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Unlocking the potential of carbon nanotubes and nano clay in concrete:assessing the bond strength and failure modes.

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Abstract: In recent times, nanotechnology has emerged as a highly promising and rapidly evolving field of research in the realm of civil engineering, particularly in the area of concrete construction. The application of nanotechnology in this field offers immense potential for the development of innovative materials with higher mechanical and physical properties, which can not only enhance the structural strength and durability of concrete but also reduce its environmental impact. This paper studies for the first time the influence of hybridized carbon nanotubes (CNTs) and nano clay (NC) on bond strength and failure modes. To determine the optimal ratio, CNTs were substituted at levels of 0.01%, 0.03%, and 0.05%, while maintaining NC at 3%. The combination of CNTs and nano clay in hybrid blends significantly enhances bond strength. In the case of cement content samples with 400 kg/m^3, the optimal ratio of 0.05% CNTs resulted in improvements of 107.2% and 92.5% at 10mm and 12mm rebars, respectively. Additionally, the same ratio gains 3.4% and 31.4% for cement content of 550 kg/m^3 for 10mm and 12mm rebars, respectively. For rebar 16mm, the optimal ratio is 0.03% CNTs, with an improvement in results of 120.34% and 110.4% for cement content of 400 and 550 kg/m^3, respectively. Mixtures with a ratio of 0.03% CNTs + 3% NC exhibit gains of 174.9% and 76.8% for bond strength test rebars 10mm and 12mm, respectively, for cement content 400 kg/m^3. For the cement content of 550 kg/m^3, the optimal ratio is 0.03% CNTs + 3% NC. The increase in bond strength is 42% and 66% for rebars 10mm and 16mm. But, at rebar 16mm, the optimal ratio is 0.01% CNTs + 3% NC; the increase is 109.96% and 75.9% for cement content of 400 kg/m^3 and 550 kg/m^3 respectively.

Keywords: Carbon nanotubes, Nano-clay, bond strength, failure modes.

1. INTRODUCTION

Concrete is the most commonly used building material, and research has been conducted to improve its mechanical properties. The most common method for improving the mechanical properties of concrete is to reinforce it with steel fibers [1-2]. Nanomaterials used as concrete reinforcing materials improve mechanical properties while also maintaining workability. Furthermore, due to recent performance improvements and mass production of nanomaterials, the use of nanomaterials as concrete reinforcing materials is increasing [3]. The mechanical properties of concrete, the concrete cover, and the diameter of the reinforcing bars all have an impact on the bond strength between reinforcing bars and concrete. According to previous research [4,5], incorporating fibers into concrete to improve its mechanical properties increases the tensile strength of concrete, increasing the bond strength between reinforcement and concrete. As a result, when the mechanical properties of concrete are improved by incorporating nanomaterials, bond performance is expected to improve, and studies on the bond mechanism of nano-reinforced concrete for applying nano-reinforced concrete to structures are increasing. Carbon nanotubes, due to their extraordinary properties such as ultra-high elastic modulus (about 1 Tpa), tensile strength (150 GPa), and thermal conductivity (about 3000 W/mK), may improve the mechanical and physical performance of monolithic materials [6,7]. Carbon nanotubes (CNTs) have excellent performance characteristics, making them an appealing material [8,9] capable of improving the mechanical performance of cement-based composites. [10,11]. R.Irshidat [12] used four percentages of CNTs, 0%, 0.05%, 0.1%, and 0.2%, and found that using 0.05% increased compressive strength by 15%. On the other hand, increasing the amount of added CNTs to 0.2% resulted in the greatest increase in flexural strength. C. Kramer [13] investigated the effect of using CNTs on cement weight fractions of 0.05% and 0.07% with foamed concrete samples. Their findings revealed a 40% and 7.5% increase in flexural and compressive strength, respectively. Heeyoung Lee et al. (2020) examined the impact of CNTs on bond strength. Various CNT ratios, including 0%, 0.125%, 0.5%, and 0.1%, were tested with a rebar diameter of 10mm. The findings revealed that specimens with a CNT ratio of 0.125% exhibited an average bond stress of 22.44 MPa, representing a 9.78% increase compared to the control specimen [14]. In a separate study, A. Haweern et al. (2018) investigated the influence of CNTs on bond strength using 12mm hot-rolled steel ribbed bars. The presence of CNTs proved more effective, particularly when radial cracking occurred, leading to an enhancement in bonding stiffness attributed to the bridging effect of carbon nanotubes. The bond strength observed was up to 14% higher than that of traditional reinforced concrete [15]. Furthermore, there are research findings that improve the compressive, tensile, and bending strength of cement composites [16]. Nano clay has more categories according to chemical composites and morphology such as bentonite, montmorillonite and kaolinite halloysite, and hectorite [17]. When extra CSH gel is produced as a result of the reaction of the residual CH from the cement reaction hydration process with NC, nano clay improves the interfacial transition zone (ITZ) between cement and aggregates [18],[19]. Nehal Hamed et al. conducted a study on the influence of NC on bond strength, exploring different cement replacement ratios of 5%, 7.5%, and 10% with NC. Cubes measuring 150*150*150mm were prepared and cast for bond strength testing using 12mm and 16mm rebars following RILEM 7-П-128 standards after 28 days. A 75mm steel bar was used for debonding length. Substituting 7.5% NC cement for 12mm rebar resulted in a 55.08% increase in bond strength compared to the control mix. Similarly, for 16mm rebars, the bond strength increased by 18.24% compared to the control mix [18]. Understanding how the bond between these nanomaterials and the cement matrix affects compressive strength and splitting tensile strength is fundamental to improving construction materials. In this discussion, we delve into the findings related to bond strength and its implications for compressive strength and splitting tensile strength under varying cement content conditions [20]. The most important factor in determining the mechanical characteristics and structural behavior of reinforced cement concrete constructions is the bonding between the concrete and reinforcement bars [21,22]. The equation for determining the bond strength in concrete through pull out test according to RILEM: bond strength = Fu / ∏ØL where: Fu- Ultimate pull-out load, Ø- Diameter of rebar, L- Bond length. The several variables that influence concrete bond strength are grade of concrete, and size diameter of rebars, and cover of concrete. Concrete bond strength is directly proportional to its grade (compressive strength). Because of its high quality, greater crack-resisting ability, and better cement paste quality, higher-graded concrete outperforms lower-graded concrete in bond strength [23]. It was discovered that increasing the concrete packing density enhanced bond strength [24]. Similar findings were presented in the literature to demonstrate that raising the grade of concrete improves bond strength due to fewer pores and denser concrete packing. Nonetheless, no linearity in development was observed [25]. As a result, a comparison of bond strength performance between plain and deformed steel bars was investigated. Deformed steel bars outperform plain/smooth bars in terms of strength, achieving two to ten times the strength of plain bars due to the interlocking mechanism offered by steel bars, which improves bond interaction [26,27]. So, the deformed rebar was used in this study. Several studies indicated that the larger the bar diameter, the poorer its bonding property with concrete surface [28-32]. The objective of this paper is to study for the first time: i) The influence of CNTs on bond strength across varying cement contents. ii) Exploring the impact of hybrid composites (CNTs & NC) on bond strength across different cement contents. iii) Studying the failure modes of rebars with different diameters in concrete with varying cement contents, in the presence of CNTs and hybrid composites (CNTs & NC). The bond strength between CNTs and NC and its influence on the compressive strength and splitting tensile strength of cement-based materials is a crucial aspect of this study. According to the previous studies described above, only one nanomaterial was used to improve the bond strength. Since bond strength results in two failure modes, the first is pull out failure and the other is splitting failure. Therefore, in this research, improving the bond strength using hybrid nanomaterials was studied. The first material works to improve compressive strength, which is nano clay, and the second material works to improve splitting tensile strength, which is carbon nanotubes. For this reason, these materials were chosen to study bond strength, this point had not been studied before. As well as the best mixture containing a hybrid of nano-clay and carbon nanotubes was chosen to improve bond strength.

2. Experimental Program:

2.1 Materials:

This paper utilized Ordinary Portland cement (OPC) type I, conforming to ASTM C150 standards [33]. The sand was utilized as fine aggregate and has a specific weight of 2.65 and a fineness modulus of 3.3. Crushed dolomite, with a nominal maximum size of 12.5mm, was employed as the coarse aggregate. CNTs was imported from Germany while NC was imported from china. Nano clay, appearing as an off-white powder, underwent treatment at 800°C for 2 hours. Its particle size ranging from 10 to 50 nm. The surface area of NC is 111.9 $m^2 g^{-1}$. The primary chemical compounds of nano clay include Al_2O^3, SiO_2, CaO, and Fe_2O_3, with respective compositions of 20.89%, 61.24%, 0.16%, and 1.06%, respectively). Carbon nanotubes, characterized by black rolled graphene sheets (Multi-Walled Carbon Nanotubes, MWCNTs), have inner diameter 5nm and outer diameter 8nm and lengths between 1 and 2 µm. Figure (1) depicts a scanning electron microscope (SEM) of carbon nanotubes.

Fig.1: The SEM of carbon nanotube particle size

2.2 Mix proportioning:

For this study, 16 concrete mixtures were prepared, each mixture had 9 cubic samples [3 cubes for 10mm rebar diameter, 3 cubes for 12mm rebar diameter, and 3 cubes for 16mm rebar diameter]. The mix proportions of the 16 concrete mixtures are explained in Table (1) and Table (2). The sand to coarse aggregates ratio of 1:1.5 and the water-binder ratio of 0.45 were used. The investigation focused on the incorporation of nanoparticles in hybrid concrete mixes, namely carbon nanotubes (CNTs) and nano clay (NC). Various ratios of CNTs (0.01%, 0.03%, and 0.05%) were added, while the percentage of NC remained constant at 3%, replacing a part of the cement. As shown in Table (1) and Table (2), different diameters of the rebars (10mm, 12mm, and 16mm) were utilized to investigate modes of failure for these diameters of rebars with different cement contents of 400 kg/m^3 and 550 kg/m^3, respectively. This investigation comprised two groups: the First group, the carbon nanotubes were mixed into a cement matrix. In the other group, hybrid composites (CNTs & NC) were mixed in concrete.

Table (1): Mixes proportions with 400 kg/m^3 cement for rebars (10mm,12mm and 16mm):

Mix	Cement	Coarse	Fine	Water	S. P	CNT	NC
AT0	400	1093	728.7	180	6	—	—
AT0.01	399.96	1093	728.7	180	6	0.04	—
AT0.03	399.88	1093	728.7	180	6	0.12	—
AT0.05	399.8	1093	728.7	180	6	0.2	—
AT0C	388	1093	728.7	180	6	—	12
AT0.01C	387.96	1093	728.7	728.7	6	0.04	12
AT0.03C	387.88	1093	728.7	728.7	6	0.12	12
AT0.05C	387.8	1093	728.7	728.7	6	0.2	12

Key of tables: A= cement content 400 kg/m^3 T= CNT= Carbon nanotube B= cement content 550 kg/m^3 C= NC= Nano clay T0.01 = Ratio of CNTs 0.01%

Table (2): Mixes proportions with 550 kg/m^3 cement for rebars (10mm,12mm and 16mm):

Mix	Cement	Coarse	Fine	Water	S. P	CNT	NC
BT0	550	906.7	604.5	247.5	8.25	0	—
BT0.01	549.945	906.7	604.5	247.5	8.25	0.055	—
BT0.03	549.835	906.7	604.5	247.5	8.25	0.165	—
BT0.05	549.725	906.7	604.5	247.5	8.25	0.275	—
BT0C	533.50	906.7	604.5	247.5	8.25	—	16.5
BT0.01C	533.445	906.7	604.5	247.5	8.25	0.055	16.5
BT0.03C	533.335	906.7	604.5	247.5	8.25	0.165	16.5
BT0.05C	533.225	906.7	604.5	247.5	8.25	0.275	16.5

Key of tables: A= cement content 400 kg/m^3 T= CNT= Carbon nanotube B= cement content 550 kg/m^3 C= NC= Nano clay T0.01 = Ratio of CNTs 0.01%

2.3 Mixing procedure:

The mixes were prepared by adding sand to coarse aggregate with a ratio of 1:1.5 and adding cement. Then, the dry materials were mixed for 2 min. The water-binder ratio was kept constant at 0.45 for all mixes. Superplasticizer was mixed with water, carbon nanotubes, and nano-clay manually for 2 min till we sure the complete dispersion of the components occurred. The mixing process was continued till we added the mixture to the dry mix. The mixer was operated for another 2 minutes. To test bond strength, the concrete was shaped into 15cm cubes, with a bond length of 7.5cm, half of the cube's side length. Various steel bar diameters of 10mm, 12mm, and 16mm were employed during casting to investigate different failure modes and the bond between the concrete and rebars. After casting, the samples were cured in water for 28 days following ASTM C31 [34].

2.4 Testing:

Pull-out tests were carried out on cube molds measuring 15cm. The specimens were cured for 28 days after casting according to ASTM C31. The Bar embedded length was half of the cube side length and was used as bond length to avoid yielding of rebar [35]. Details of pull-out samples are shown in Fig.2.

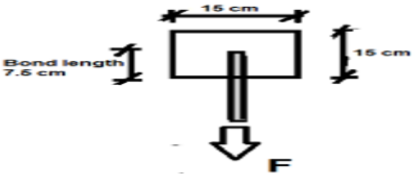


Fig 2: Details of pull-out test samples

3. Results and Discussion:

3.1 Compressive strength and tensile strength:

For compressive strength, the optimal ratio of 0.05% CNTs with a cement content of 400 Kg/m^3 improved compressive strength by 27.82% and 31.79% at 7 and 28 days, respectively. Hybrid mixes containing CNTs and nano clay improved compressive strength by 39.26% and 56.35% for 400 Kg/m^3 at 0.03% CNTs + 3% NC, and 36% and 19.33% for 550 Kg/m^3 at 0.01% CNTs + 3% NC, respectively, after 7 and 28 days. Adding CNTs and nano clay increased tensile strength by 136% for cement content of 400 Kg/m^3 at a hybrid mix ratio of 0.03% CNTs + 3% NC, and 62.4% for cement content of 550 Kg/m^3 at a hybrid mix ratio of 0.01% CNTs + 3% NC.

3.2 Bond strength:

There are two main modes for bond strength failure when the steel reinforcement bar is subjected to tension force, namely, pull-out failure and splitting failure. The outcomes of adhesion & friction between rebar and concrete produce bond forces, leaving it to be able to transfer by bearing on the deformation of the bar. Equal and opposite bearing stress act on the concrete. Two components of stresses are generated, radial and longitudinal. If the concrete cover exceeds 4.5 times the diameter of the rebar, the longitudinal component dominates, leading to pull-out failure as per RILEM 7-∏-128 [36]. Conversely, with a concrete cover less than 4.5 times the diameter of the rebar, the radial component dominates, resulting in splitting failure. The study may reveal situations where combining carbon nanotubes (CNTs) and nano-clay (NC) yields synergistic bond strength. This synergy has the potential to enhance compressive strength beyond what could be achieved with individual nanomaterials [37].

3.2.1 Rebar 10 mm and 12 mm:

For rebar 10mm and 12mm, the concrete cover is more than 4.5 times of diameter of the rebar, the longitudinal component dominates. Therefore, the pull-out failure was happened. The bond strength results of CNTs concrete mixes with a cement content of 400 kg/m^3 are shown in Fig. (3). The bond strength increased by 107.2% and 92.5% for steel bars 10mm and 12mm respectively for mixes containing 0.05% CNTs compared to the control mix. The bond strength was 12.3 MPa for 10mm rebar diameter and 16.13 MPa for 12mm rebar for the cement replacement by 0.05% of CNTs compared to 5.94 MPa for 10mm and 8.38 MPa for 12mm (control mix). These results suggest that the addition of CNTs at the specified ratio can effectively strengthen the bond between concrete and steel reinforcement, thereby enhancing the overall durability and structural integrity of concrete elements. This is because CNTs have been effective, and bonding stiffness increased when radial cracking was introduced, therefore the bond strength was increased. This is caused by the bridging effect of carbon nanotubes [15]. Furthermore, samples containing 3% nano-clay (NC) demonstrated a bond strength increase of 110.9% for 10mm diameter steel bar and approximately 41.4% for 12mm diameter steel bar. The highest bond strength was achieved with a hybrid concrete mix comprising 0.03% CNTs and 3% NC, reaching 16.33 MPa for 10mm bar and 14.82 MPa for 12mm bar, marking an increase of approximately 174.9% and 76.8% for 10mm and 12mm bars, respectively, compared to the control mix. This indicates the synergistic effect of combining CNTs and NC, resulting in superior bond strength performance compared to using either material individually.

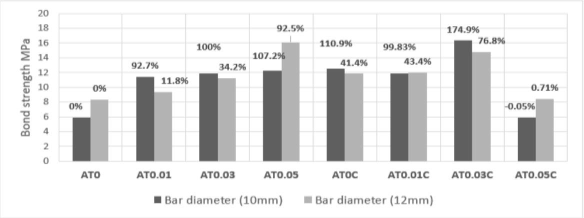


Fig.3: Bond strength for different ratios of CNTS and hybrid ratios for 400 Kg/m^3

The bond strength results of CNTs concrete mixes with cement content of 550 kg/m^3 are shown in Fig. (4). Replacing 0.05% of cement with CNTs, the bond strength measured 12.52 MPa for 10mm diameter steel bars and 12.55 MPa for 12mm diameter steel bar, compared to 5.94 MPa for 10mm and 8.38 MPa for 12mm for the control mix. The improvement of bond strength was 3.4% and 31.4% for the diameter of steel bars 10mm and 12mm respectively compared to the control mix. On the other hand, samples containing only 3% NC showed a more modest increase in bond strength, by 38.6% for 10mm diameter steel bars and 38.8% for 12mm diameter steel bars. The highest bond strength was achieved with hybrid concrete mixes comprising 0.01% CNTs and 3% NC, reaching 18.24 MPa for 10mm bars and 15.74 MPa for 12mm bars, representing increases of 50.83% and 64.8% respectively compared to the control mix.

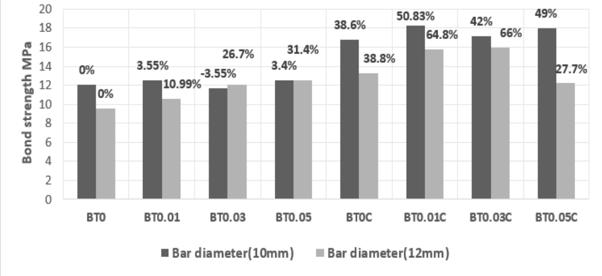


Fig.4: Bond strength for different ratios of CNTS and hybrid ratios for 550 Kg/m^3

3.2.2 Rebar 16mm:

The bond strength results of CNTs concrete mixes for 16mm rebar diameter are shown in Fig. (5) while Fig. (6) shows the bond strength results of concrete containing (CNTs + NC). For 16mm rebar samples, the concrete cover is less than 4.5 times of rebar diameter, so there wasn't enough concrete cover and splitting failure was the dominant behavior RIREM [36] as shown as in Fig.(7). The highest bond strength recorded was 15.49 MPa for a sample containing 0.03% CNTs, representing a remarkable 120.34% improvement compared to the reference mix with a cement content of 400 kg/m³. Similarly, the bond strength enhancement for samples containing 0.01% CNTs was 116.3% compared to the control mix with a cement content of 550 kg/m³. Results of samples containing only 3% NC showed an increase of 83.2% for a cement content of 400 kg/m³ and 44.4% for a cement content of 550 kg/m³. This is because NC produces more CSH gel, which increases the pozzolanic reactivity of NC particles and improves the ITZ zone, resulting in increased bond strength when compared to the control mix [19]. The bond strength of hybrid concrete mixes utilizing 0.01% CNTs and 3% NC increased by 109.96% for the cement content of 400 kg/m³ and 75.9% for the cement of 550 kg/m^3 compared to control mix. It was noted that addition of more than 0.01% CNT's to NC concrete mix resulted in a reduction of the failure load. This decrease in measured load may be due to the higher surface hardness provided by higher grades of concrete [38]. However, the reason for the noticed reduction in failure load needs further investigation in order to clarify this behaviour. The increase in bond strengths observed in samples with 10mm, 12mm, and 16mm rebars, resulting from the cement replacement with CNTs and NC particles can be attributed to several factors. Firstly, the pozzolanic reactivity of NC particles which improves the bond between the rebar and the cement matrix. Moreover, CNTs serve as bridges between the hydrated compounds in cement. Finally, the fine particles of CNTs and NC can fill the pores, thereby making the cement matrix denser.

Figure (7) shows: (a) pull-out failure mode that happened with 10mm and 12mm rebar diameters, (b) splitting failure mode that happened with 16mm rebar diameter.

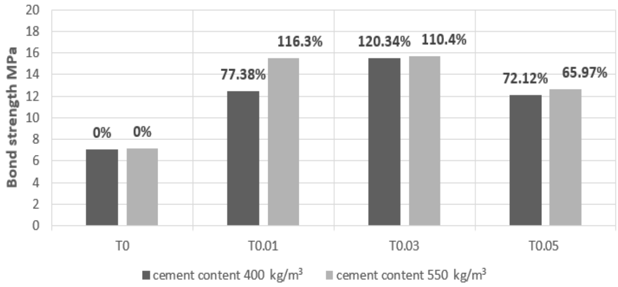


Fig.5: Bond strength for different ratios of CNTs and bar diameter of 16mm

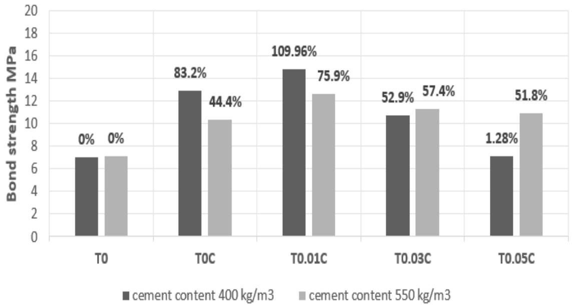


Fig. 6: Bond strength for different (NC + CNTs) samples and bar diameter of 16mm

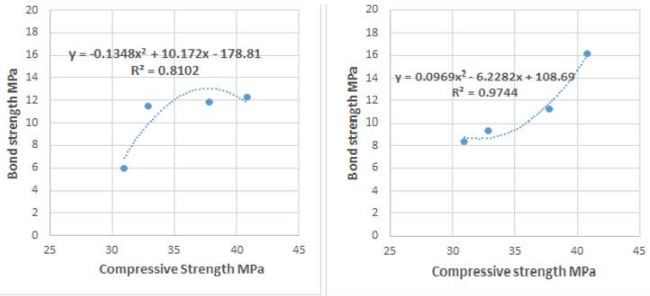
(a) (b)

Fig.7: Modes of failure (a) pull out failure (b) splitting failure

3.3 Relation between bond strength and compressive strength and tensile strength:

3.3.1 Relation between bond strength and compressive strength:

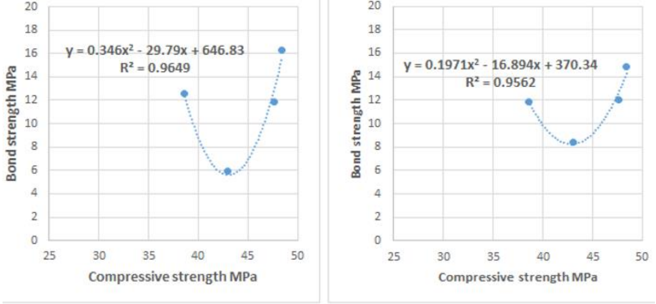
For bar diameter 10mm and 12mm, the cover concrete is more than 4.5 times of bar diameter so, the pull-out failure is occurred. For this reason, figures (8-11) show relations between bond strength for 10mm and 12mm bar diameter and compressive strength. It was noticed that bond strength reaches a maximum value of approximately 14 MPa (+/- 4 MPa), regardless of the compressive of the concrete. This maximum bond strength value remains consistent for both 10mm and 12mm diameter bars, irrespective of the components of the mixture. In Mix 400 kg/m³, the bond strength peaks at compressive strength ranging from approximately 30 MPa to 50 MPa, while for Mix 550 kg/m³, the peak bond strength occurs at compressive strength ranging from 45 to 60 MPa. It was concluded that increasing the concrete grade up to M35 enhances bond strength; however, beyond this point, a decrease in bond strength is observed due to the higher surface hardness provided by higher grades of concrete [38]. For bar diameter 16mm, the cover concrete is less than 4.5 times of bar diameter so, the splitting failure is occurred.



(a) (b)

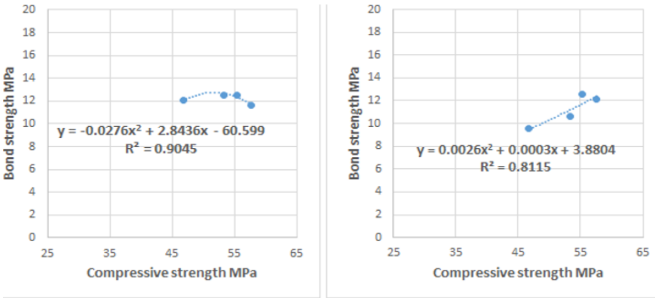
Fig.8: (a) Relation between bond strength for bar diameter 10mm and compressive strength at different CNTs ratios cement content with 400 kg/m^3 (b) Relation between bond strength for bar diameter 12mm and compressive strength at different CNTs ratios cement content with 400 kg/m^3

Where Y= Bond strength MPa, X= Compressive strength MPa



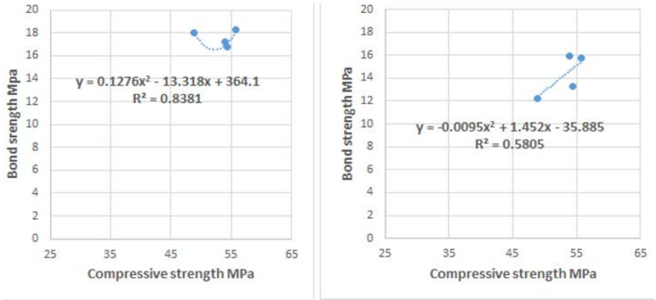
(a) (b)

Fig.9: (a) Relation between bond strength for bar diameter 10mm and compressive strength at hybrid ratios cement content with 400 kg/m^3 (b) Relation between bond strength for bar diameter 12mm and compressive strength at hybrid ratios cement content with 400 kg/m^3



(a) (b)

Fig.10: (a) Relation between bond strength for bar diameter 10mm and compressive strength at different CNTs ratios cement content with 550 kg/m^3 (b) Relation between bond strength for bar diameter 12mm and compressive strength at different CNTs ratios cement content with 550 kg/m^3

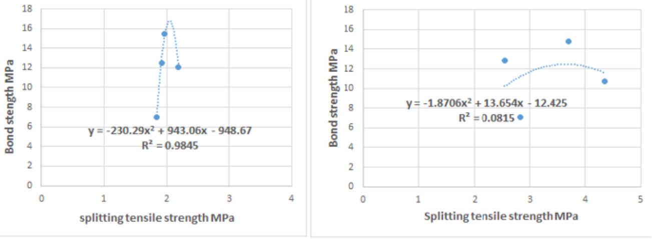


(a) (b)

Fig.11: (a) Relation between bond strength for 10mm and compressive strength at hybrid ratios cement content with 550 kg/m^3 (b) Relation between bond strength for 12mm and compressive strength at hybrid ratios cement content with 550 kg/m^3

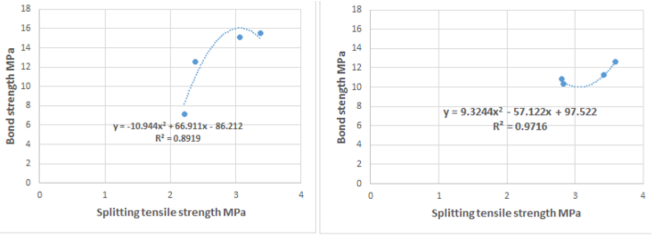
3.3.2 Relation between bond strength and tensile strength:

Figures 12 and 13 show the relation between the bond strength for 16mm bar diameter and splitting tensile strength for different cement contents and different ratios of CNTs and hybrid ratios. It was noticed that bond strength reaches a maximum value of approximately 14 MPa (+/- 4 MPa). This maximum bond strength value remains consistent for 16mm diameter bars, irrespective of the components of the mixture. In Mix 400 kg/m³, the bond strength peaks at tensile strength ranging from approximately 1.5 MPa to 4 MPa, while for Mix 550 kg/m³, the peak bond strength occurs at tensile strength ranging from 2 to 4 MPa.



(a) (b)

Fig.12: (a) Relation between bond strength for 16mm and splitting tensile strength at different CNTs ratios cement content with 400kg/m^3 (b) Relation between bond strength for 16mm and splitting tensile strength at hybrid ratios cement content with 400kg/m^3 Where Y= Bond strength MPa, X= Splitting tensile strength MPa

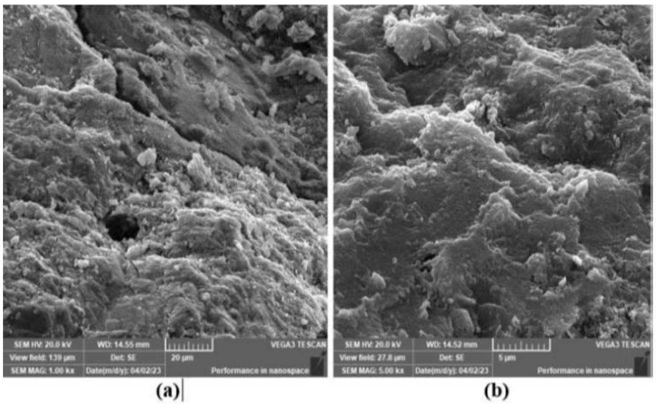


(a) (b)

Fig.13: (a) Relation between bond strength for 16mm and splitting tensile strength at different CNTs ratios cement content with 550kg/m^3 (b) Relation between bond strength for 16mm and splitting tensile strength at hybrid ratios cement content with 550kg/m^3

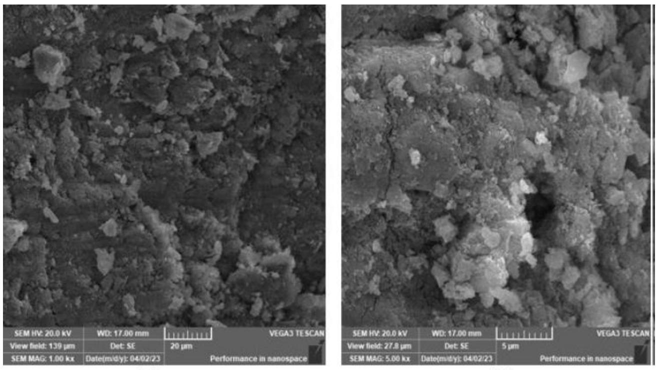
3.4 Microstructure investigation on concrete mixes.

Fig. 14 depicts paste's overall porosity texture of control mix containing 400 kg/m^3 cement. We can examine the distribution of pores and how they are related. The granular texture may suggest partially hydrated cement particles and the start production of calcium silicate hydrates (C-S-H) gel. Fig.15 shows a more detailed look of the C-S-H gel and possibly other hydration products of **(BT0)** mix with 550 kg/m^3 cement. The structure in this image is dense and compact, highlighting the better binding matrix that provides the cement paste with its strength. The cement matrix has a more CSH, compacted and denser in mixture BT0. Fig.16 shows the presence of larger, identifiable crystals in the cement paste **(AT0.03C)**. These could be calcium hydroxide (CH) crystals produced as a byproduct of cement hydration. The needle-like or plate-like features are characteristic of CH. This image indicates denser cement matrix due to the presence of NC and consequently better bond. Fig.17 provides a closer look at the crystalline formations of mixture **BT0.03C**, which may be ettringite or monosulfoaluminate, that can form during the hydration process. These needle-like structures are typical in hydrated cement paste and can affect the paste's mechanical qualities. The image also shows the role of CNTs bridging effect to delay crack propagation and improve bond strength.



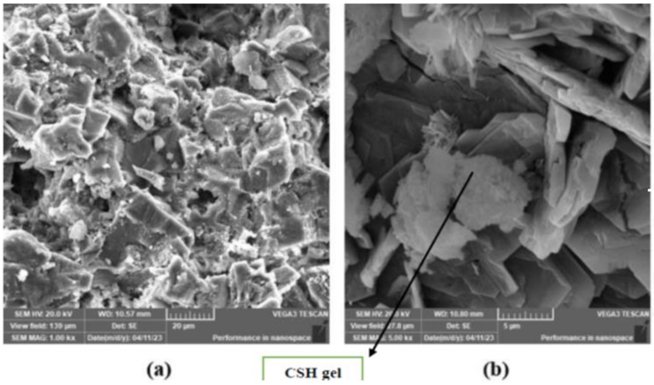
(a) (b)

Fig. 14: SEM micrograph of Control mix with 400 Kg/m^3 cement (AT0) (a) SEM MAG 1.00 KX (b) SEM MAG 5.00 KX



(a) (b)

Fig.15: SEM micrograph of Control mix for 550 Kg/m^3 cement (BT0) (a) SEM MAG 1.00 KX (b) SEM MAG 5.00 KX



(a) (b)

Fig.16: SEM micrograph of (AT0.03C) mix with 400 Kg/m^3 cement (a) SEM MAG 1.00 KX (b) SEM MAG 5.00 KX

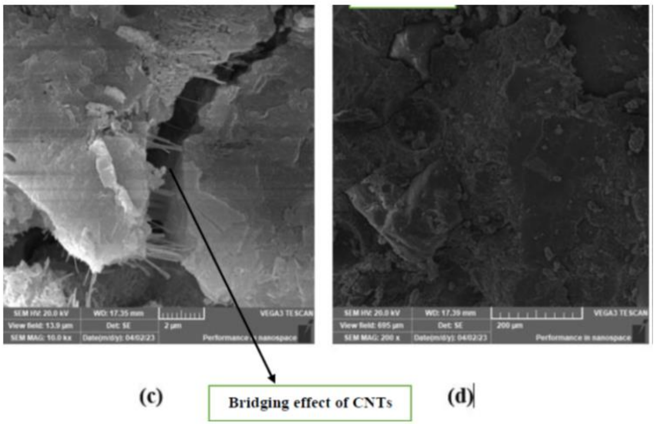


Fig.17: SEM micrograph of (BT0.03C) mix with 550 Kg/m^3 cement (a) SEM MAG 1.00 KX (b) SEM MAG 5.00 KX

4. Conclusions:

The study shows that including CNTs and NC greatly improves concrete bond strength, with optimal percentages varied according to rebar diameter and cement contents. The hybrid mix of CNTs and NC improves bond strength while also influencing failure modes, implying a synergistic effect that would improves concrete's overall performance.

1- The optimal ratio of carbon nanotubes (CNTs) and nano clay (NC) to improve bond strength was observed to be 0.03% CNTs + 3% NC. This ratio resulted in remarkable gains of 174.9% and 76.8% for 10mm and 12mm rebar samples, respectively, at a cement content of 400 kg/m^3.

2- At a cement content of 550 kg/m^3, the optimal ratio for enhancing bond strength was achieved with 0.01% CNTs + 3% NC, leading to significant gains of 50.83% and 64.8% for 10mm and 12mm rebar samples, respectively.

3- For 16mm rebar samples, the optimal ratio of CNTs was 0.03% for cement content of 400 kg/m^3, resulting in a substantial increase in bond strength values of 120.34%. While for cement content of 550 kg/m^3, the optimal ratio of CNTs was found to be 0.01%, resulting in an increase in bond strength values of 116.3%.

4- The use of hybrid composites consisting of CNTs and NC further enhanced the bond strength of 16mm rebar samples. The optimal ratio for this hybrid composite was (0.01% CNTs + 3% NC), resulting in an increase of 109.96% for cement content of 400 kg/m^3, and an increase of 75.9% at a cement content of 550 kg/m^3.

5- This study demonstrates the significant potential of incorporating CNTs and nano clay as effective additives for enhancing the bond strength of concrete. These results provide valuable insights into the optimal ratios of these additives, enabling engineers and researchers to achieve the best results in terms of bond strength enhancement.

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