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Investigating the Effect of Nano Clay on Concrete-Rebars Bond Strength Modes

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Abstract— Normal concrete has low tensile strength, so it was supplied with steel rebars in order to improve the tensile strength of the structural concrete. The presence of bond between rebars and the surrounding concrete leads to transfer the tensile stresses from the concrete to the rebars and vice versa. In recent years, it was found that the addition of pozzolanic materials to concrete lead to enhance its bond strength by enhancing the interfacial transition zone (ITZ) between aggregates and cement blends and between aggregates and the rebars, and since there is a growing interest in investigating the effect of nano materials addition on concrete properties, a research plan was prepared to investigate the effect of nano-clay (NC) as a material with pozzolanic reactivity on the concrete bond strength common modes of failure. This was extensively studied by using various percentages of NC (5, 7.5, and 10%) as cement partial replacement after being dispersed in water by using bath sonicator. The results revealed that the optimum percentage for cement substitution by NC was found to be 7.5%. The compressive strength, splitting tensile strength, splitting bond strength and pull out bond strength were enhanced by 51.72%, 28.05%, 18.24%, and 55.05% as compared to those of the control mix. The presence of NC particles enhanced the bond strength for both bond strength modes of failure; Pullout, and splitting as a result of enhancing the compressive strength and splitting tensile strength respectively.

Index Terms— Nano Clay, Sonication, Bond strength, Pullout, Splitting tensile, Microstructural analysis.

1 Introduction

The ordinary concrete has low tensile strength, so it was provided with steel re-bars in order to enhance the tensile strength to be used in structural concrete. The presence of bond between re-bars and the surrounding matrix led to transfer the tensile stresses from the steel re-bars to the concrete and vice versa and performs as a composite material. These tensile stresses are transferred by friction and adhesion between re-bars and surrounding concrete [1], [2].

From previous researches that focused on studying the bond behavior between re-bars and concrete, the factors that have significant effect on bond strength were identified, authors [3]-[8] indicated the influence of the strength of concrete, authors [6] ,[7], [9] indicated the influence of concrete cover, and authors [10,11] indicated the influence of the re-bars geometry. For deformed re-bars, the presence of ribs results increasing the interlock and the bond between the concrete surface and the ribs in the deformed re-bars.

In recent years, it was found that the cement partial replacement by pozzolanic materials such as silica fume and fly ash to concrete enhance its bond strength, where pozzolanic materials react with the residual CH from the cement hydration process and produce extra CSH gels which enhances the interfacial transition zone (ITZ) between aggregates and cement blend, and also enhances the bond between the steel rebar and concrete which in turn, enhances the bond strength [7], [12, [13].

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Nanotechnology is defined as the restructuring of materials to be in Nano size (less than 150nm) to form materials with new properties and functions [14]. Recently, nanotechnology applications have become more widespread in the construction engineering. Nano materials such as nano silica enhance the bond strength due to its pozzolanic reactivity, and also due to its filling effect results in well compacted, dense and uniformly restructured matrix, and consequently enhance the ITZ between rebar and surrounding concrete to perform as a composite material, and protect the steel rebars [7].

Nano-clay (NC) is one of the pozzolanic materials which researchers have focused on investigating its effect on cement mortar and concrete recently. Authors [16]- [23] studied the influence of using NC particles as cement replacement on the mechanical properties of concrete such as; the compressive strength, tensile strength, and flexural strength, but none of the reached research work was studying the effect of NC addition on the bond strength of concrete. On the other hand, there are some studies investigated the bond strength enhancement using other additives such as Nano-silica [7].

The aim of this research plan is to investigate the effect of NC after being dispersed in water by using bath sonicator on the bond strength of concrete by using various re-bars diameters to study the bond strength modes of failure, and determine the optimum NC percentage to improve the bond strength as well as the other common mechanical properties of concrete.

2 Experimental Program

2.1 Material

Ordinary Portland Cement (OPC) used in this research was CEM I (42.5 N) in according to ASTM C150 [24]. Nano-clay (NC) used in this research was an off-white powder. (Table 1)

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shows the chemical composition of used NC and (Figure1) shows the particles size distribution of sonicated nano-clay (SNC) by using Mastersizer 3000 laser diffraction particle size analyzer. The NC specific surface area was found to be 51050m²/kg and with average particle size of 0.13µm. Natural sand is used as fine aggregates with particles size below 0.5mm with specific gravity of 2.58 g/cm³, and fineness modulus of 2.25. Crushed clean dolomite is used as coarse aggregate of maximum size of 12 mm and specific gravity of 2.96 g/cm³. The mixtures aggregates consist of an incorporation of fine sand and crushed dolomite with percentage of 35% and 65% by weight respectively. The super plasticizer used is (Sika Visco Crete 3425), an aqueous solution of modified polycarboxylates.

TABLE 1
THE CHEMICAL COMPOSITION OF USED NC

Element	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	TiO_2	Na_2O	L.O.I
Content%	61.24	1.06	20.89	0.16	0.22	1.61	0.71	13.12

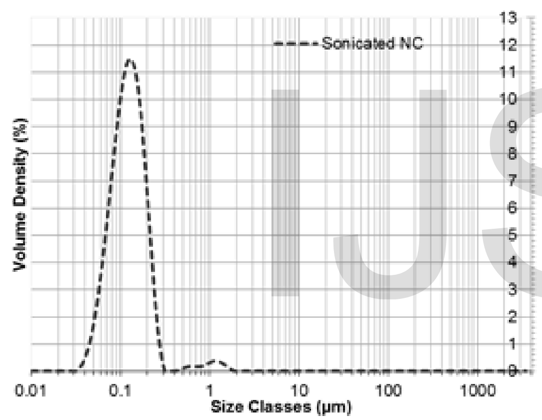

Fig. 1 Particle size distribution of SNC

2.2 Mixture Proportions

The mixtures are prepared with cement substitution by different percentage of NC (0%, 5%, 7.5% and 10%). NC particles are used after being sonicated in equal amount of water using indirect bath sonicator to help dispersing its particles and decrease the formation of agglomerations [25]. A modern ultrasonication bath is used for NC particles dispersion with constant time of 5 min. The mix proportions of NC concrete mixes (kg) per 1 m³ are shown in Table 2.

TABLE 2
MIXES COMPONENTS OF NC CONCRETE MIXES

Mix	Cement	Aggregates	Water	S.P.	SNC
C	450	1706	192	2.7	-
SNC5	427.5	1706	192	2.7	22.5
SNC7.5	416.25	1706	192	2.7	33.75
SNC10	405	1706	192	2.7	45

2.2 Testing

The workability test is executed according to ASTM C143 [26]. Cubes of (100×100×100) mm³ are prepared and casted for implementing compressive strength test after 7 and 28 days according to BS EN 12390-3 [27]. Cylinders of (100 mm diameter and 200 mm in height) are prepared and casted for implementing splitting tensile strength test after 28 days according to ASTM C 496 [28]. Cubes of (150×150×150) mm³ are prepared and casted for implementing the bond strength test after 28 days for steel re-bars of diameter of 12 and 16mm according to RILEM 7-II- 128. In order to investigate the effect of the presence of NC particles on the bond strength modes of failure, a 75mm length of polyvinyl chloride tubing is used to debond the steel bar rooted inside the specimen which makes the bond sliding failure dominates over other types of failure as like yielding of steel reinforcement [29], Figure 2 show a schematic of the pullout test specimen. Finally, two chosen samples of concrete representing the optimum percentage of SNC, and the control mixes were examined after 28 days to study the microstructural analysis by Scanning electron microscope (SEM) test and X-ray Diffraction (XRD) test.

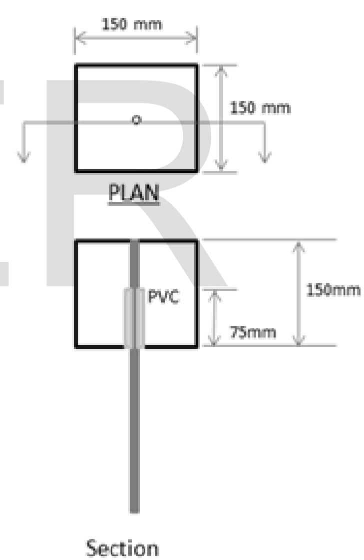

Fig. 2 Schematic of pull out test specimen

3 RESULTS AND DISCUSSION

3.1 Workability

Figure 3 shows the slump of SNC concrete mixes. Generally, increasing the cement substitution percentages by SNC slightly decreased its workability. The higher the cement substitution percentage, the lower the slump reading.

The lowest slump reading reached 19cm for 10% cement substitution by SNC rather than 23cm slump of the control mix (without NC).

The slight decrease in workability with SNC concrete mixes can be attributed to the influence of the ultra-sonication in breaking down the agglomerates into singly dispersed parti-

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cles or smaller agglomerates and even primary particles. Ultra-fine particles act as filler to the nano pores in the matrix, while the existence of relatively small agglomerates of NC particles retains a smaller portion of the mixing water. In addition, NC properties show high absorption of water molecules which lead to increase the water demand, and consequently, make the mixes drier than the control mix [21].

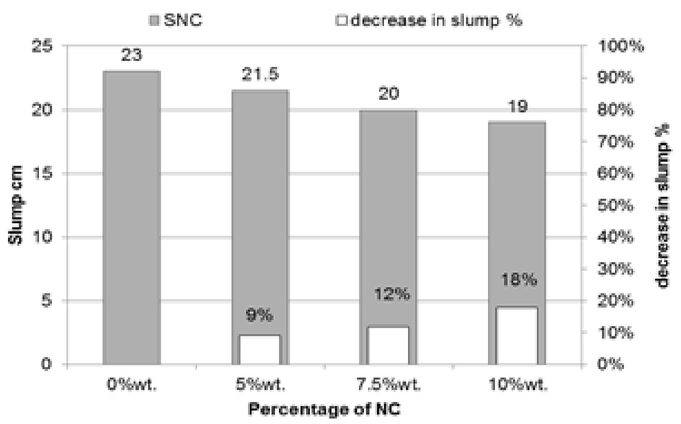

Fig.3. Slump of SNC concrete mixes.

3.2 Compressive Strength

Figures (4 and 5) show the compressive strength results of SNC concrete mixes. Generally, the cement substitution by SNC enhanced the early (7days), and late (28days) ages compressive strength for all concrete mixes.

The highest compressive strength at 7 days reached 41.2MPa for 7.5% cement substitution by SNC rather than 26.5MPa for the control mix, as for at 28 days, the highest compressive strength reached 57.2MPa rather than 37.7MPa for the control mix, the enhancements of compressive strength were 55.47% and 51.72% at 7 days and 28 days respectively as compared to the control mix.

The compressive strength at the early, and the late ages were enhanced with increasing the cement substitution percentages by SNC up to 7.5%, and then, it was decreased with the use of 10% NC substitution, Noteworthy that the 10% NC substitution was still higher than the control mix. This can be explained by the fact of van der Waals force where the greater the number of NC particles added, the greater their ability to assemble around each other and form agglomerations without any chemical interactions in the concrete mixes. These agglomerations form non-hydrated spots which weaken the bond between the cement and aggregates, and therefore, reduce the compressive strength of concrete [21], [22], [30].

For the cement substitution by (5% and 7.5%) SNC, the compressive strength enhanced significantly at the early age as compared to that of the control mix. This can be attributed to; 1) the filling effect of NC particles due to its nano size which fills the existing pores in concrete matrix and makes the matrix be well compacted, denser and uniformly restructured [21], [22], [31], [33]. 2) The high pozzolanic reactivity of NC particles which reacts with excess CH forming extra C-S-H gel which enhance the ITZ between aggregates and cement blends resulting in enhancing strengths [7], [17], [18], [28], [34]. The NC pozzolanic reactivity will affect the bond strength by reducing the existence of CH particles by two means; when CH contacted to water, the CH will dissolve, and results in increasing the porosity of concrete and make it much vulnerable to chemical attacks, and when water containing dissolved sulfate penetrates the concrete, CH reacts with Sulfate ions and form late ettringite needles and thus, the cracks will occur in concrete. 3) NC particles act as a nucleus for cement hydration gels which leads to the formation reinforced C-S-H [20], [21], [22], [35].

The enhancement ratio of 7days compressive strength to 28 days for cement substitution by (5% and 7.5%) SNC indicates the good dispersion of NC particles at small concentrations which lead to enhance the efficiency of NC particles to act as fillers to the nano pores of the matrix, and higher its pozzolanic reactivity.

For 10% cement substitution by SNC, the slight enhancement of 28 days compressive strength was thought to be due to the high particle concentration at using a steady volume of water which results in increasing the inter-particles collision. Whenever NC particles collide, they merge together and increase the formation of NC agglomerations. These agglomerations had low reactivity and needed a longer time than 28 days to complete the pozzolanic reaction and react with the excess CH to form an extra C-S-H gel and to enhance the concrete strength [21]. While, these agglomerates can still fill part of the pores in the matrix and result in much compacted matrix.

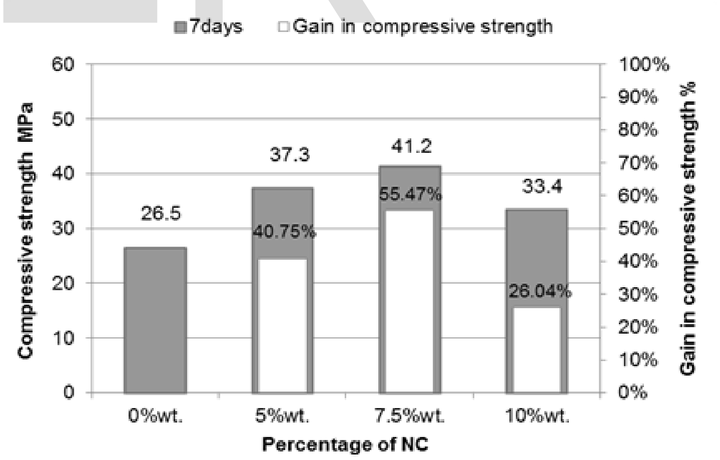

Fig.4. Compressive strength of SNC concrete mixes at 7days and the gains in compressive strength as compared to the control mix.

3.3 Splitting Tensile Strength

Figure 6 show the splitting tensile strength results of SNC concrete mixes. Generally, the cement substitution by SNC enhanced the late age (28 days) splitting tensile strength for all concrete mixes. The splitting tensile strength results showed the same trend as the results of the compressive strength.

The highest splitting tensile strength reached 4.2MPa for 7.5%

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cement substitution by SNC rather than 3.28MPa the control mix, the enhancement of splitting tensile strength was 28% as compared to the control mix.

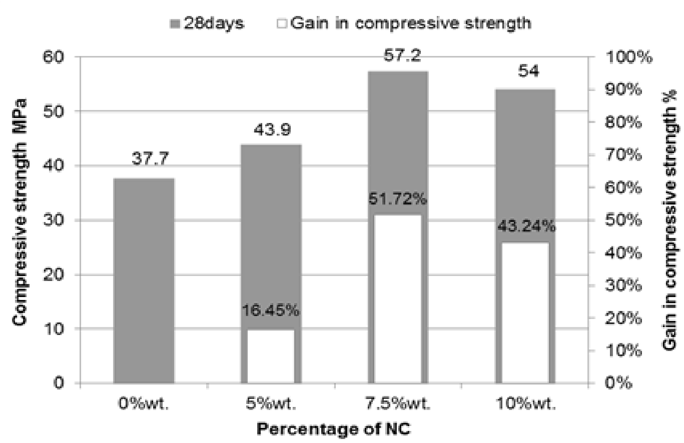

Fig.5. Compressive strength of SNC concrete mixes at 28days and the gains in compressive strength as compared to the control mix.

The splitting tensile strength enhancement for cement substitution by NC particles can be attributed directly to Needle action system of NC particles due to the shape of NC particles which are flaky, elongated, thin, and platy [22]. When tensile cracks occur in the matrix, NC platelets may inhibit and limit the propagation of the tensile micro-cracks [22], [36]. Besides the filling effect, the high pozzolanic reactivity, and nucleation effect of NC particles which enhance the compressive strength, and consequently, enhance the tensile strength of concrete.
The splitting tensile strength at 28 days was enhanced with increasing the cement substitution percentages by SNC up to 7.5%. After that, it was decreased with 10% SNC substitution, Noteworthy that the 10% SNC substitution was still higher than the control mix.

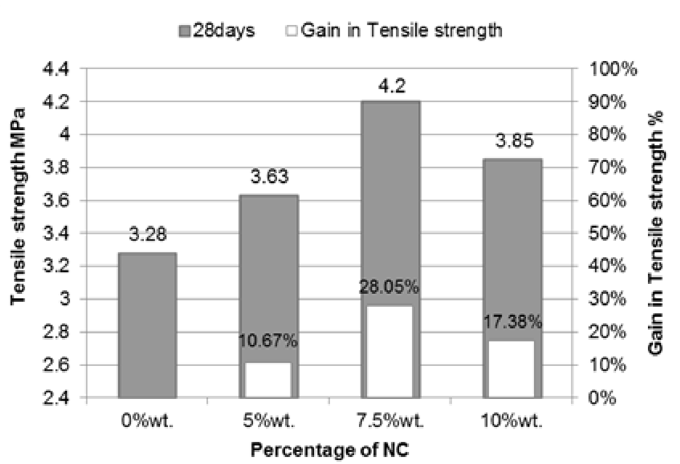

Fig.6. Tensile strength of SNC concrete mixes and the gains in tensile strength as compared to the control mix.

3.4 Bond Strength

According to RILEM 7-II- 128, Concrete cover affects whichever behavior of the bond strength will prevail. If there is enough concrete cover around the bar (more than 4.5 the rebar diameter), the pull out behavior will occur. While in the absence of enough concrete cover (less than 4.5 the rebar diameter), the splitting behaviour will occur [29].

Although adhesion and friction are present when a deformed bar is loaded for the first time, these bond-transfer mechanisms are quickly lost, leaving the bond to be transferred by bearing on the deformations of the bar. Equal and opposite bearing stresses act on the concrete. The forces on the concrete have both a longitudinal and a radial component. The latter causes circumferential tensile stresses in the concrete around the bar. Eventually, the concrete will split parallel to the bar, and the resulting crack will propagate out to the surface of the beam. The splitting cracks follow the reinforcing bars along the bottom or side surfaces of the beam, a pull-out failure can occur, where the bar and the annulus of concrete between successive deformations pull out along a cylindrical failure surface joining the tips of the deformations[37], and it is was confirmed with Torre-Casanova et al. [9] who presented equations for distinguishing splitting failure as a function of the tensile properties of concrete and for distinguishing pull-out failure as a function of the compressive properties of concrete.

3.4.1 Rebars – 12mm

Figures (7 and 8) show the bond strength results of SNC concrete mixes. Generally for 12 mm re-bars specimens, the concrete cover was more than 4.5 the rebar diameter, so there were enough concrete covers and the pull-out was the dominant behavior [7], [29], [38], as shown in fig.9.

The pull-out performance is directly affected by the compressive strength of the concrete mix, so the bond strength performance of 12mm specimens followed the same trend of the compressive strength [7], [9], as shown in fig.8.

The highest bond strength reached 29.62MPa for the cement substitution by 7.5% SNC rather than 19.1MPa the control mix, the enhancement of bond strength was 55.08% as compared to the control mix.

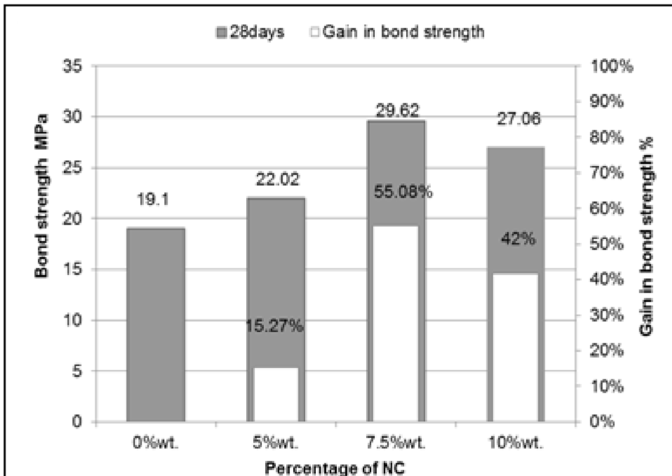

Fig.7. Bond strength of SNC mixes using 12mm rebar and the gain in bond strength as compared to the control mix.

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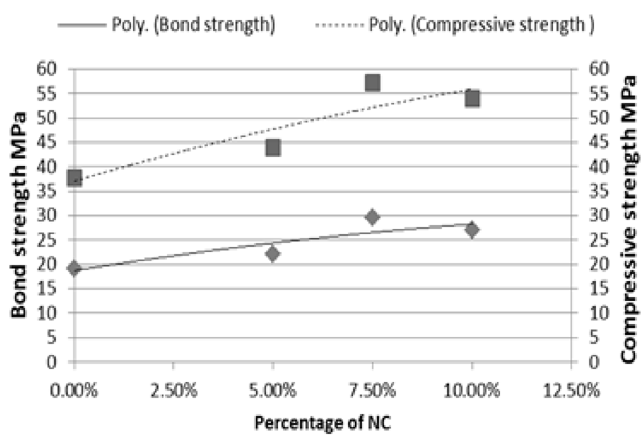

Fig.8. Relation between 28 days compressive strength and 12mm rebars bond strengths of SNC concrete mixes.

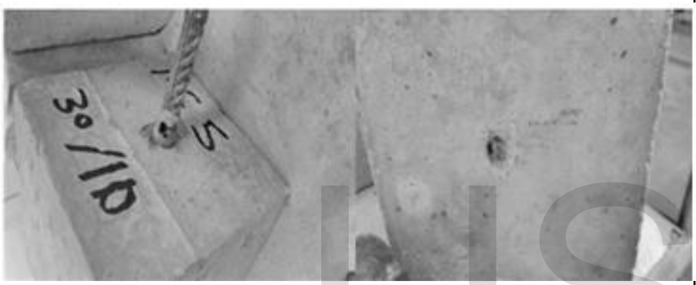

Fig.9. the pullout behavior for 12mm rebars

3.4.2 Rebar – 16mm

Figures (10 and 11) show the bond strength results of SNC concrete mixes. Generally for 16 mm re-bars specimens, the concrete cover was less than 4.5 the rebar diameter, so there weren't enough concrete covers and the splitting was the dominant behavior [7],[29], as shown in fig.12.

The splitting performance is directly affected by the tensile strength of the concrete mix, so the bond strength performance of 16mm specimens followed the same trend of the splitting tensile strength [7], [9], as shown in fig.11.

The highest bond strength reached 24.94MPa for the cement substitution by 7.5% SNC rather than 21.09MPa the control mix, the enhancement of bond strength was18.24% as compared to the control mix.

For 16 mm re-bars specimens, the concrete cover was less than 4.5 the rebar diameter, so there weren't enough concrete covers and the splitting was the dominant behavior.

The improvement of bond strengths for both; 12mm, and 16mm rebars specimens with cement substitution by SNC can be attributed to; (1) Pozzolanic Reactivity of NC particles which results in produce extra C-S-H gel which enhances the ITZ between aggregates and cement blended. And also enhances the bond between the steel rebar and concrete which in turn, enhances the concrete strengths. (2) NC particles act as a nucleus for cement hydration gels which leads to the formation reinforced C-S-H. (3) The filling effect of NC particles which results in well compacted, denser and uniformly re-structured matrix. (4) Needle action system of NC particles due to the shape of NC particles which are flaky, elongated, thin, and platy.

The bond strengths for both; 12mm, and 16mm rebars specimens was enhanced with increasing the cement substitution percentages by SNC up to 7.5%. After that, it was decreased with 10% SNC substitution, Noteworthy that the 10% SNC substitution was still higher than control mix. This can be attributed to the van der Waals force when adding a large percentage of NC particles. It assembles around each other and forms relatively large agglomerations which fail to act as filler to the nano pores in the matrix and hindered its pozzolanic reactivity resulting in weaken ITZ between aggregates and cement blends, and consequently, weaken the bond between concrete and steel rebar, and therefore, reduce the bond strength of concrete.

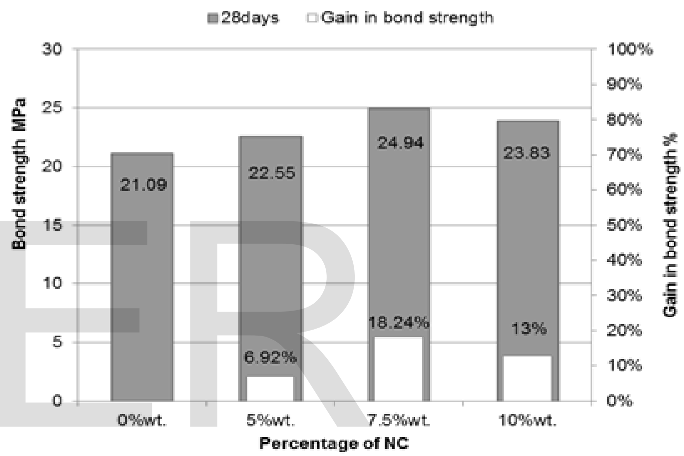

Fig.10. Bond strength of SNC mixes using 16mm rebar and the gain in bond strength as compared to the control mix.

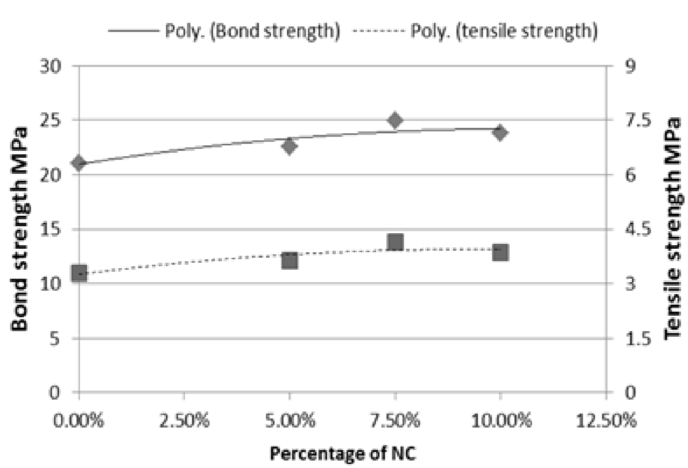

Fig.11. Relation between 28 days tensile strength and 16mm rebars bond strengths of SNC concrete mixes.

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Fig.12: the splitting behavior for 16mm rebars.

3.5 Scanning Electron Microscopy (SEM)

Scanning Electron Microscope (SEM) images were taken to study the micro-structure for the materials of two different specimens showing the effect of NC presence after being subjected to ultra-sonication as compared to control mix without NC substitution.

Figures (13 and 14) show the SEM micrographs for the control and SNC 7.5 % mixes, as for the SEM plates representing the morphology and structure of the control sample as compared with the NC incorporated cement systems, the found structures are highly identifying the reasons behind the previously discussed mechanical properties, i.e. the control mix showed much weaker performance in most of the mechanical properties as compared to the NC systems.

The ettringite needles, as well as the calcium hydroxide crystals can be easily identified in the control mix micrograph (fig.13a, and 13b), in addition to the existence of relatively large voids, moreover, the CSH particles is interfering with the calcium hydroxide crystals, and the ettringite needles which lead to weak, inconsistent matrix as it can be seen in the micrographs (fig.13b, and fig.13c).

While for the SNC micrographs, the presence of the NC particles within the cement matrix enhanced the consistency and homogeneity of the mix resulting in a more compacted matrix (fig.14a, and 14b).

It can be easily recognized from the SNC matrix micrographs that the presence of NC particles led to minimizing the void ratio within the matrix resulting in a more dense matrix, this could be due to the previously discussed filling effect where the NC particles fills all the nano sized pores, in addition this could be due to the reactivity of the NC particles with the residual CH from the cement hydration process resulting in a higher amount of CSH gels.

From the SNC micrographs, and in addition to the dense, well compacted matrix, and the spread presence of the CSH component within the matrix, a very significant action of the NC particles is recognized, where the NC sheet like shape acted as bridge connecting both sides of the crack together and preventing the propagation of the crack in a performance close to the fibers action when arresting the cracks. (fig.14a, 14b, and 14c)

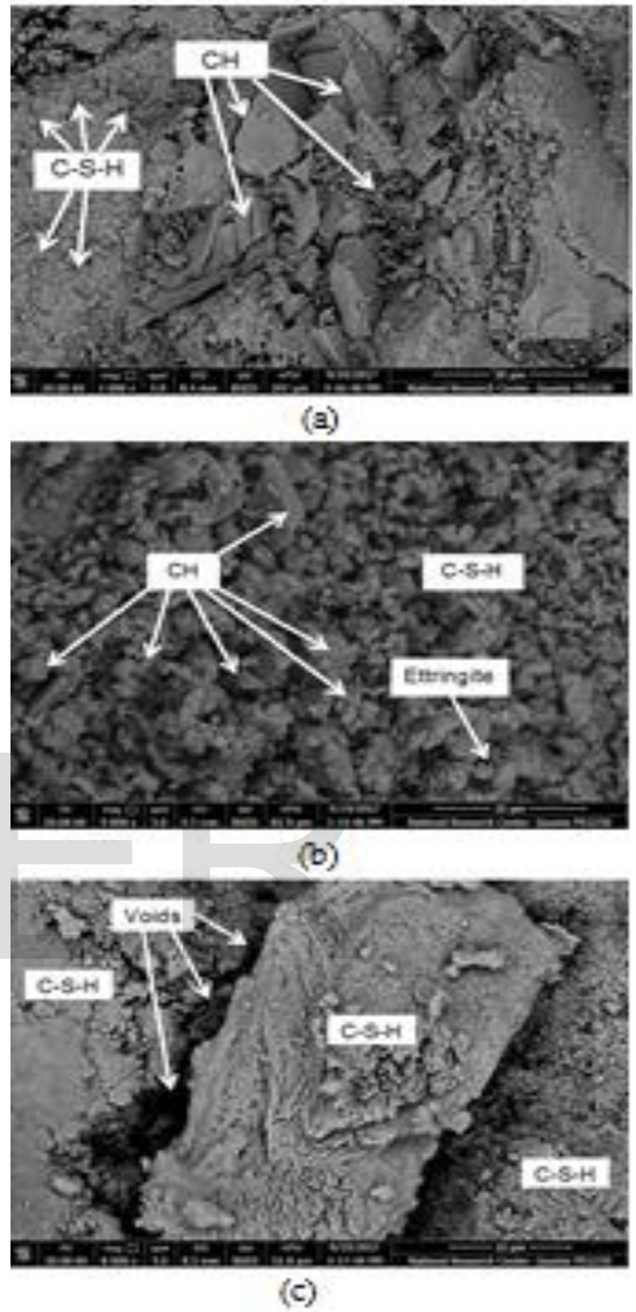

Fig.13. the SEM micrographs of the control mix.

3.6 X-ray Diffraction (XRD)

XRD was performed to detect changes in the hydration products due to the presence of NC after being subjected to ultra-sonication, and as compared to the hydration products of a control sample without the presence of NC particles.

Fig.15 show the XRD peaks of the control (C) and (SNC7.5%) mixes, due to their crystalline nature, calcium hydroxide and calcium carbonate peaks appear clearly in the XRD diagrams, while amorphous materials such as calcium silicate hydrate cannot be directly detected by this technique [39].

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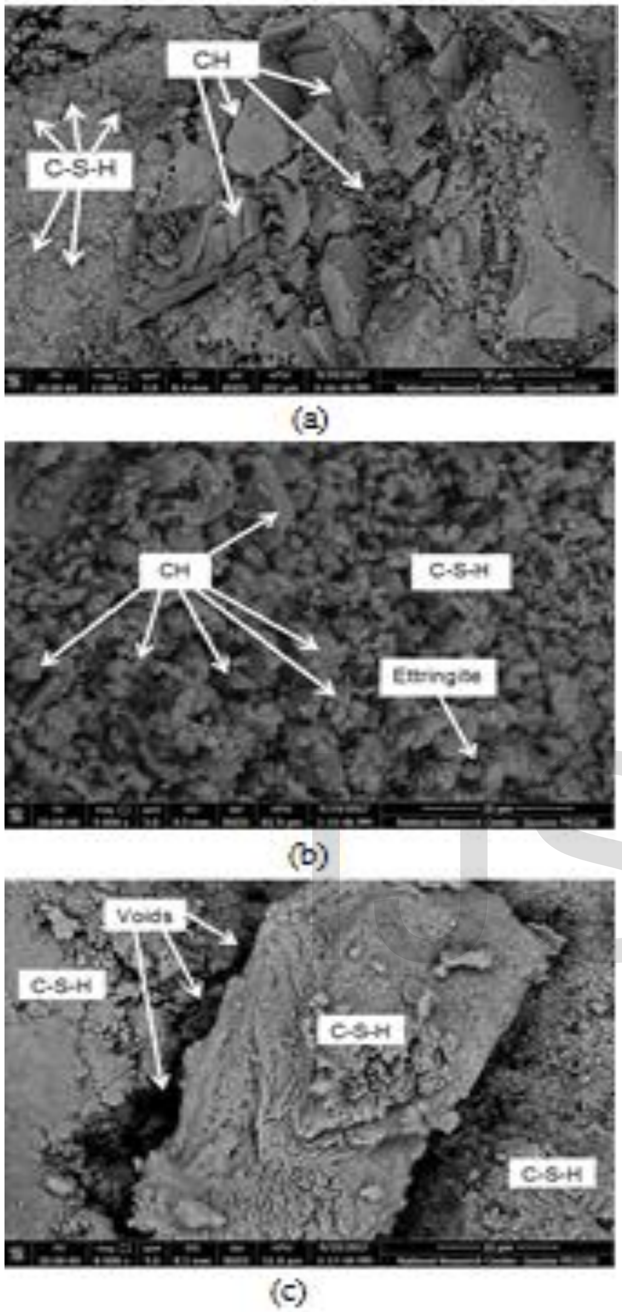

Fig.14. the SEM micrographs of SNC7.5% mix.

The calcium hydroxide peaks could be clearly found in the control mix, while by using the NC as cement replacement, the CH peaks decreased significantly for the mixes containing SNC particles.
The decrease of the CH peaks directly indicates the reactivity of the NC particles, and indirectly indicates higher C-S-H content in the mixes with NC substitution as a result of the reaction of the silica and aluminosilicate components in the NC with the excess calcium hydroxide (CH) from cement hydration to produce extra Calcium-Silicate-Hydrate (C-S-H) gel which enhances the ITZ between aggregates and cement pastes and enhances the concrete strength.
The SNC 7.5 mix, showed much lower peaks of the CH than the control mix.

The calcite (CC) peaks followed the trend of the calcium hydroxide peaks, which also indicates much lesser content of CH in the mixes containg NC as compared to the control mix. The presence of the CH in large amounts ease the reaction with the CO_2 in the air producing more calcite ($CaCO_3$) as a result of the carbonation process, see equation (1).

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ ___________ Eq. (1)

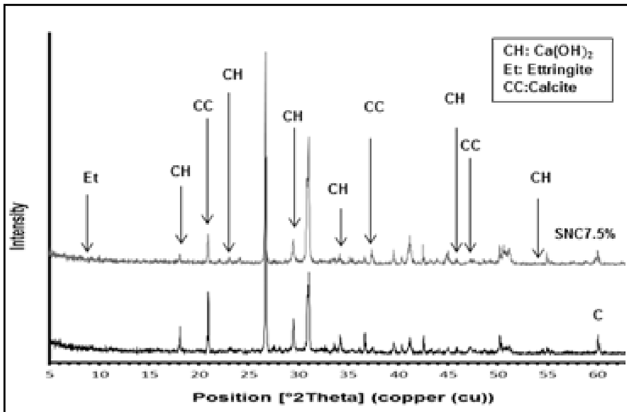

Fig.15. XRD of the control and SNC7.5% concrete mixes.

4 CONCLUSIONS

The following conclusions can be drawn from the test results;
1. Increasing the cement substitution by SNC slightly decreased the workability as compared to the control mix
2. The optimum percentage of NC substitution to enhance the compressive strength was 7.5% with gains of (55.47% and51.72%) at (7 and 28 days) respectively as compared to that of the control mix.
3. The optimum percentage of NC substitution to enhance the splitting tensile strength at 28 days was 7.5% with gain of 28.05% as compared to that of the control mix.
4. For 12mm re-bar specimens, the pull-out was the dominant behavior. The optimum percentage for cement substitution by SNC to improve the pull out bond strength for12 mm steel rebar is 7.5% with gain of 55.08% as compared to the control mix.
5. For 16 mm re-bar specimens, the splitting was the dominant behavior. The optimum percentage for cement substitution by SNC to enhance the splitting bond strength for 16mm steel rebar is 7.5% with gain of 18.24% as compared to the control mix.
6. SEM showed the three major effect of the NC with the cement matrix; (1) filling effect, (2) pozzolanic reactivity, and (3) needle effect.
7. XRD indicates the higher reactivity of SNC as compared to the control mix resulting in a denser and well compacted matrix.
8. Finally, the presence of NC particles enhanced significantly the bond strength for both common modes of failure.

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