EFFECT OF NANO SILICA ON CONCRETE BOND STRENGTH MODES OF FAILURE

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ABSTRACT: Steel bars are required in order to provide the concrete with the tensile strength that is needed in structural concrete. Bond means the interaction between reinforcing steel and the surrounding concrete, which allows transferring of tensile stress from the steel into the concrete and vice versa. The best ways to enhance the concrete bond strength are by improving the ITZ between aggregates and the mortar between aggregates and the steel re-bars. Recently, those ways were achieved by using pozzolanic materials. The presented research aims to study the effect of adding nano silica (up to 4.5%) on the concrete-steel bond modes of failure. The results revealed that by the addition of 3% nano silica as partial replacement of cement (wt.%), the compressive, splitting tensile, splitting bond and pull out bond strengths increased by 43.5, 12, 16 and 38.5% respectively as compared to normal concrete. It was also concluded that Nano silica enhanced the bond strength for both modes of failure, Pullout and splitting, due to the improvement in the mechanical properties.

Keywords: Nano silica; Bond strength; Pullout; Splitting tensile; Microstructural analysis.

1. INTRODUCTION

Bond is the interaction between reinforcing steel and the surrounding concrete, that allows the tensile stress to transfer from the steel into the concrete and vice versa. It is the mechanism that allows the anchorage of reinforcing bars and influences many other important features of structural concrete such as section stiffness and crack control [1]. Similarly the bond between development length of reinforcing steel and concrete is essential for composite action in reinforced concrete construction [2,3]. It is known that the use of deformed bars can greatly enhance the concrete-steel bond strength. There are three main components that determine the bond strength between the adjacent ribs of a reinforcement bar. These components are the bearing stresses against the faces of ribs (mechanical interlock), shear stresses due to adhesion along the bar surface and the friction between bars with concrete in the rib dales and the surrounding concrete. It can be said that the highest contribution to bond strength comes from mechanical interlock [4]. Adequate bond between reinforcing bars and concrete is essential for the required performance of reinforced concrete structures. Torre-Casanova et al. showed [5] that the pullout and splitting failures depend on the concrete cover (for low concrete covers splitting failure occurs while pull-out failure for others cases). Concrete bond strength can be enhanced by different ways like by improving the ITZ between aggregates and the mortar between aggregates and the steel re-bars. Recently, those ways were achieved by the use of pozzolanic materials such as silica fume and fly ash as cementituios materials [5,6]. Nowadays, nanotechnology is one of the most active research areas that encompass a number of disciplines including civil engineering and construction materials. It has attracted scientific interest due to the new uses of particles in nanometer scale. Nano materials are important with cement to react with the excess CH in order to produce additional C-S-H which has the ability to enhance mechanical properties of concrete, refine the pore structure to densify the cement matrix reinforcement steel bar. Among these materials, nano silica is one of the most important pozzolanic materials that attract the scientists' attention. Although a lot of studies have been made to investigate the influence of nano silica on different properties of cement composites (compressive, tensile and flexural strengths), some properties haven't been studied well enough like bond strength of nano silica concrete. The aim of the current research program is to investigate the effect of adding nano silica on concrete bond strength using different re-bars diameters, in addition, the compressive and tensile strengths of nano silica concrete will be examined. Scanning electron microscopy will be introduced to help interpreting the behavior of nano silica concrete.

2. EXPERIMENTAL PROGRAM

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement Type I was used. The grade used was CEM I 52.5 N. The chemical analysis and physical properties of cement are listed in Table 1.

2.1.2. Nano silica

The used commercial nano silica has particles of average size of 20 to 80 nm. (Fig. 1 and 2) show the TEM and XRD of nano silica respectively while the chemical analysis and physical properties of nano silica are listed in Table1. From the X-ray diffraction patterns of silica nano-particles it is clear that the silica is observed at a peak centered at 2 Theta $(\Theta) = 23$ °, which reveals the amorphous nature of the silica nanoparticles.

2.1.3. Fine aggregate

Natural available clean sand with particles size smaller than 0.5 mm and specific gravity of 2.58g/cm3 and fineness modulus of 2.25 was used as fine aggregate.

2.1.4. Coarse aggregate

Clean Crushed dolomite of maximum size of 12 mm and specific gravity of 2.96g/cm3 was used as coarse aggregate.

2.1.5. Mixed aggregate

The aggregates for the mixtures consist of a combination of crushed dolomite and fine sand with percentage of 65% and 35% by weight respectively. .

2.1.6. Superplasticizer

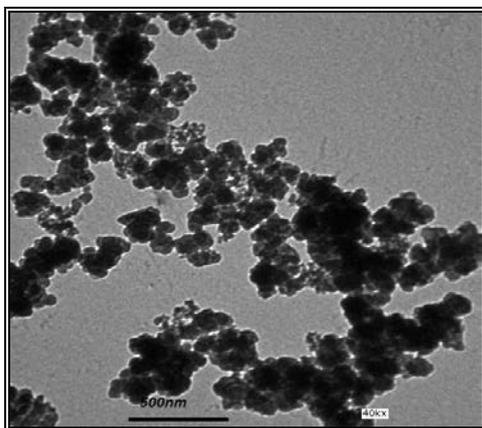The used polycarboxylate has a polyethylene condensate defoamed based admixture (Glenium C315 SCC).

Fig.1: TEM of nano silica particles

2.2. Methods

2.2.1. Test mixes

The experimental works are divided into four parts. The first part investigated the effect of using 1%, 3% and 4.5% (by wt.) nano silica as partial replacement of cement on the compressive strength of concrete while the second and third parts investigated the tensile and bond strengths of nano silica concrete using the same percentages of

nano silica, respectively. The final part presented micro structure analysis of the mixes through SEM. The Used mixes and its components are given in Table 3
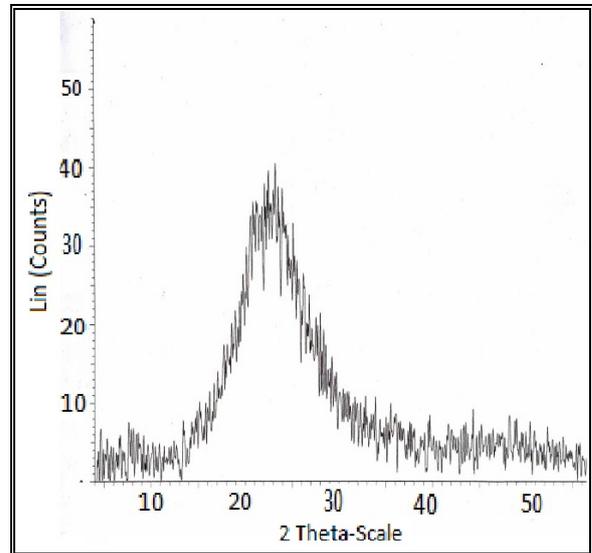

Fig.2: XRD of nano silica particles

Table 1

Element	Cement (wt. %)	Nano silica (wt.%)
SiO_2	20.13	99.17
Al_2O_3	5.32	0.13
Fe_2O_3	3.61	0.06
CaO	61.63	0.14
MgO	2.39	0.11
SO_3	2.87	---
Na_2O	0.37	0.4
K_2O	0.13	---
L.O.I	1.96	---
P_2O_5	---	0.01

Chemical composition of cement and Nano Silica

Table 2

Mix	Cement	Agg.	W	S.P.	N.S.	Slump cm
0	450	1706	192	2.7	0	21
1	443.25	1706	192	2.7	6.75	16
3	436.5	1706	192	2.7	13.5	8
4	429.75	1706	192	2.7	20.25	5.5

Mixes components (kg) per 1 m3

2.2.2. Mixing procedure

The mixtures were prepared with different nano silica replacement ratios of 1.5%, 3% and 4.5% by weight of cement in the mix. For helping in the dispersion of nano silica particles (to decrease the effect of nano silica agglomerations), indirect sonication using bath sonicator was applied. A modern ultra-sonication bath was used in nano silica dispersion with different times according to nano silica percentage, 9 mins for 1.5% ,12 mins for 3% and 15 mins for 4.5%. The water to cement ratio for all mixtures was 0.43. The aggregates which were used in the mixtures consist of a combination of crushed dolomite and fine sand, with sand percentage of 35% by weight.

2.2.3. Specimens preparation

A. Compressive strength

Cubes of (100 mm*100 mm*100mm) were cast for 7 and 28 days compressive strength test as per ASTM C 39. The test was carried out with rate of 0.5 N/mm2/sec using the universal testing machine SHIMADZU 1000 KN.

B. Splitting Tensile strength

Cylinders of 100mm diameter and 200 mm in height were cast for 7 and 28 days tensile strength test. The test was carried out with rate of 0.25 N/mm2/sec using the universal testing machine SHIMADZU 1000 KN.

C. Bond strength test

Cubes of (150 mm*150 mm*150mm) were cast for bond strength test of steel re-bars of 12 and 16 mm. Half of the length of the embedded part of the bar was de-bonded using polyvinyl chloride tubing to avoid yielding of steel reinforcement. It is recommended to cast the bars into concrete cubes providing a clear cover of 4.5 times bar diameter from the bar to the center of each side of the horizontal cross section to grantee the pull out behavior [7]. The mentioned condition was achieved using 12 mm re-bars unlike 16 mm re-bars to investigate the effect of nano silica on bond strength modes of failure. Figure 3 contains details of the pullout test specimens using 12 mm re-bars.

D. Scanning electron microscope (SEM)

Scanning electron microscope (SEM) was used for characterizing the concrete mixtures and investigating the effect of nano silica on concrete matrix and chemical reactions. In addition, it was also helpful in interpreting the results of the samples. The images were taken from samples after 28 days of curing using Quanta FEG 250 (FEI, USA) with Image processor Up to 4096 x 3536 pixels (~14 MP).
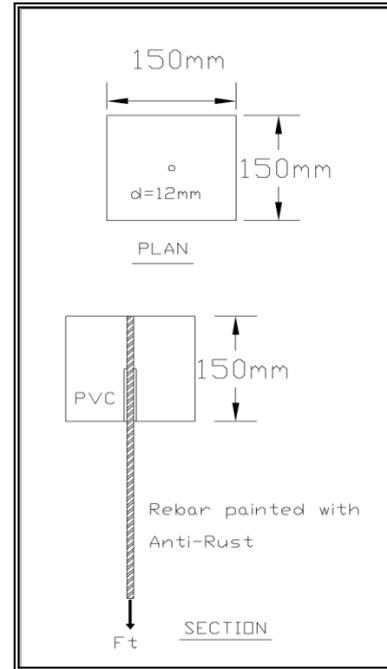

Fig.3: Pull out test specimens' details

3. RESULTS AND DISCUSSION

3.1. Compressive strength

As it can be seen from Figures (4 and 5), adding nano silica increased slightly the 7 days compressive strength reaching 385 kg/cm^2 by the addition of 4.5 % nano silica instead of 340 kg/cm^2 for the control mix (containing 0% nano silica). The gain in the early age compressive strength reached (3, 4.5, and 13.5%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. The slight increase in the early age compressive strength indicates the presence of relatively large number of small size agglomerates in the nano silica mixes. Such agglomerates need longer time to react with the excess CH to form additional C-S-H gel which is the main factor affecting the compressive strength increase. Despite its low reactivity in the early age, the agglomerated nano silica particles acted as fillers leading to a decrease in the porosity of the matrix resulting in a relatively better compaction and consequently a higher compressive strength. As for the 28 days results, adding nano silica increased significantly the compressive strength. The strength reached 610 Kg/cm^2 by the addition of 3 % nano silica instead of 426 Kg/cm^2 for the control mix. This can be attributed to the action of nano silica as nuclei for cement phases to promote cement hydration due to its pozzolanic reactivity with CH increasing the production of C-S-H gel that has a significant positive effect on the cohesion between aggregates and the mechanical properties of concrete. Late age compressive strength was improved by

increasing nano silica percentage up to 3% then a decrease in strength was observed by the addition of 4.5% nano silica. The gain in 28 days compressive strength reached (17.5, 43.5, and 29%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. It is worth noting here that the (4.5%) mix is still higher in strength than the control mix. This can be attributed to the fact that the more the number of silica nano particles the higher the capability of these particles to gather around each other in the matrix due to the van der waals force contributing to the agglomeration of nano particles in concrete matrix (without happening of any chemical reaction). Although relatively larger agglomerates need longer time than the 28 days to react with the excess CH resulting from cement hydration process to form C-S-H gel, the present large nano silica agglomerates acted as fillers to the nano pores which mainly were the reason for the observed increase in the compressive strength as compared to the control mix. It was stated that nano-particles can fill a notable part of voids existing in the matrix of cement paste even in agglomerated manner, regarding their ultra-fine dimension.[8] Although at early stages agglomerates can affect the gain in strength significantly, larger and /or agglomerated particles in the mix that had not completely dissolved in solution will lead to the porosity reduction in the pores/capillaries of the CSH gel by packing into some of these voids. The density of the CSH will slightly increase in the plastic form and convert into a denser compressive bearing structure after the hydration process completion by the 28th day [9]. That explains why increasing agglomerated nano silica particles slightly increased early strength, while significantly increased the late strength.

3.2. Tensile Strength of Nano silica Concrete

From figures (6 and 7) it can be seen that tensile strength of nano silica concrete has the same trend of the compressive strength. The 7 days tensile strength value reached 34 Kg/cm2 by the addition of 3 % nano silica instead of 30.5 Kg/cm2 for the control mix. The gain in 7 days tensile strength reached (2, 12, and 6.5%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. While the 28 days tensile strength value reached 41.5 Kg/cm2 by the addition of 3 % nano silica instead of 37 Kg/cm2 for the control mix. The gain in 28 days tensile strength reached (3.5, 12, and 3.5%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. The tensile strength improved by increasing nano silica percentage up to 3% then decrease in strength was observed by the addition of 4.5% nano silica. This can be attributed to that tensile strength of nano silica concrete has two

main behaviors: the first one occurs when the nano silica particles are well dispersed which lead to more dense and homogenous C-S-H gel, better interfacial transition zone (ITZ) between aggregates and cement paste. While the second behavior occurs when the nano silica particles are agglomerated and cannot easily disperse within the matrix, and due to their high surface energy, they become more agglomerated during mixing process and a weak area of empty spaces such as voids appears. Consequently, the structure formed in such conditions cannot be compacted or homogenous [7]. It was found that C-S-H gels from pozzolanic reaction of the agglomerates cannot function as binder and there even existed ITZ between the large reacted agglomerates and the bulk paste. [10].
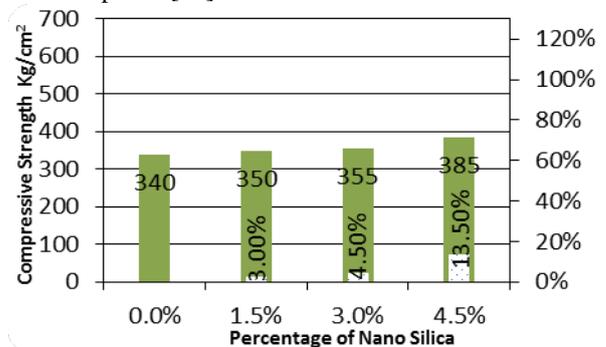
Fig.4: 7 days compressive strength the gain in strength as compared to control mix.
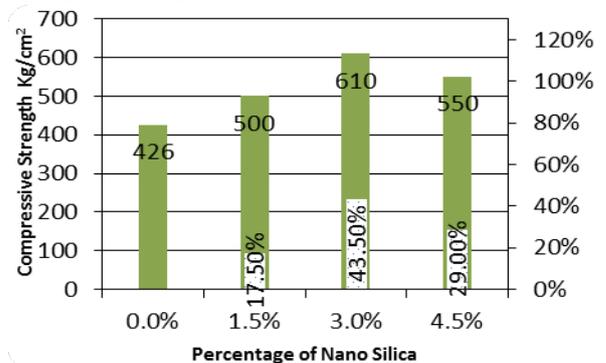
Fig.5: 28 days compressive strength and the gain in strength as compared to control mix.
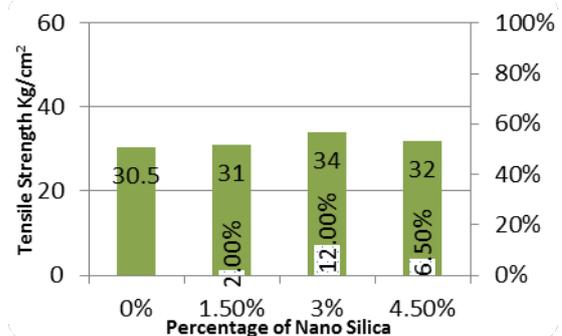
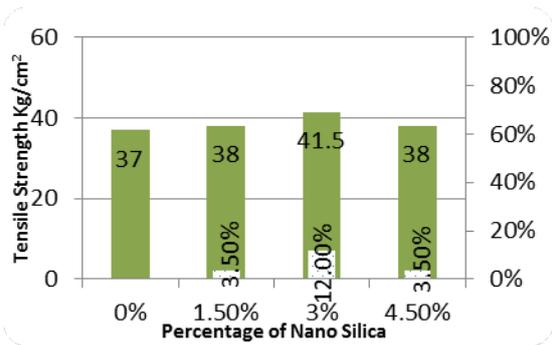Fig.6: 7 days tensile strength and the gain in strength as compared to control mix.

Fig.7: 28 days tensile strength and the gain in strength as compared to control mix.

3.3. Bond Strength of Nano Silica Concrete

Bond strength of concrete has two main behaviors pullout and splitting. When the steel re-bars subjected to tension forces the Lugs on the steel bars affect concrete with two-way stresses, radial and longitudinal. If the longitudinal stresses are very high, concrete will be crushed and the behavior of pullout will be the dominant behavior. On the other hand, if the radial stresses are higher than concrete tensile strength, this may be due to the absence of enough cover (weak confinement); the behavior of splitting will be the dominant behavior.

3.3.1. 12 mm re-bars bond strength

For 12 mm re-bars specimens there was enough cover to guarantee the slippage behavior (figure 8) so the dominant factor to affect the bond strength was the compressive strength. As mentioned before, nano silica significantly enhanced the compressive strength due to production of more C-S-H gel which increases the bond between concrete and reinforcement subsequently it significantly enhanced the bond strength of 12 mm re-bars too. From figure 9 it can be seen that The bond strength value reached 301 Kg/cm2 by the addition of 3 % nano silica instead of 217.5 Kg/cm2 for the control mix (containing 0% nano silica). The gain in bond strength reached (12, 38.5, and 2.5%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. Finally, figure 10 proves that 12 mm re-bars bond strength results have the same trend of compressive strength.

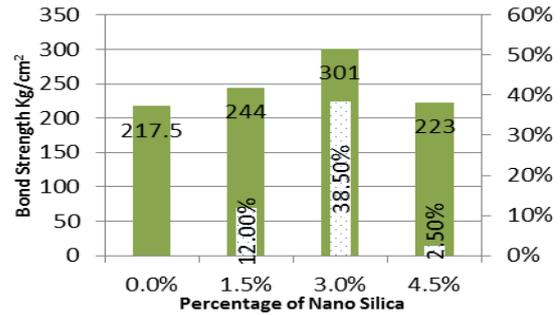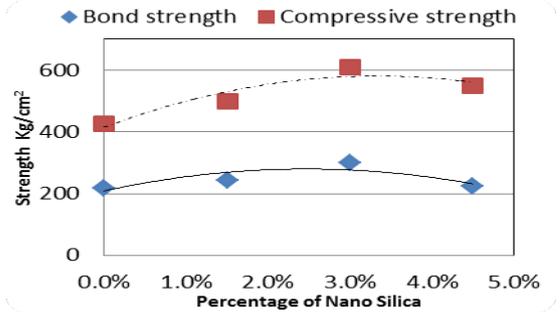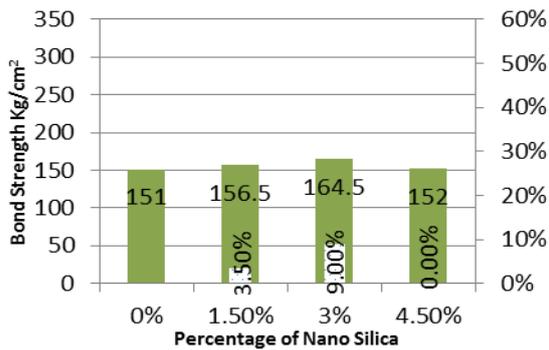Fig.9: Bond strength and gain in bond strength using 12mm re-bars.

3 Fig.10: Relation between 28 days compressive and 12mm re-bars bond strengths.

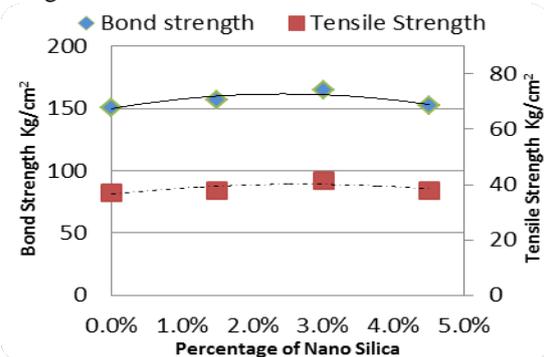#### 3.3.2. 16 mm re-bars bond strength

For 16 mm re-bars specimens there was not enough cover to guarantee the splitting behavior (weak confinement) so the dominant factor to affect the bond strength was the tensile strength. As mentioned before, nano silica slightly improved the tensile strength of concrete subsequently it slightly enhanced the bond strength of 16 mm re-bars too. From figure 12 it can be seen that the bond strength value reached 164.5 Kg/cm2 by the addition of 3 % nano silica instead of 151 Kg/cm2 for the control mix. The gain in bond strength reached (3.5, 9, and 0%) by the addition of (1.5, 3, and 4.5%) nano silica respectively. Finally, figure 13 proves that 16 mm re-bars bond strength results are in a good agreement with the tensile strengthof nano silica concrete. Our results are in a good agreement with Torre-Casanova et al. [5] who proposed equations that distinguish splitting failure (function of the concrete tensile properties) and pull-out failure (function of the compressive concrete properties)

Fig.8: 12 mm re-bars slippage behavior.

Fig.11: 16 mm re-bars splitting behavior.

4   Fig.12: Bond strength and gain in bond strength using 16mm re-bars.

5   Fig.13: Relation between 28 days tensile and 16mm re-bars bond strengths.

3.4. Scanning Electron Microscope (SEM)

Scanning Electron Microscope images were taken to compare between the micro structure of nano silica concrete and normal concrete. In addition, they were also taken to study the effect of using nano silica on the matrix components. The SEM images are shown in Figures (14 to 17)

As for the SEM plates, the morphology structure in control samples, when compared with nano silica systems, is in agreement with the results that were mentioned before.

Calcium silicate hydrate plates as well as calcium hydroxide crystals and Aft needles were clearly identifiable in the control specimen as well as the voided and the porous structure of paste figure 14, While for low percentages nano silica (1.5%, and 3%) specimens, the calcium silicate hydrate plates were clearly dominating with a well compacted structure, as for the high volume nano silica (4.5%), calcium silicate hydrate plates can also be clearly found but with some agglomerated nano silica surrounding the hydration products figures (15, 16 and 17).

As a conclusion nano silica presence contributed to producing higher levels of calcium silicate hydrate [11]. As the nano silica's high reactivity acted as a nucleating point [12] to bind the hydration products together [13]. This phenomenon may explain the high strength and performance of the specimens containing nano

silica. Nano Silica can absorb the calcium hydroxide crystals and reduce the size and amount of the Ca(OH)2 crystals, thus making the interfacial transition zone of aggregates and denser. Nano silica particles can fill the voids of the C–S–H gel structure and act as nucleus to tightly bond with C–S–H gel particles, making binding paste matrix denser, durability and long-term mechanical properties of concrete are expected to be increased. Micrograph of the nano silica concretes, which reached the highest compressive and bond strengths, revealed that these samples have an interfacial transition zone (ITZ) denser than those on the control sample. The interfacial transition zone is denser because nano silica particles can fill the space between cement grains, so they can improve the behavior in two different ways: (i) due to packing effect, and (ii) due to reacting with Ca(OH)2 to form more C‑S‑H.

the observations from the SEM images showed also that the nanoparticles were not only acting as a filler, but also as an activator to promote hydration process and to enhance the cement paste microstructure if the nanoparticles were good and uniformly dispersed. The micrograph also showed that the microstructure of concrete with nano-silica was more homogeneous, uniform and compacted than that of the normal concrete.

The performed SEM examination verified the mechanism discussed in results and nano-silica particles were found to influence the hydration behavior and lead to the differences in the microstructure of the hardened paste. The microstructure of the mixture incorporating nano silica revealed a dense, compact formation of hydration products and a reduced number of Ca(OH)2 crystals.

Through SEM observation, a clear microstructure improvement of the hardened cement paste and the ITZ in concrete by adding nano-silica can be recorded regardless of its agglomerate size. It was revealed that C–S–H gels from pozzolanic reaction of the agglomerates cannot function as binder. The cement hydration gels did not penetrate into the pozzolanic gels nano-silica reduced the porosity of hardened concrete because of the super pozzolanic performance and the production of higher amounts of C–S–H gel. Moreover, the microstructure was considerably enhanced due to the micro and nano-filling effects. Portlandite crystals were reduced in size and quantity as a consequence of the pozzolanic reaction and the growth of crystal control by nano-silica. For 3% nano silica mixes the SEM results showed the best compacted mixes and a higher amount of the C-S-H than those found in the other mixes. This confirms the gain in compressive, tensile and bond strengths that was reported earlier by using 3% nano silica Figure 16.
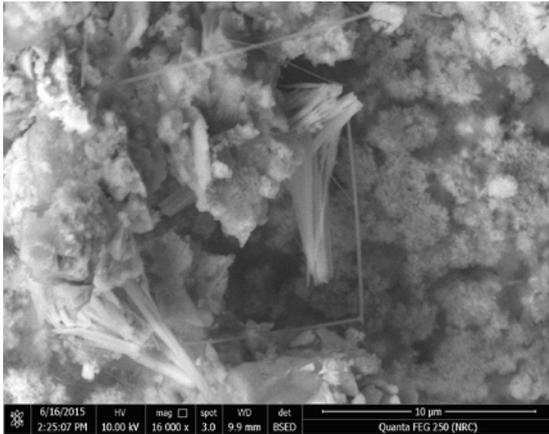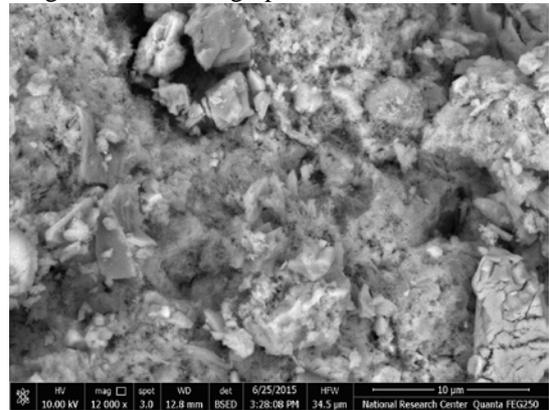
Fig.14: SEM micrograph of 0% W mixes.

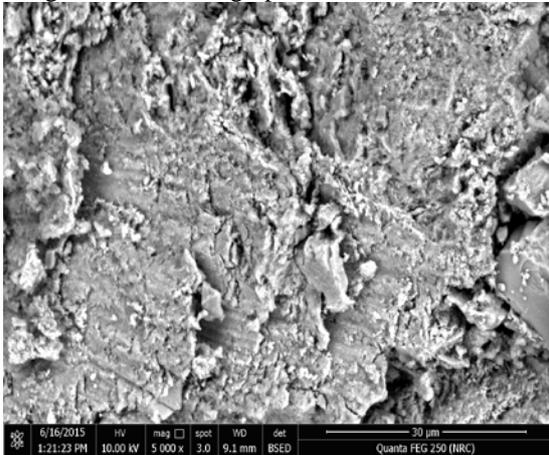Fig.15: SEM micrograph of 1.5% W mixes.
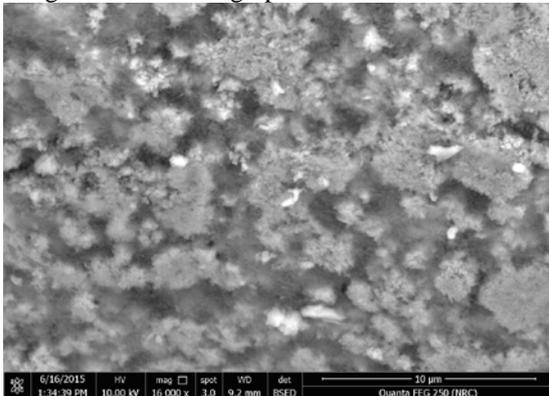

Fig.16: SEM micrograph of 3% W mixes.

Fig.17: SEM micrograph of 4.5% W mixes.

4. CONCLUSION

4.1 Compressive strength

- Generally, adding nano silica increased slightly the 7 days compressive strength of all mixes. The 7 days compressive strength value reached 385 kg/cm2 by the addition of 4.5 % nano silica instead of 340 kg/cm2 for the control mix.

- As for the 28 days results, adding nano silica increased significantly the compressive strength of all mixes. The strength reached 610 Kg/cm2 by the addition of 3 % nano silica instead of 426 Kg/cm2 for the control mix.

- Optimum percentage of nano silica to improve late age compressive strength was 3% with gain equals to 43.5% (610 kg/cm2) as compared with control water mix 0%W (426 kg/cm2).

4.2 Tensile strength

- Generally, early and late age tensile strengths were improved by adding nano silica.

- The optimum percentage of nano to improve early age tensile strength was 3% (34 kg/cm2) with gain equals to 12% as compared with control mix (30.5 kg/cm2).

- The optimum percentage of nano to improve late age tensile strength was 3% (41.5 kg/cm2) with gain equals to 12% as compared with control mix (37 kg/cm2).

4.3 Bond strength

- Nano silica enhanced the bond strength for both modes of failure, Pullout and splitting, due to the improvement in the mechanical properties

- Bond strength of 12 mm re-bars has the same trend of the compressive strength (pull out performance), while bond strength of 16 mm re-bars has the same trend of the splitting tensile strength (Splitting performance).

- The optimum percentage of nano silica to improve bond strength of 12mm bars is 3% (301 kg/cm2). The gain in bond strength reached 38.5% as compared to control mix (217.5 kg/cm2).

- While the optimum percentage of nano silica to improve bond strength of using 16mm re-bars is 3% (gain 9% as compared to control mix)

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