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Performance Of High Strength Concrete Utilizing Silica Fume, Nano-Silica And Steel Fibers With Different Cementitious Contents

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ABSTRACT

The use of High Strength Concrete is increasing largely nowadays due to its unique properties. The addition of pozzolanic materials such as silica fume and nano-silica as a partial replacement of cement in concrete is considered beneficial as it improves its properties and in the same time reduces the amount of CO_2 emitted in the atmosphere during cement manufactory. Adding steel fiber to high strength concrete can improve its ductility, toughness and impact resistance in addition to its strength. The effect of adding silica fume, amorphous nano-silica and steel fibers to the concrete mix on its compressive and splitting tensile strengths was considered in this study at different cementitious contents. Amounts used were 10 % of silica fume and 1 % of nano-silica by weight of cement as partially replacing the same amounts of cement. 2 % of steel fiber by weight of concrete was also used. 500, 600, and 700 kg/m3 cementitious contents were used. SEM micrograph images and EDX spectrum were made on some concrete specimens. Specimens were tested at the age of 28 and 56 days. Concrete prepared with silica fume and nano-silica showed larger compressive and splitting tensile strengths than the control mix. Adding steel fibers resulted in further increase in strength with even larger percentage in the case of tensile strength and this can be related to their ability to control and bridge these cracks.

1. Introduction

Using high strength concrete, HSC, is gradually increasing day-by-day as a result of its distinguished properties in terms of increased strength, low permeability and hence good durability [1]. The manufactory process of Portland cement is considered as a main reason for emitting CO2 into the atmosphere. Therefore, the use of pozzolanic materials partially replacing some amount of cement reduces the consumption of cement in the concrete manufactory. Thus using pozzolanic materials is considered beneficial as it allows fewer amounts of cement to be considered and in the same time concrete with more strength and better durability is obtained. Silica fume is one of the efficient pozzolanic materials used in concrete, which

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improves its microstructure. It fills the gaps in between the cement particles leading to a fine pore structure. Also, it reacts with calcium hydroxide available in the hydrating cement resulting in additional C-S-H gel formation [2-4].

Nano silica (NS) as one of the partial substitution alternatives of cement is attractive for several researchers. The effect of its use in concrete on its fresh and hardened properties was studies by many researchers.

A comparison between the effect of adding micro silica (silica fume) and nano-silica to concrete on its performance was the aim of several studies [5-7]. The impact of adding instant 5% Silica fume partially replacing cement together with nano silica of different replacements ranging from 0% to 4%, all partially replacing cement was studied by Yunchao et al. [7]. It was found that 5% of silica fume and 3% of nano silica yielded the maximum compressive strength obtained, while 5% of silica fume and 2% of nano-silica resulted in the optimum splitting tensile strength in that study.

Qing et al. [8] showed that the paste-aggregate interface bond strength was improved using nano silica. It was also found in other studies that nano silica has higher pozzolanic activity than silica fume. It was suggested by LI et al. [9] that the pavement abrasion resistance could be increased using nano silica. Lin et al. [10] showed that the uniform dispersion in the cement paste of nano silica resulted in the acceleration of the cement hydration as a result of its high activity. Thus nano silica has the potential to be used with concrete as a result of its unique properties. Therefore, more efforts are needed to insure the efficiency of using nano silica particles with cement in concrete and its effect on the behavior of concrete as can be seen in its compressive and tensile strengths.

The effect of adding NS to concrete was considered in an experimental study [11], where 0.5%, 1.0% and 1.5% NS were added to concrete replacing the same amount of cement by weight and compressive and tensile strengths of those mixes were obtained. A comparison was made with the results of the control mix without NS. It was found that the concrete mix having 1% NS gave larger strengths than those, which were having 0.5 % and 1.5% NS at 500, 600 and 700 kg/m^3 cementitious contents and at ages of 28 and 56 days.

Likewise, a comparison was made between the impact of adding SF and NS on the strength of HSC at 500, 600 and 700 kg/m^3 cementitious contents [11, 12]. 10% silica fume and 1% nano silica were added to concrete replacing the same amounts of cement. It was found that the 1% NS concrete mix yielded a compressive strength of about 90% of that of the 10% SF concrete mix and that was related to its nano size. The 10% SF and 1% NS concrete mix yielded a compressive strength of about the same value as that of the 10% SF mix and that might be related to the free lime limited amount present for the reaction with SF and NS.

The impact of using steel fiber on the performance of cement pasted composite materials, which contained silica fume (SF), was studied by Lin et al. [13] and they found that adding of steel fibers to silica fume (SF) composites increased significantly the tensile strength, toughness and impact resistance, while the compressive strength and abrasion resistance improved slightly. Madhavi et al. [14] studied the effect of mineral and chemical admixtures on fiber reinforced self-compacting concrete and it was reported that adding steel fibers and poly-probylene fibers increased its compressive and tensile strengths.

The impact of adding steel fiber and nano silica on the properties of concrete was also studied [15].

The effect of adding silica fume, amorphous nano-silica and steel fibers to the concrete mix on its compressive and splitting tensile strengths was considered in this study at different cementitious contents.

2. Materials and methods

Portland cement, C, of type I, grade 52.5 and manufactured in Egypt was used in this study. Its specific gravity was 3.15. Coarse aggregate used, C.A, was a crushed aggregate passing 10 mm sieve and retained on 5 mm sieve. Its specific gravity was 2.64. Fine aggregate, F.A, was sand (zone п) of 2.95 fineness modulus. Silica fume, S.F, with 93.9% SiO_2 was used. Nano silica, N.S, used as an amorphous pozzolanic material was having 19.4 nm size of its spherical particles and 90.9% SiO_2. The steel fibers used were made of steel, hooked at their ends, 8 mm diameter and 30 mm long with length to diameter ratio of 3.75. Finally, tap water was used in this work.

The concrete mix proportions for mixes containing 500, 600 and 700 kg/m^3 cementitious contents, C.C are shown in Table (1). For each C.C there were the control mix with Portland cement, C, a mix with 2 % steel fibers by volume of concrete, CF, a mix with both 10% S.F and 1% N.S as partially replacing cement, CSN, and a mix having 10% S.F, 1% N.S, and 2 % steel fibers together, CSNF.

Coarse and fine aggregates and Cement were first dry mixed. The superplasticizer was added to water and mixed thoroughly and then they were added to the dry mix and mixing was continued. Silica fume was added and mixed with the dry mix in mixes

containing S.F. For mixes containing NS, it was put on the mix of water and superplasticizer, sonicated for about 15 minutes at 37° centigrade using the ultra-sonic cleaner and then they were added to the dry mix. Quantity of steel fiber was spreaded on the mix during mixing in mixes containing steel fibers.
The slump of the slump test was kept equal to 5 to 10 Cm for all mixes by changing the ratio of the superplasticizer in the different mixes. The superplasticizer was Master Glenium RMC 315.
Concrete cubes of 10 mm side length and cylindrical specimens of 100 mm diameter and a length of 200 mm were prepared from the different mixes, water cured and tested at the age of 28 and 56 days to obtain the strengths under compression and splitting tension.

3. Results, analysis and discussion

The test cured samples used in the Scanning Electron Microscope (SEM) and the Energy Dispersive X-ray (EDX) analysis were cut directly from crushed cubes at 90 days age and they had a regular shape and flat surface with a cementitious content of 500 kg/m3. They were taken from a control specimen (C) and from a specimen with only 1% nano silica (CN).
A structure that is porous and having the paste with some micro- cracks can be seen in Fig. (1) at low and high magnifications for the control specimen (C). The main constituents of the control paste as obtained by the spectrum of the EDX analysis (Fig. (2)) were CaO (68.26 % weight), SiO2 (16.87 %), Al2O3 (6.27 %), Fe2O3 (3.93 %) and SO3 (4 %) with CaO to SiO2 ratio estimated and found to be 4.05.

Table (1): Proportions of mixes containing different cementitious contents.

Cementitious content, kg/ m^3	Mix symbol	Cement content, kg/m^3	S.F, kg/ m^3	N.S, kg/m^3	Steel fibers, %	C.A/F.A	W/C	Superplasticizer, %
500	C	500	-	-	-	2:1	0.32	1.50%
	CF	500	-	-	2	2:1	0.32	1.50%
	CSN	445	50	5	-	2:1	0.32	1.50%
	CSNF	445	50	5	2	2:1	0.32	1.50%
600	C	600	-	-	-	2:1	0.32	2%
	CF	600	-	-	2	2:1	0.32	2%
	CSN	534	60	6	-	2:1	0.32	2%
	CSNF	534	60	6	2	2:1	0.32	2%
700	C	700	-	-	-	2:1	0.32	2%
	CF	700	-	-	2	2:1	0.32	2%
	CSN	623	70	7	-	2:1	0.32	2%
	CSNF	623	70	7	2	2:1	0.32	2%

A structure with fewer pores and less micro-cracks can be seen in Fig. (3) for a specimen with only 1% nano silica (CN). The main constituents that can be seen in the paste Bulk zone with 1% N.S as given by EDX spectrum (Fig. (4)) were CaO (18.37 % weight), SiO2 (76.62 %), Al2O3 (1.43 %), Fe2O3 (2.53 %) and SO3 (1.04 %) with CaO to SiO2 ratio estimated and found to be 0.24. This agrees with the pozzolanic reaction that happened between the nano silica and the calcium hydroxide.

The effect of adding 2% steel fibers by volume of concrete together with 1% NS and 10% micro silica as partially replacing cement by weight on the mechanical behavior of HSC is presented here for mixes of 500, 600 and 700 kg/m3 cementitious contents and a comparison was made with the results of the respective control mixes without steel fibers nor nano and micro silica.

3.1 The effect of adding silica fume, nano-silica and steel fiber on the compressive strength of HSC

Table (2) and Fig. (5) presents the 28 days compressive strength results for test specimens containing 2% steel fibers (CF), specimens containing 1% NS and 10% SF (CSN), and specimens containing both 2% steel fibers and 1% NS and 10% SF (CSNF) in addition to the control concrete test specimens without the three additions (C). From the data shown it can be noticed that adding 2% steel fibers to concrete increased the compressive strength of test specimens at 28 days by 16%, 5% and 9% for 500, 600, and 700 kg/m3 cement contents, respectively. That can be related to the effect of steel fibers in controlling and bridging cracks and in resisting the shear stresses resulting in failure of concrete specimens under compression. Results also show that the compressive strength of the test specimens having both steel fibers and nano and micro silica are more or less the summation of the compressive strengths of both specimens containing steel fibers and specimens containing both nano and micro silica. Values of 89.7 MPa, 98.8 MPa, and 106 MPa were obtained from specimens containing the three additions at 500, 600, and 700 kg/m3 cementitious contents, respectively. These values gave 45%, 36%, and 39% increases in the compressive strength in comparison to the values of the respective control concrete mixes at 500, 600, and 700 kg/m3 cementitious contents, respectively.

Table (2) and Fig. (6) give the values of the 56 days compressive strength for the same group of test specimens. It can be seen that the results are similar in trend to those obtained at 28 days. Yet, the strength gain obtained at 56 days in compression compared to that of the 28 days was little in case of test specimens containing steel fibers similar to the control specimens, while it was higher for specimens having micro and nano silica and thus for specimens containing both steel fibers and micro and nano silica. Values of the compressive strength of 100.9 MPa, 105 MPa, and 108.5MPa were obtained from specimens containing the three additions at 500, 600, and 700 kg/m^3 cementitious contents, respectively, which were actually the maximum compressive strength values obtained in this study. These values gave 54%, 40%, and 40% increases in the compressive strength in comparison to the values of the respective control concrete mixes at 500, 600, and 700 kg/m^3 cementitious contents, respectively.

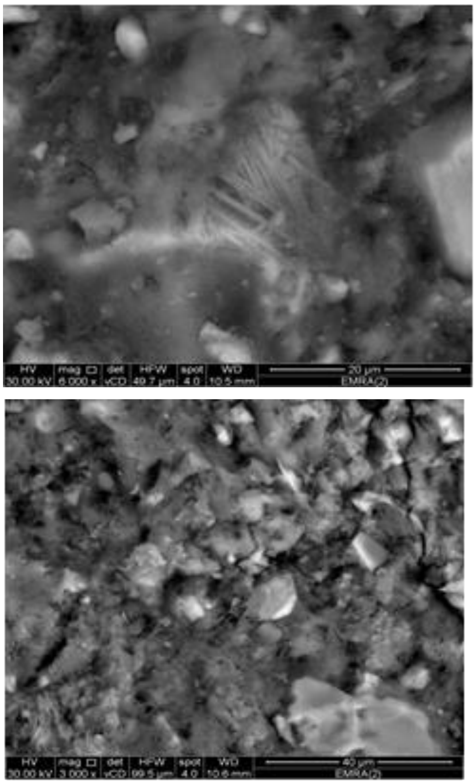
Fig. (1): SEM micrograph images for the control specimen (C).

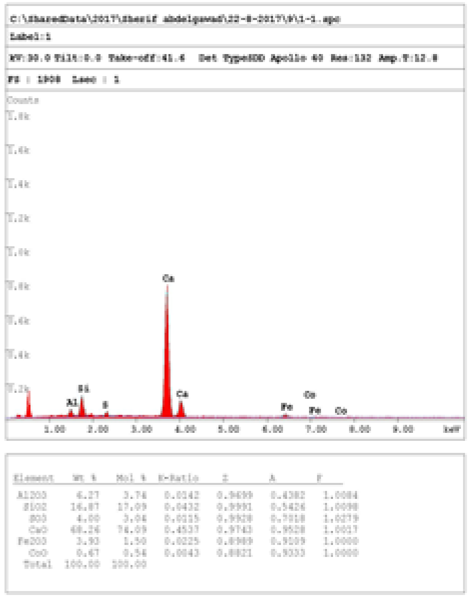

Fig. (2): EDX spectrum for the control specimen (C).

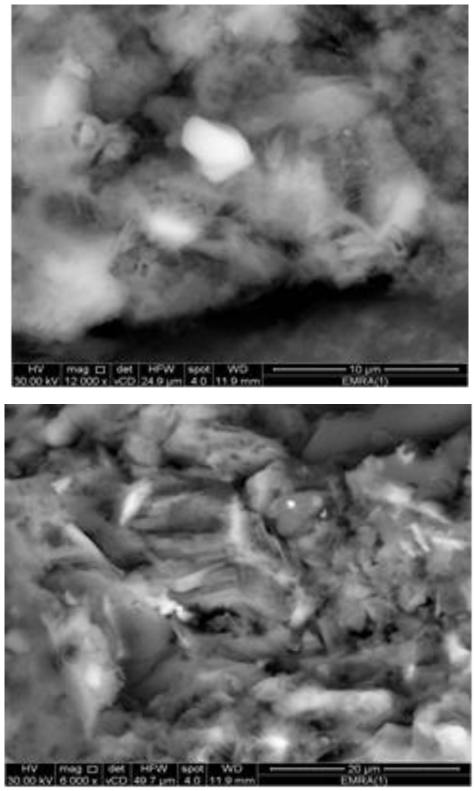
Fig. (3): SEM images for the 1% nano silica hardened cement paste (CN).

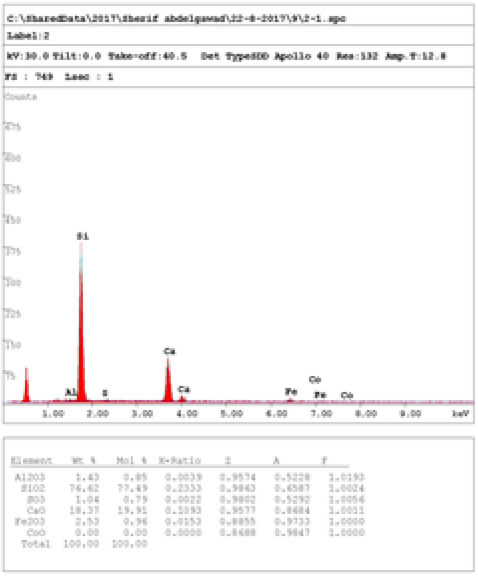

Fig. (4): EDX spectrum for the hardened cement paste having 1% nano silica (CN).

Table (2): Test results of the compressive strength for concrete mixes containing micro silica, nano silica and steel fibers

Mix symbol	500 kg/m³ C.C			
	at 28 th day		at 56 th day	
	σ_c, MPa	Relative	σ_c, MPa	Relative
C	61.8	100%	65.5	100%
CF	72.3	116%	75.5	115%
CSN	80.5	130%	93.2	142%
CSNF	89.7	145%	100.9	154%
Mix symbol	**600 kg/m³ C.C**			
	at 28 th day		**at 56 th day**	
	σ_c, MPa	**Relative**	**σ_c, MPa**	**Relative**
C	72.6	100%	74.7	100%
CF	75.6	105%	77.6	105%
CSN	84.4	117%	95.6	127%
CSNF	98.9	136%	105	140%
Mix symbol	**700 kg/m³ C.C**			
	at 28 th day		**at 56 th day**	
	σ_c, MPa	**Relative**	**σ_c, MPa**	**Relative**
C	75.8	100%	77.2	100%
CF	82.6	109%	84.3	109%
CSN	93.9	123%	96.2	124%
CSNF	106	139%	108.5	140%

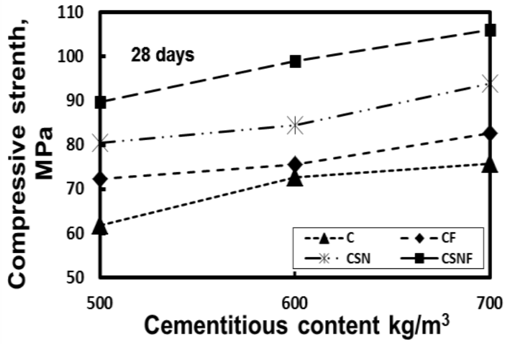

Fig. (5): 28-day compressive strength vs. cementitious content for the different mixes of concrete.

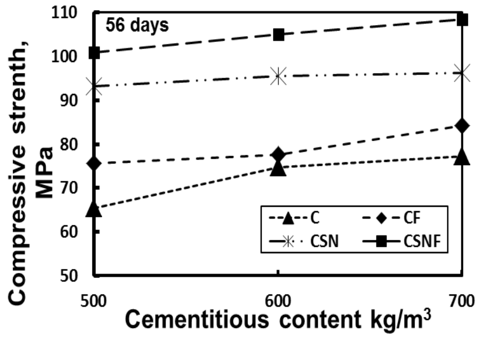

Fig. (6): 56 day compressive strength vs. cementitious content for the different mixes of concrete.

3.2 The Effect of adding silica fume, nano-silica and steel fiber on the splitting tensile strength of HSC

The test results of the splitting tensile strength of concrete, σ_{st}, at 28 and 56 days are shown in Table (3) for 500, 600, and 700 kg/m^3 cementitious contents for the same mixes containing 2% steel fibers (CF), combined 1% NS and 10% micro SF (CSN), and both 2% steel fibers and combined 1% NS and 10% SF together (CSNF) in addition to the control reference mix without these additions (C). Fig. (7) gives the splitting tensile strength results at 28 days. It is clear that adding 2% steel fibers by volume of concrete increased the concrete splitting tensile strength by about 18%, 21%, and 26% as compared to the reference mixes at 500, 600, and 700 kg/m^3 cementitious contents, respectively. This contribution of the steel fibers in increasing the splitting tensile strength of the test specimens is higher than their contribution in increasing the specimens compressive strength, which was 16%, 5%, and 9% at 500, 600, and 700 kg/m^3 cementitious contents, respectively, as was mentioned in the previous section.

One further notice and unlike the results of the compressive strength of similar specimens, the splitting tensile strength increase as a result of adding 2% steel fibers was more than that obtained due to the presence of combined 1% NS and 10% micro silica. This shows the effectiveness of steel fibers in increasing the tensile strength of concrete, which can be related to their ability to control and bridge the cracks. It is even more interesting that test specimens containing both 2% steel fibers and combined 1% NS and 10% micro silica gave splitting tensile strength values at 500, 600, and 700 kg/m3 cementitious contents even higher than the summation of strength result values of each of the 2% steel fibers mix and the 1% NS and 10% micro silica mix separately. Therefore, it can be concluded that the contribution of steel fibers in increasing the splitting tensile strength increased with the increase in the concrete mix strength. Fig. (8) presents the results of the splitting tensile strength at 56 days for the same mixes. It can be concluded that similar results in trend were obtained here at 56 days as those obtained at 28 days. Splitting tensile strengths of 10.3, 11.9, and 12.2 MPa could be obtained at cementitious contents of 500, 600, and 700 kg/m^3, respectively, which were about 172, 188 and 180% of the strength values of the respective cement control mix. It is worth to mention here that Lin et al. [13] found that adding of steel fibers to silica fume (SF) composites increased significantly the tensile strength, toughness and impact resistance, while the compressive strength and abrasion resistance improved slightly.

Table (3): Splitting tensile strength test results for concrete mixes containing micro silica, nano silica and steel fibers

Mix symbol	500 kg/m^3 C.C			
	at 28th day		at 56th day	
	σ_{st}, MPa	Relative	σ_{st}, MPa	Relative
C	5.7	100%	6	100%
CF	6.7	118%	7.4	124%
CSN	6.4	112%	7.3	121%
CSNF	8.9	155%	10.3	172%
Mix symbol	600 kg/m^3 C.C			
	at 28 th day		at 56 th day	
	σ_{st}, MPa	Relative	σ_{st}, MPa	Relative
C	6.2	100%	6.3	100%
CF	7.5	121%	8.5	135%
CSN	6.8	110%	7.2	114%
CSNF	10.5	170%	11.9	188%
Mix symbol	700 kg/m^3 C.C			
	at 28th day		at 56th day	
	σ_{st}, MPa	Relative	σ_{st}, MPa	Relative
C	6.6	100%	6.7	100%
CF	8.3	126%	9.0	134%
CSN	7.3	107%	7.5	111%
CSNF	11.3	170%	12.2	180%

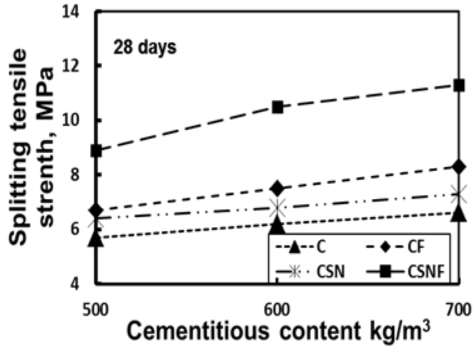

Fig. (7): 28 day splitting tensile strength vs. cementitious content for the concrete mixes.

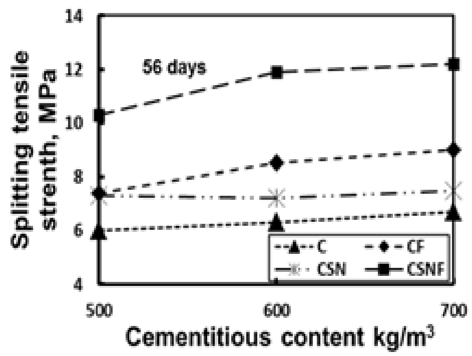

Fig. (8): 56 day splitting tensile strength vs. cementitious content for the concrete mixes.

3.3 Ratio between compressive strength and splitting tensile strength

The relation between tensile strength and compressive strength in terms of the ratio between them, σ_{st}/σ_c, for the different mixes was calculated and given in Table (4). Figs. (9) and (10) show this ratio vs. the cementitious content for the different mixes at 28 and 56 days, respectively. Many researchers reported that the ratio σ_{st}/σ_c decreased with the increase in the cement content at 28 days [16, 17]. Unlike other concrete mixes, the concrete mix containing 2% steel fibers and also the concrete mix containing 2% steel fibers together with the nano

and micro silica showed an increase in the σ_{st}/σ_c ratio with the increase in the cementitious content

Table (4): Results of σst/σc of concrete mixes containing steel fibers, nano and micro silica.

Mix symbol	C.C of 500 kg/ m^3		C.C of 600 kg/ m^3		C.C of 700 kg/ m^3	
	at 28th day	at 56th day	at 28 th day	at 56 th day	at 28 th day	at 56 th day
C	0.092	0.092	0.085	0.084	0.087	0.087
CF	0.093	0.098	0.099	0.110	0.100	0.107
CSN	0.080	0.078	0.081	0.075	0.078	0.078
CSNF	0.099	0.102	0.106	0.113	0.107	0.112

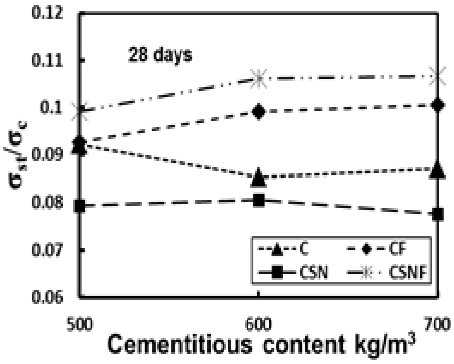

Fig. (9): σst/σc vs. cementitious content, C.C, for the concrete mixes at 28 days

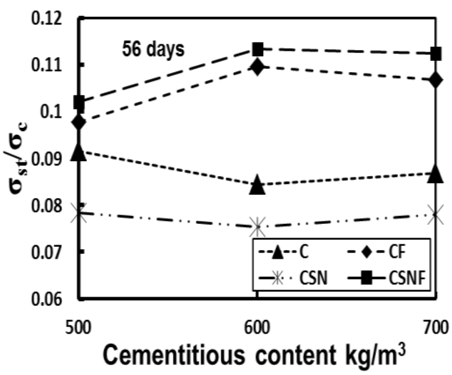

Fig. (10): σst/σc vs. cementitious content, C.C, for the concrete mixes at 56 days.

from 500 to 700 kg/m^3 and also as the test age of concrete increased from 28 to 56 days. It is clear that this is related to the effectiveness of steel fiber in increasing the concrete tensile strength as was explained earlier.

3.4 Failure mode of test specimens

Photo (1) show the mode of failure of a concrete specimen containing 2% steel fibers and both nano and micro, where steel fibers can be seen crossing the boundaries of the failure surface. Considering the mode of failure under the splitting tensile strength test, cylindrical specimens showed the traditional splitting into two portions mode of failure along the length of the cylinder due to the indirect tensile stresses with also steel fibers seen crossing the boundaries of the failure surface (photo (2)).

Photo (1): Failure mode for a concrete specimen of 2 % steel fibers with nano and micro silica under the compression test

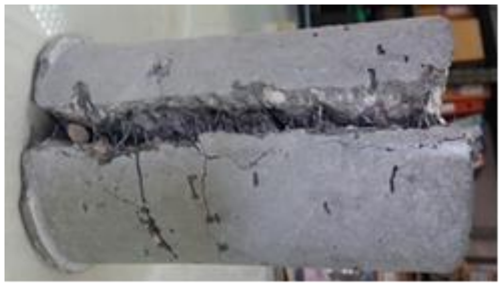

Photo (2): mode of failure for a concrete specimen of 2 % steel fibers with nano and micro silica under the splitting tensile strength test.

4. Conclusions

The following conclusions can be drawn within the scope of this study:

1. Adding 2% steel fibers increased the compressive strength of the concrete mixes at 28 days by 16%, 5%, and 9% as compared to the reference mixes of 500, 600, and 700 kg/m^3 cement contents, respectively.
2. The contribution of steel fibers in increasing the concrete splitting tensile strength was even higher than their contribution in increasing their compressive strength and

this can be related to their ability to control and bridge these cracks.

3. Adding 2% steel fibers increased the concrete splitting tensile strength at 28 days by 18%, 21%, and 26% as compared to the reference mixes with 500, 600, and 700 kg/m^3 cement contents, respectively.
4. Adding 2% steel fibers resulted in a gain in concrete compressive and splitting tensile strengths at 56 days similar to that of the control concrete mix when comparing to the strengths at 28 days.
5. Unlike the results of the compressive strength of similar specimens, the splitting tensile strength increase as a result of adding 2% steel fibers was more than that obtained due to the presence of combined 1% NS and 10% micro silica.
6. Concrete mixes containing 1% NS, 10% micro silica, and 2% steel fibers gave the highest compressive and splitting tensile strengths obtained at 500, 600, and 700 kg/m^3 cementitious contents.
7. Concrete mixes containing 1% NS, 10% SF, and 2% steel fibers gave 100.9, 105, and 108 MPa compressive strengths and 10.3, 11.9, and 12.2 MPa splitting tensile strengths at 56 days at 500, 600, and 700 kg/m^3 cementitious contents, respectively.

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