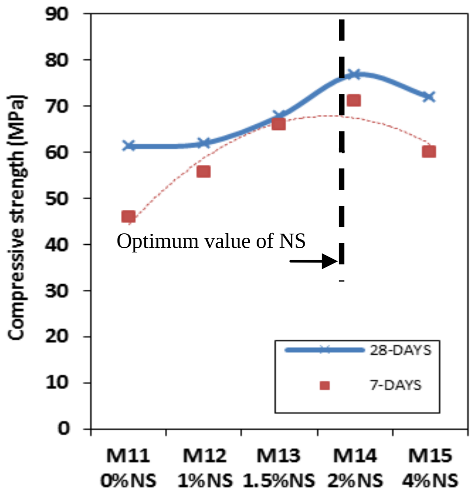

Fig. 3.f Compressive strength for mixes with 0.9% SF.

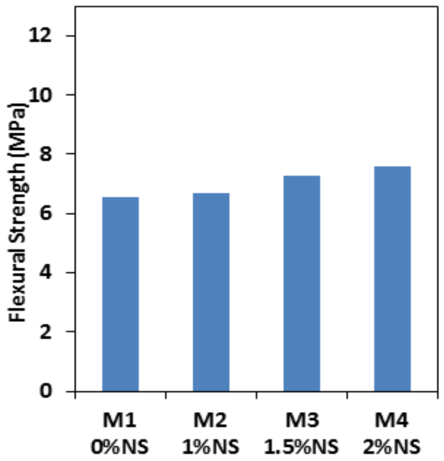

Fig. 4.a Flexural strength for Group G1 with 0%SF.

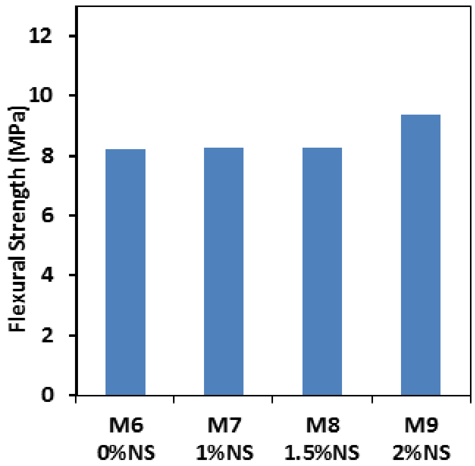

Fig. 4.b Flexural strength for Group G2 with 0.45%SF.

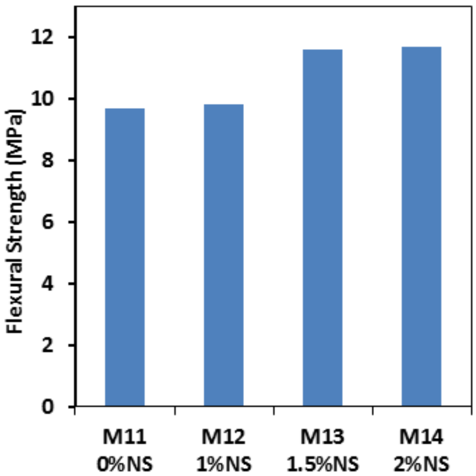

Fig. 4.c Flexural strength for Group G3 with 0.9%SF.

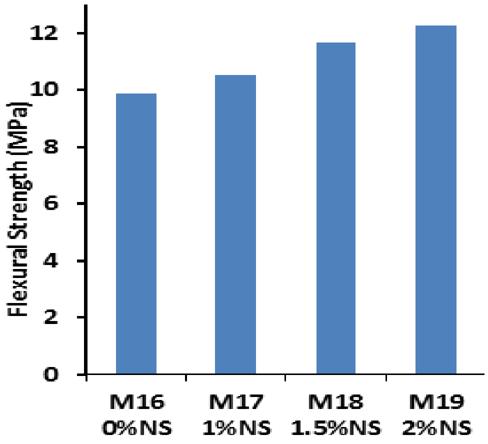

Fig. 4.d Flexural strength for Group G4 with 1.35%SF.

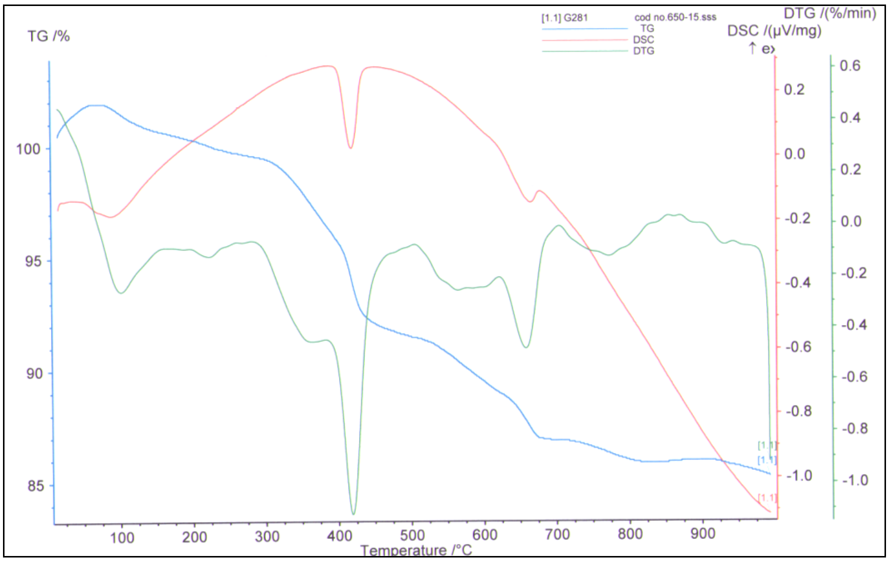

Fig. 5.a TGA/DSC/DTG results for cement paste with NS of 0 wt%.

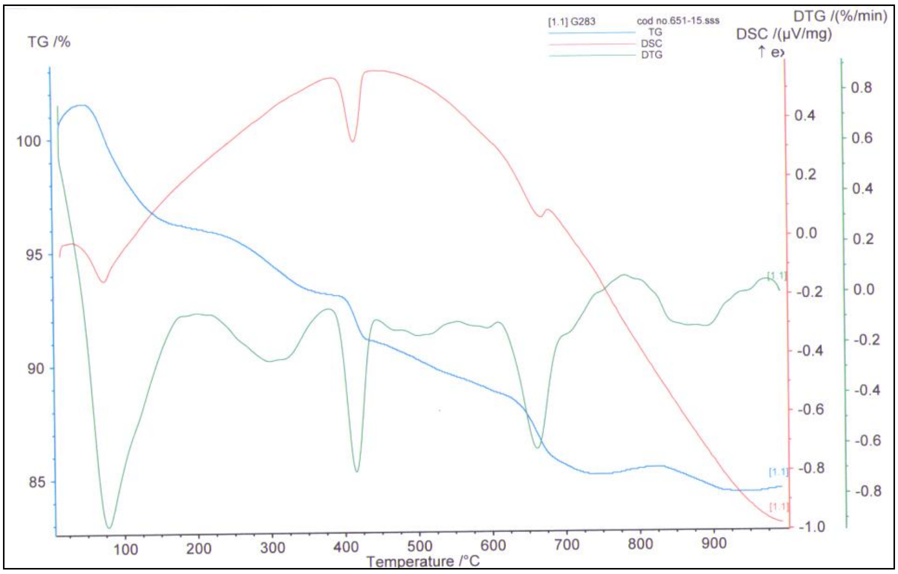

Fig. 5.b TGA/DSC/DTG results for cement paste with NS of 1.5 wt%.

4.2. Tables

Table 1: Chemical composition of OPC (wt%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I
Cement	21.03	4.09	3.03	61.45	1.74	3.50	0.48	0.37	4.08

Table 2: Mixture proportions of SF and NS blended concretes.

Group	Mix	SF (%)	NS (%)	Quantities (kg/m^3)		
				Cement	NS	SF
G1	M1	0	0	450	0	0
	M2		1	445.5	4.5	0
	M3		1.5	443.25	6.75	0
	M4		2	441	9	0
	M5		4	432	18	0
G2	M6	0.45	0	450	0	30
	M7		1	445.5	4.5	30
	M8		1.5	443.25	6.75	30
	M9		2	441	9	30
	M10		4	432	18	30
G3	M11	0.9	0	450	0	60
	M12		1	445.5	4.5	60
	M13		1.5	443.25	6.75	60
	M14		2	441	9	60
	M15		4	432	18	60
G4	M16	1.35	0	450	0	90
	M17		1	445.5	4.5	90
	M18		1.5	443.25	6.75	90
	M19		2	441	9	90
	M20		4	432	18	90

Table 3: Modulus of elasticity results.

Mix	SF (%)	NS (%)	Modulus of elasticity (MPa)
M1	0	0	20054.43
M2		1	23204.05
M3		1.50	24352.15
M4		2	24558.90
M6	0.45	0	29616.82
M7		1	33933.87
M8		1.50	35090.80
M9		2	35983.70
M11	0.90	0	36812.02
M12		1	37394.99
M13		1.50	38265.27
M14		2	38834.09
M16	1.35	0	32822.79
M17		1	33357.23
M18		1.50	35129.76
M19		2	36017.87

V. CONCLUSION

The following can be concluded from presented research:

1. Compressive strength of mixes with NS content of 1.5 wt% and 0.45% SF improved by 33.6% compared to that with 0.45% SF and without NS.
2. Utilizing optimum NS content of 2 wt% with 0% SF, 0.9% SF and 1.35% SF improved compressive strength about 39.1%, 124.8% and 114.6% respectively compared samples without either NS or SF.
3. Mixes with more than 2 wt% NS as cement substitution decrease the compressive strength of concrete.
4. SF highly improves the mechanical properties of concrete and the optimal level of SF content is achieved with 0.9% with all ratios of NS.
5. 0.45% SF improves compressive strength at 7 days of age to be more than compressive strength at 28 days of age for mixes without SF at the same NS content of (0, 1, 1.5 and 4) wt%.
6. Using 0.45% SF without NS gives compressive strength more than all mixes that contain NS but without SF.
7. The optimum ratios of NS and SF are concluded to be 2 wt% and 0.9% respectively. Hence, lead to improving compressive strength 124.8% compared to samples without either NS or SF.
8. The optimum ratios of NS and SF are concluded to be 2 wt% and 0.9% respectively; hence lead to doubling the modulus of elasticity compared to samples without either NS or SF.
9. Improvement in flexural strength for samples of 2 wt% NS and 1.35% SF compared to samples without NS and SF is 87.7%.
10. Workability decrease by increasing of either NS or SF due to the increasing surface area of powder materials after adding nanoparticles that need more water for wetting the binder particles.
11. TGA results show that using nano silica reduce calcium hydroxide in cement mixture structure that can be due to its pozzolanic activity.

The addition of NS reduces the pore size structure of concrete by filling micro cracks. Enhancement porosity and water permeability will be published in the near future.

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