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Experimental Study of Multi-Walled Carbon Nano-tubes in Cement Mortar for Structural Use

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ABSTRACT

This paper studies the behaviour of a flexural specimen reinforced with two types of multi-walled carbon nano-tubes (MWCNTs) based on outer diameter (OD), *viz.*, Type I- CNT (OD: 10-20 nm) and Type II- CNT (OD: 30-50 nm) to explore the strength aspects for structural use. Flexural specimens were made by varying the MWCNT content from 0.1 to 0.5 wt.% of cement. For evaluating mechanical properties, such as load-deflection, tests were performed on CNT- admixed specimens under flexure. An attempt has also been made to explore the optimum concentration of MWCNT additions that gave ideal performance with respect to mechanical properties. Reinforcement of mortar flexural specimens with Type II- CNTs revealed improved outcomes as compared to Type I- CNT counterparts. Flexural and compressive strengths are enhanced by 22% and 33%, respectively, compared to control specimens when Type II- CNT was used in the cementitious matrix. Based on the parametric study, a tentative optimum CNT concentration (0.3% by weight of cement) has been proposed..

KEYWORDS: Carbon nano-tubes, Nano-materials, Flexural strength, Load-deflection curves, Porosity, Water absorption.

INTRODUCTION

Carbon nanotubes (CNTs) has got main attention by researchers in the field of nanotechnology. In the recent past, researchers showed particular curiosity in developing nanotechnology for cement to produce high-strength composites. Nanotechnology is used with advantage to manipulate physical and chemical behaviours of cement hydration. In cementitious composites, the advantage of exceptional mechanical properties of CNTs can be effectively employed as reinforcement fillers. Apart from extremely high strength and modulus of elasticity, carbon nano-tubes have aspect ratios varying from 1000:1 to 2,500,000:1 (Makar et al., 2005). The main advantage of high aspect ratio of CNT is that it can be dispersed on a very fine scale than other types of commonly used fibers (Makar, J., Margeson, J. and Luh, 2005). Therefore, crack-arresting mechanism of a CNT-reinforced matrix is fast as compared to conventional cement matrix. This bridging effect in the presence of CNTs assures lesser crack widths and ultimately manifests the transfer of load across fine cracks. Therefore, these CNT properties support their use as reinforcement fillers in cementitious composites.

CNT has been discovered by Lijima (1991) and since then, it has been extensively applied in different engineering uses. This is possible because of its enormous strength and extremely high Young's modulus (Lijima, 1991). Improving flexural

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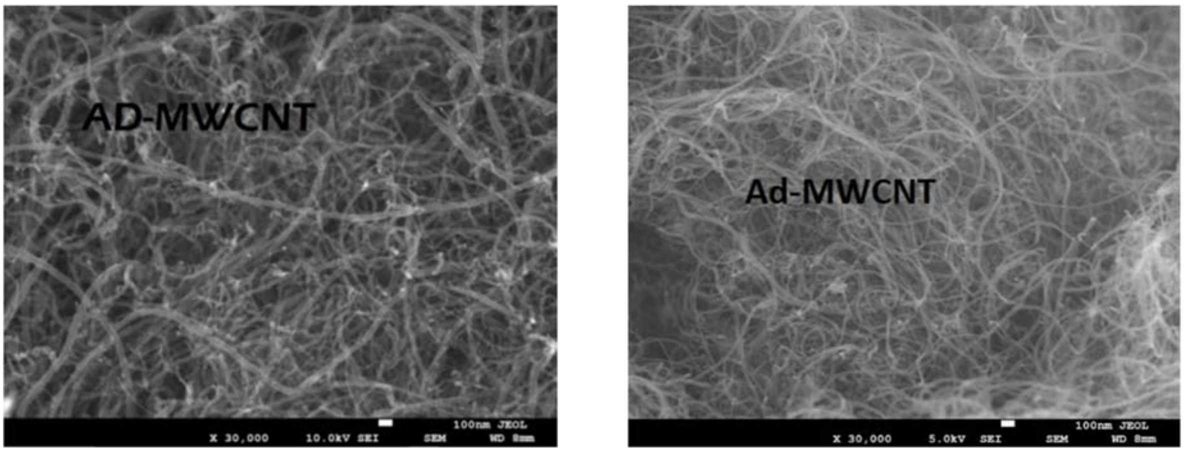
performance, ductility and energy absorption capacity of cementitious composites is quite common by incorporating different types of fibers (Emon et al., 2016). Consequently, exploration on developing suitable nanotechnology for mortar and concrete through addition of nano-fibers, such as CNTs, has been of significant interest in the recent past. Due to low production cost, MWCNTs have been more widely used by past researchers than single-walled carbon nanotubes. Li et al. (2005) investigated both treated and untreated MWCNTs in cementitious composites and reported that strength properties of composites treated with CNTs were marginally higher in comparison to untreated counterparts. Manzur and Yazdani (2014) studied the effect of different sizes and dosage rates of MWCNTs on the properties of cement composites and recommended a CNT concentration between 0.1-0.3% to produce cement composites. Enhancement in flexural strength by 7% was reported by Khashaba (2015) using 0.2% MWCNTs in cement paste. By use of only small amount of MWCNT (0.08%), Konsta-Gdoutos stated improved flexural strength by 25% (Konsta-Gdoutos et al., 2010). More recent work by Jeevanagoudar et al. (2017a) investigated the reinforcing effect of MWCNTs on a range of properties of cement mortars. Hallad et al. (2017) obtained 88% increase in flexural strength by using a combination of MWCNTs and carbon micro-fibers (CMFs) in the matrix. Manzur and Yazdani (2010) investigated the effect on compressive strength by using two different MWCNT sizes and found 15-25% increase in compressive strength. Later, Manzur and Yazdani (2015) in a similar study with treated MWCNTs recommended a CNT concentration by weight of cement for strength aspects. For optimum mix ratio, increase in compressive and flexural strengths was found to be 15% and 19.5%, respectively. In one of the studies, exceptional reinforcing behaviour of MWCNTs was demonstrated by the improved compressive strength and reduced water absorption (Jeevanagoudar et al., 2017b). Influence of CNTs on various properties, like physical, mechanical, electrical and piezoresistive sensitivity of cementitious materials was critically reviewed by Rashad (2017). In the study of Makar and Chan (2009), the process of cement hydration admixed with CNTs was explained. It was observed that the hydration process was accelerated in the presence of CNTs.



(a) (b)

Figure (1): SEM images of (a) type I- CNTs and (b) type II- CNTs

Water absorption characteristics, such as coefficient of permeability and water sorptivity, were shown to decrease for cement matrix reinforced with MWCNTs due to denser microstructure (Han et al., 2013). In one of the studies, the compressive strength of mortar was found to decrease by enhanced porosity of the composites (Chen et al., 2013). In a recent paper, Lee et al. (2018) investigated the performance of cement mortar admixed with nano-silica and showed that 1% nano-silica and 0.03% CNT performed better in terms of reduced water absorption characteristics. It is, therefore, obvious that CNT addition within cement matrix has many effects on strength and physical properties and showed variable results. Further, past studies also pointed to the fact that the performance of CNT composites depends on several important factors, like nano-tube size, nano-tube concentration, nano-tube treatment,… etc., as well as mixing issues.

Though many studies were carried out on evaluating the flexural and compressive strengths of CNT-reinforced cement composites, the issue of diameter has a crucial impact on the performance and behaviour of CNT- admixed mortars. However, this issue has not been addressed in general. Moreover, criteria such as load-deflection and properties like density, porosity and water absorption of CNT- reinforced composites are also lacking. With this goal in mind, an effort has been made in this study to investigate strengths, physical properties and load-deflection characteristics of flexural specimens added with two types of CNTs (based on outside diameter) and compare them with those of plain specimens to highlight their usefulness as additives in cement mortar. For uniform dispersion of CNTs, ultrasonic energy along with polycarboxylate-based superplastisizer were utilized. Three-point flexural bending tests were performed to study the load-deflection characteristics of flexural specimens prepared using Type I- and Type II-CNTs after curing periods of 7, 14 and 28 days. Five dosage rates of 0.1%, 0.2%, 0.3%, 0.4% and 0.5% by weight of cement were used to prepare the specimens. High-resolution electron microscopy was performed to substantiate the outcomes of the CNT- admixed mortar with microstructure at the fractured surfaces. Comprehensive investigation revealed that Type II- CNT- admixed flexural specimens gave optimum results when compared to Type I- CNT- admixed specimens as well as to plain mortar specimens.

Experimental Work

Materials and Methods

OPC 43-grade (Ultra Tech) and standard sand as per IS: 650-1991 supplied by Tamil Nadu Minerals, Ltd., Chennai were used in the study. MWCNTs manufactured by Ad-Nano Technologies Pvt. Ltd, Karnataka were used as procured in casting CNT composites. Catalytic Chemical Vapour Deposition (CCVD) process was used to produce these CNTs. Fig. 1 shows the Scanning Electron Micrographs (SEMs) of the two types of MWCNTs. The morphological structure shows that CNTs are randomly distributed and jumbled. In the morphological structure, CNTs are also shown to be in different sizes and lengths. The physical properties of both Type I- and Type II- CNTs, as supplied by the manufacturing company, are shown in Table 1. A polycarboxylate-based superplastisizer, supplied by Chemcon Tecsys; trade name ‘‘CONXL-PCE DM 09’’, was used to help in uniform distribution of CNTs in water.

Table 1. Physical properties of multi-walled carbon nano-tubes

Physical properties	Type I- CNT	Type II- CNT
Colour	Black	Black
Purity (%)	>99	>99
Average Outer Diameter (nm)	10 -20	30 -50
Average Length (μm)	1-5	10-20
Amorphous carbon (%)	<1	<1
Surface Area (m^2/g)	370	400
Average aspect ratio	200	375

Dispersion of MWCNTs

Separate batches for Type I- CNTs were prepared at five different percentages (0.1 through 0.5wt.% of cement). For Type II- CNTs, identical batches were made at same concentrations by cement weight. For all the specimens, a constant water cement ratio of 0.5 was used. For each batch, three replicates were made and tested after curing periods of 7, 14 and 28 days. The mean values as well as standard errors of the means for the specimens were computed after respective curing periods. Different techniques were used by various researchers for dispersion of MWCNTs; however, the sonication technique was the most commonly technique used. In this study, measured quantity of MWCNTs was first mixed with mixture of water and superplastisizer (0.4% of SP by weight of cement was added to water). Bath sonicator was employed for 30 minutes to achieve uniform dispersion of CNTs in water. The various stages of sonication are shown in Fig. 2 (a)-(d).

Mixing and Sample Preparation

After completion of sonication process, required quantity of sonicated water with a water-to-cement ratio of 0.5 was poured into the cement-sand mixture (1:3). The resulting mixture was then mixed together for 7 min in a multi-speed planetary blender. Table 2 shows the mix proportions used in the study. Moulds conforming to IS: 10078-1982 were used to prepare the specimens. Specimens were cast by pouring mixtures into moulds of 160mm × 40mm × 40mm size. The moulds were lightly oiled inside before use. The samples were kept in the moulds under moist condition for 24 h and finally immersed in water for flexural strength tests after 7, 14 and 28 days. Control specimens were also prepared using the same procedure.

Testing Procedures

Three-point Load Test on Beams

A three-point bending testing frame was used for flexural testing. It consists of a load cell and an LVDT to measure displacement. Two roller supports of 10 mm diameter, 100 mm apart, were used during testing. The third roller having same diameter and at the same distance from the first two supports was used to transmit the load ‘P’ on the opposite side of the sample, as shown in Fig. 3. Rate of loading was kept as 50±10 N/s during testing. Flexural testing machine along with specimen after failure are shown in Fig. 4. The following formula is used to calculate the flexural strength as per IS: 4031 (Part 8) – 1988.

$$R = \frac{6M}{B^3}$$

where,

$R =$ Flexural strength of the specimen;

$M =$ Maximum bending moment under central-point loading;

$B =$ Side of the prism square cross-section.

Compressive Strength Test

After flexural strength tests, the specimens were cut from the ends to cubes of 40 mm × 40 mm × 40 mm size from the uncracked portions of the specimens as per IS: 4031 (Part 8) – 1988. Each prism was tested for compressive strength by placing an area of 40 mm × 40 mm between two hard metal plates in a compression testing machine of 45 kN capacity provided by AIMIL, Bangalore. The load was applied at the rate of 200 kg/cm^2/min.

(a) Mixing water with superplasticizer

(b) Mixing water with superplasticizer and MWCNT

(c) Sonication for dispersion of MWCNT

(d) Sonicated water after 30 minutes of sonication

Figure (2): Different stages of sonication

Tests for Density, Porosity and Water Absorption

These tests were performed on 40 mm × 40 mm × 40 mm size cubes (derived from the uncracked portions after flexural strength test) before performing compression testing. Density is determined as per IS: 1528 (Part 15) – 2007. Dry weight (W_d) of the cubical specimen was determined after oven drying at a temperature of 100 to 110 °C for one day. The specimens were then immersed in water for 24 hours. Then, saturated weight (W_{ssd}) was determined. After immersing the saturated specimen in water, its apparent submerged weight (W_w) was taken.

Density was determined by using the following formula:

$$Density = \frac{W_d}{W_w - W_{ssd}}$$

As high porosity decreases mechanical strength and durability of cementitious materials, porosity is an important parameter of study in evaluating quality and functionality of cement composites. For calculating the porosity at various curing ages (7, 14 and 28 days), the water immersed weight (W_w) and saturated surface dry weight (W_{ssd}) have been measured. Dried specimen weight (W_d) was measured after being kept in an oven at a temperature of 105 ± 5˚C. To compute porosity, the following formula has been employed:

$$P = \frac{W_{ssd} - W_d}{W_{ssd} - W_w} \times 100$$

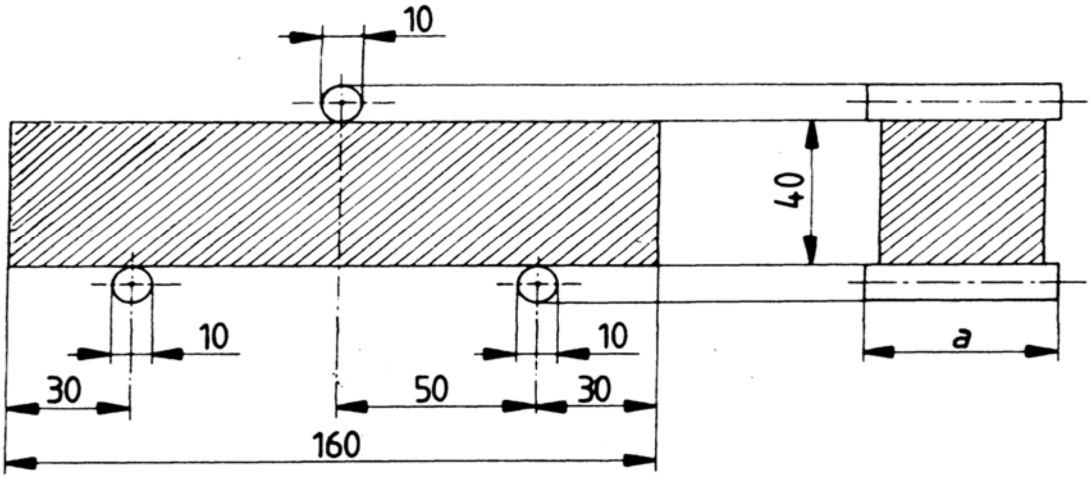
where P denotes the porosity percentage, W_{ssd} is the saturated surface dry specimen weight, W_w is the specimen weight taken in the immersed water condition and W_d represents the specimen weight under dried condition. Past studies have successfully employed this method of porosity determination for cementitious composites (Chen et al., 2013).

Water absorption test was performed on mortar cubes with various wt.% of CNTs at various curing periods (7, 14 and 28 days) after drying at 105 ˚C in an oven for one day. After removing from the oven, specimens were allowed to reach room temperature. The specimens were weighed on an electronic balance of high accuracy. Their dry weight (W_d) was recorded. These specimens were then immersed in water for 24 h and after removing loose water by paper tower, their weight is again taken and recorded as W_{ssd}. The following relation is used to calculate water absorption:

$$Water\ absorption\ (\%) = \frac{W_{ssd} - W_d}{W_d} \times 100$$

Electron Microscopy Images

After compressive strength tests, crushed sample pieces were used for microstructure analysis at the University Sophisticated Instruments Facility (USIF), Aligarh Muslim University, Aligarh, India. Scanning Electron Microscope (SEM) from JOEL, Japan was used for in-depth analysis and interpretation of the variations in the microstructure of the composite matrix.



(All dimensions are in mm)

Figure (3): Flexural strength testing as per (IS: 4031 (Part 8) - 1988)

Figure (4): Flexural specimen after failure

Table 2. Details of test specimens

Specimen constitution	CNT (% wt. of cement)	Superplastisizer (% wt. of cement)	Sonication time (min.)
Control Specimen (Plain)	0.0	0.4%	0
Type I- 0.1% CNT	0.1	0.4%	30
Type I- 0.2% CNT	0.2	0.4%	30
Type I- 0.3% CNT	0.3	0.4%	30
Type I- 0.4% CNT	0.4	0.4%	30
Type I- 0.5% CNT	0.5	0.4%	30
Type II- 0.1% CNT	0.1	0.4%	30
Type II- 0.2% CNT	0.2	0.4%	30
Type II- 0.3% CNT	0.3	0.4%	30
Type II- 0.4% CNT	0.4	0.4%	30
Type II- 0.5% CNT	0.5	0.4%	30

Table 3. Outcome for CNT composite beams under three-point flexural test: ultimate load and maximum deflection

S. No.	Specimen reference	Age of testing (days)	Ultimate load (kN)	Maximum deformation (mm)
1	Type I- 0.3% CNT	7	2.45	0.213
2	Type II- 0.3% CNT	7	2.65	0.26
3	Type I- 0.3%CNT	14	2.84	0.24
4	Type II- 0.3% CNT	14	2.98	0.27
5	Type I- 0.3% CNT	28	3.14	0.20

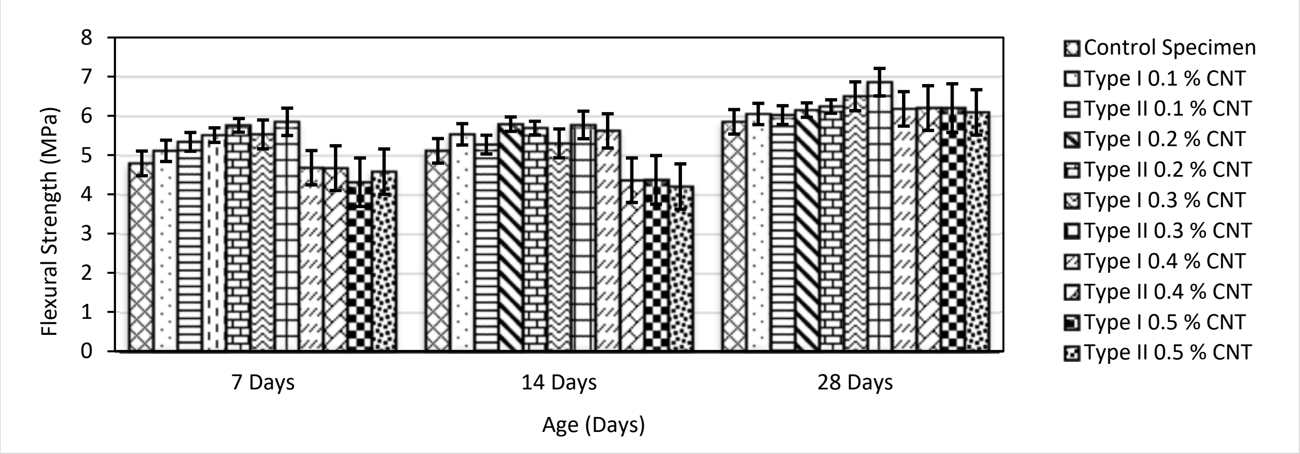


Figure (5): Average flexural strength values for various CNT specimens

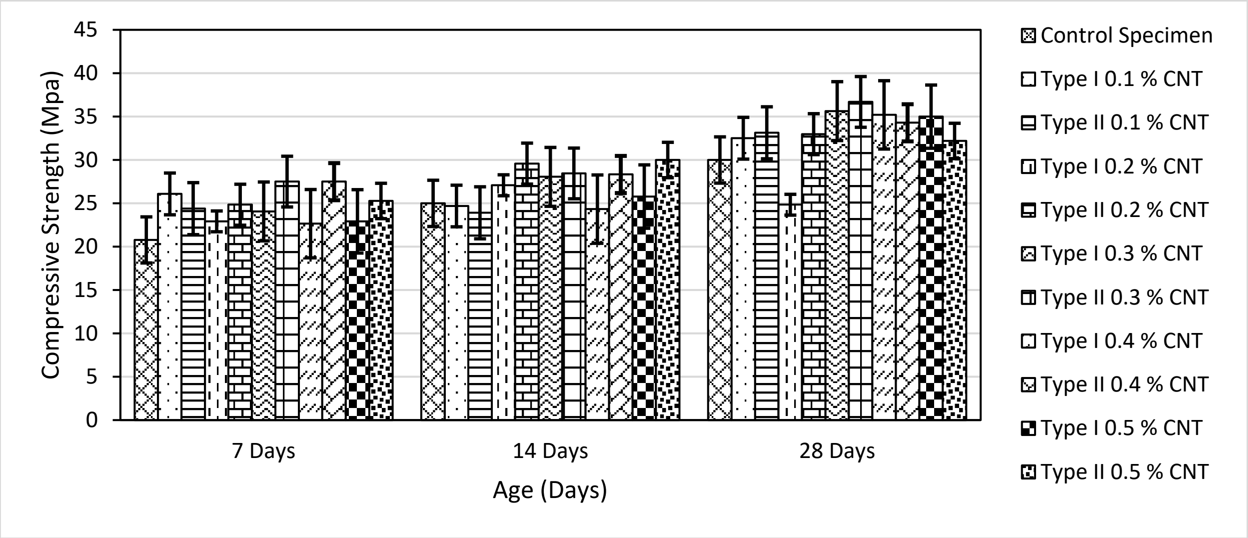


Figure (6): Average compressive strength values for various CNT specimens

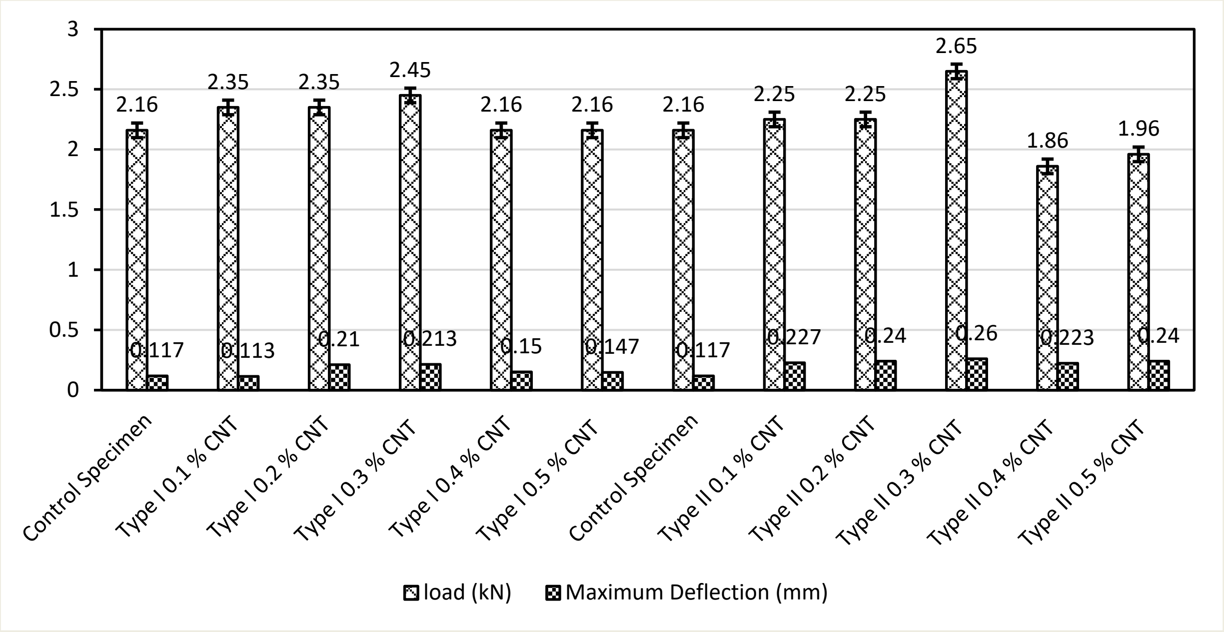


Figure (7): Load-deflection curves for various CNT beams at 7 days

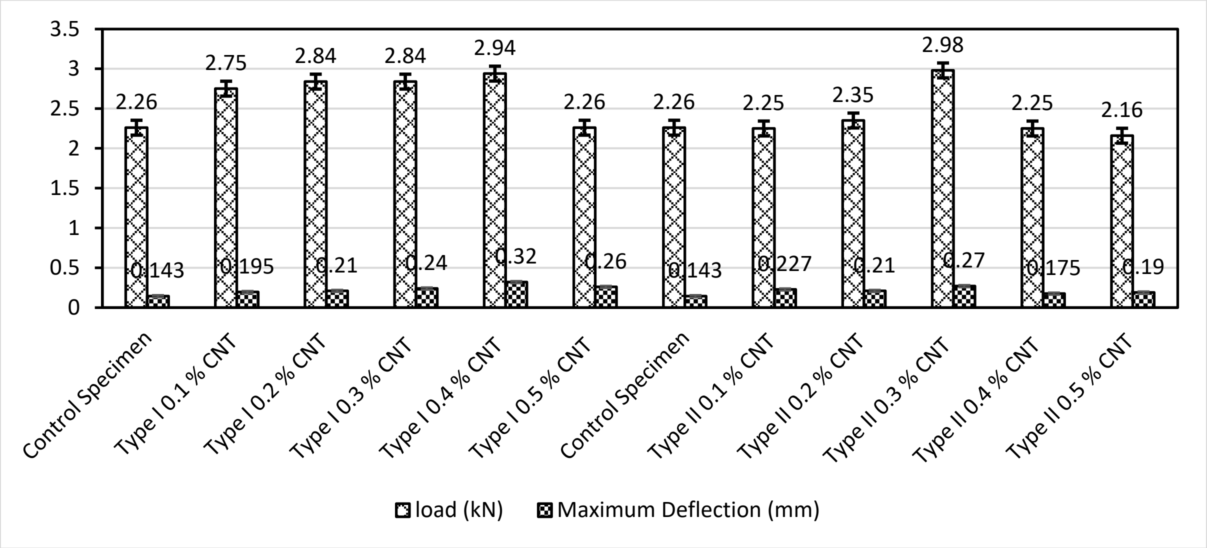


Figure (8): Load-deflection curves for various CNT beams at 14 days

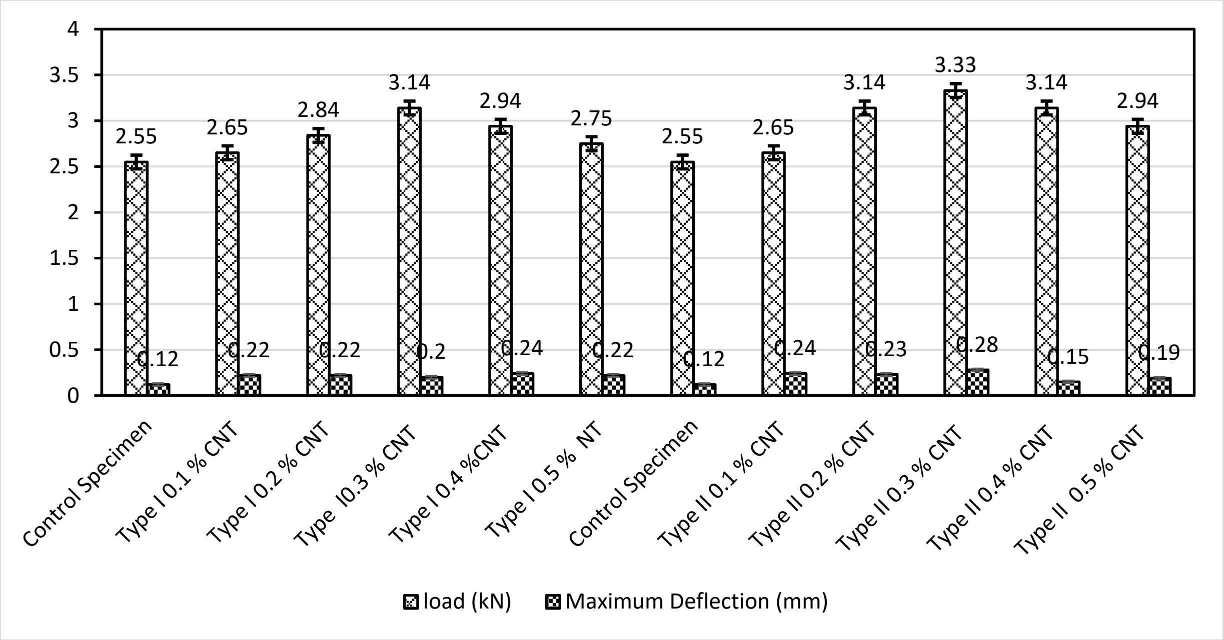


Figure (9): Load-deflection curves for various CNT beams at 28 days

RESULTS AND DISCUSSION

For each batch at 7, 14 and 28 days, various properties were evaluated, *viz*., flexural strength, compressive strength, load-deflection characteristics, density, porosity and water absorption. Figs. 5 through 13 show the results with average values in comparison to control specimens. For each specimen, the mean value as well as standard error of the mean are shown by bar charts. The top and bottom error bars represent the third and first quartile, respectively.

Flexural Strength Test Results

Fig. 5 depicts the flexural strength of mortar specimens with various wt.% of CNTs at 7, 14 and 28 days of immersed water curing. It shows an increasing trend in flexural strength with curing period, which can be due to more hydration with curing time. This strength enhancement follows an uptrend up to 0.3 wt.% CNT content, beyond which a falling trend was observed. This is due to augmentation in the hydration process in the presence of CNTs. Further, CNTs also act as reinforcing agents which ultimately fill the voids and pores along with forming hydrated compounds. Higher amounts of MWCNTs (beyond 0.3%) have a tendency of agglomeration, thus creating weaker zones and consequently strength reduction is observed. Overall, Type II- CNT specimens perform better in terms of strength contribution as compared to Type I- CNT specimens. This could be due to the fact that at high aspect ratio, the crack bridging mechanism is more effective, leading to higher strengths. The highest increase in flexural strength (22%) was shown at 7 days in Type II- 0.3% CNT specimens when compared to control specimens. The same values for Type I- 0.3% CNT specimen show an improvement of 15% compared to its counterpart. The increase in strength at 28 days for the specimens with Type II- 0.3% CNT and Type I- 0.3% CNTs was found to be 17% and 11%, respectively. A higher increase in strength at early ages indicates that the presence of CNTs initiates quick hydration at early ages (0-7 days). It is also found that above 0.3% CNT, the strength shows a decreasing trend compared to control specimens at respective curing periods. Therefore, the optimum concentration of CNTs is found to be 0.3 wt.% of cement for obtaining high-strength mortars.

Compressive Strength Test Results

Compressive strength of mortar specimens for various wt.% of CNTs at different ages is shown in Fig. 6. It is found that at all curing periods, compressive strength increases up to 0.3 wt.% CNTs. The maximum 7-day strength under compression was found for composites with Type II- 0.3% CNT specimens. The maximum increase in compressive strength was about 33% compared to control specimens. Identical values are obtained for increase in compressive strength at 14 days. At 28 days, a lesser increase in strength (22%) was obtained compared to control specimens. Again, a higher increase in strength at early ages indicates that the presence of CNTs accelerates the process of hydration. Beyond 0.3% CNT addition, a falling trend is observed in compressive strength. As the amount of CNT was increased, more aqueous solution was required for proper sonication and additional water stick to the CNT surface due to larger surface area of CNTs. Consequently, strength reduction is observed due to less workability. Also, higher dosage rate of CNT has greater tendency to agglomerate and, therefore, uniform dispersion is difficult to achieve. In turn, CNTs fail to fill the nano-space within cement grains, which is very important for achieving proper reinforcement behaviour. So, there exists an optimum CNT concentration that could result in desired properties of the cementitious specimens. It is also observed that Type II- CNT composites produced higher strengths as compared to Type I- CNT composites at almost all percentages of CNT- admixed mortar specimens. Manzur et al. (2010) obtained similar results in their study for finding the optimum percentage of CNTs in mortars.

Load-Deflection Curves

Based on the three-point flexural test, the optimum percentage of Type I- and Type II- CNTs was evaluated for reinforcing plain mortar flexural specimens. Five dosage rates of 0.1%, 0.2%, 0.3%, 0.4% and 0.5% were used to prepare the flexural beams. Testing was performed at ages of 7, 14 and 28 days. Load-deflection data and ultimate load taken by flexural specimens were recorded. The optimum concentration of CNT by wt.% of cement was determined on the basis of maximum load-carrying capacity of the specimens. Testing of CNT- reinforced flexural specimens was performed under three-point loading to estimate load-deflection characteristics. For comparative study, comparisons were made with the results of plain mortar flexural specimens. The ultimate load-carrying capacity of various CNT- reinforced specimens at various curing ages is provided in Table 3. The load-deflection curves for various concentrations of Type I- and Type II- CNT beams at 7 days under three-point loading test are presented in Fig. 7. The load-deflection curves for various concentrations of Type I- and Type II- CNT beams at 14 and 28 days are presented in Fig. 8 and Fig. 9, respectively. The ultimate load-deflection curves for various concentrations of Type I- and Type II- reinforced CNT beams are shown in Fig. 10. Optimum percentages of Type I- and Type II- CNT in the cementitious composites that will give maximum load supporting power of the flexural specimens were arrived at. An increasing trend in ultimate load-carrying capacity is observed up to 0.3 wt. % of both Type I- and Type II- CNT beams for all curing periods. Further, specimens with Type II- CNT showed maximum ultimate load, since these composites have an inclination to undertake more deflections and are thus responsible for added toughness to the cementitious composites. Therefore, Type II- 0.3% CNT beams are considered to be best performing from both strength and deflection perspectives.

From Fig. 10, it follows that Type II- admixed CNT flexural specimens showed higher deflection as compared to Type I-admixed CNT flexural specimens as well as to control specimens. The reason behind this can be the fact that load-supporting power of CNT specimens was enhanced due to large surface area presented by Type II- CNTs at the interface between matrix and filler. As concentration of CNT in the cementitious matrix increased, further enhancement in strength was observed till it reaches its maximum at 0.3% CNT and this may be due to packing of nano-spaces by CNT fillers to hold the matrix.

As the amount of CNT was more than 0.3%, more aqueous solution was required for proper sonication and excess water sticked to the CNT surface because of higher surface area of CNTs. This gives rise to strength drop due to less workability. Also, higher dosage rate of CNTs has greater tendency to agglomerate and, therefore, uniform dispersion is difficult to achieve. In turn, CNTs fail to fill the nano-space within cement grains which is very important for achieving proper reinforcement behaviour. So, there exists an optimum CNT concentration that could result in desired mechanical properties of composites.

Results of Tests for Density, Porosity and Water Absorption

The inclusion of nano-tubes in cement mortar shows an increase in density from 7 to 28 days (Fig. 11). At 7 and 14 days, quite identical results were found. Composites with Type II- CNTs show better density results (4-5%) as compared to Type I- CNT composites (3-4%). The increase in density can be attributed to the fact that small voids and pores in the cementitious matrix are effectively filled by CNTs, leading to higher density of the composites. At higher dosage rates, CNTs have a greater tendency to agglomerate; therefore, uniform dispersion is difficult to achieve. In turn, CNTs fail to fill the nano-space within cement grains and consequently density will decrease. Therefore, the optimum content of CNTs for obtaining denser composites is found to be 0.3 wt.%.

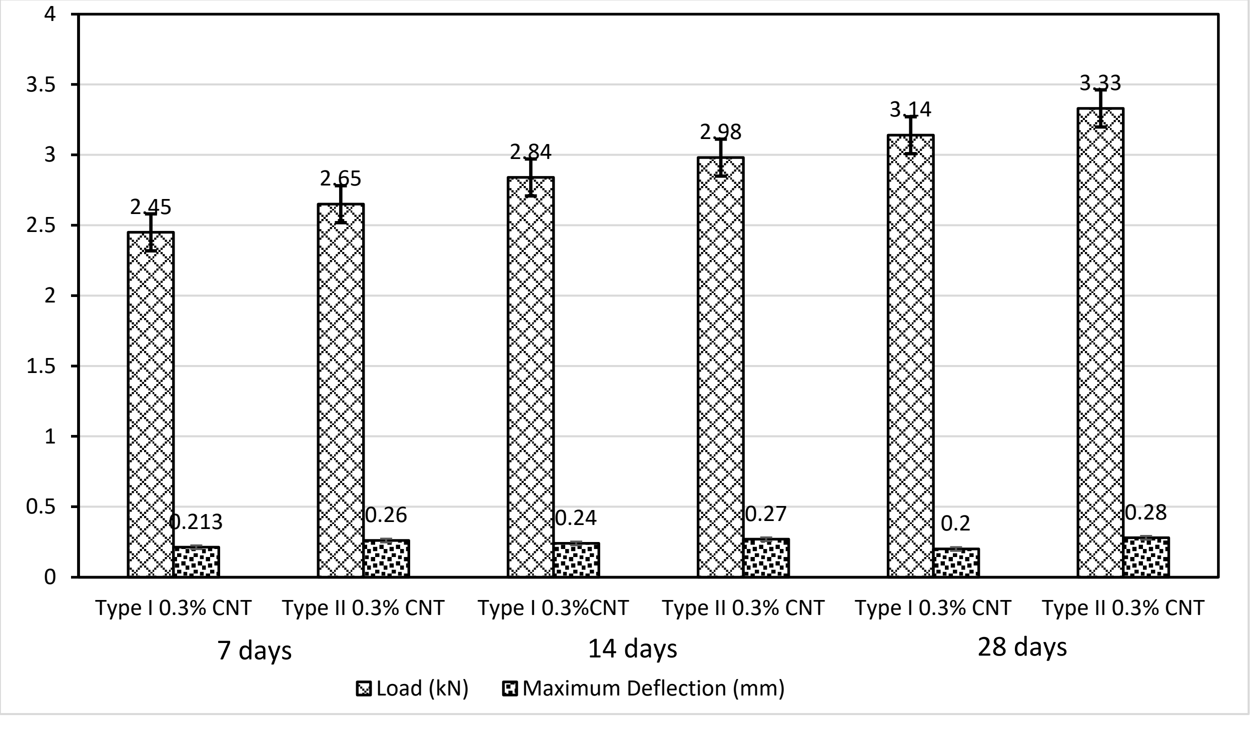


Figure (10): Ultimate load-deflection curves for type II- CNT beams at various curing periods

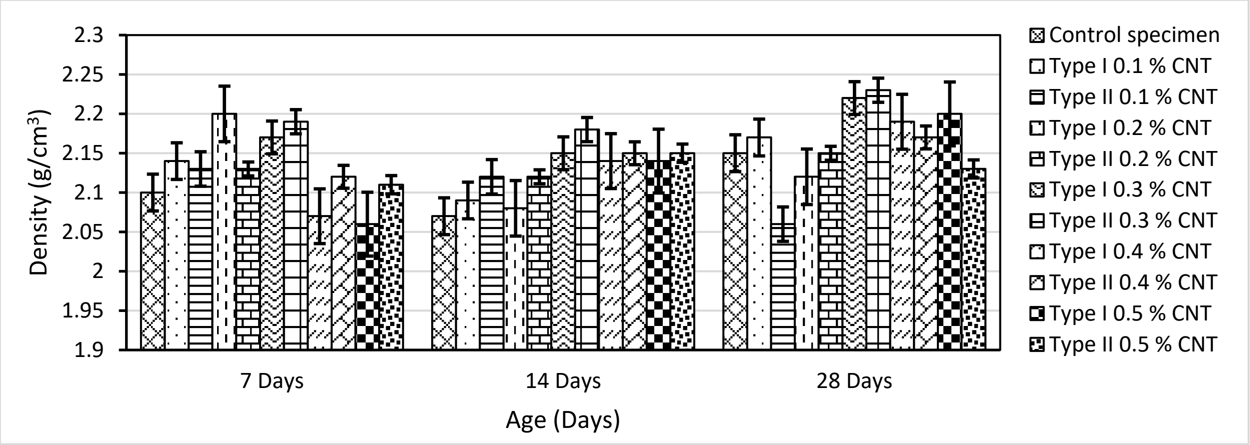


Figure (11): Density of mortar specimens with different wt.% of CNTs

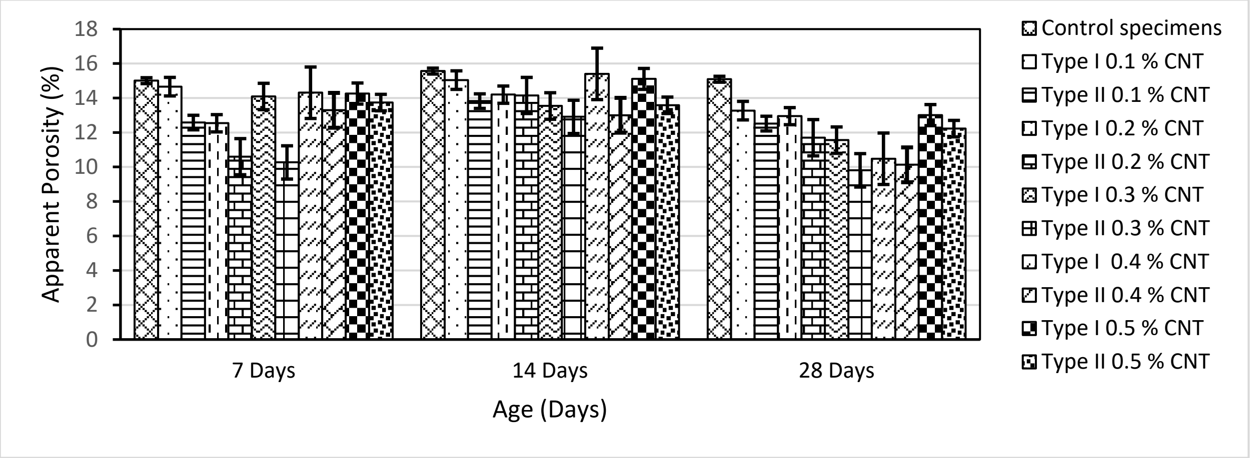


Figure (12): Apparent porosity of mortar specimens with different wt.% of CNTs

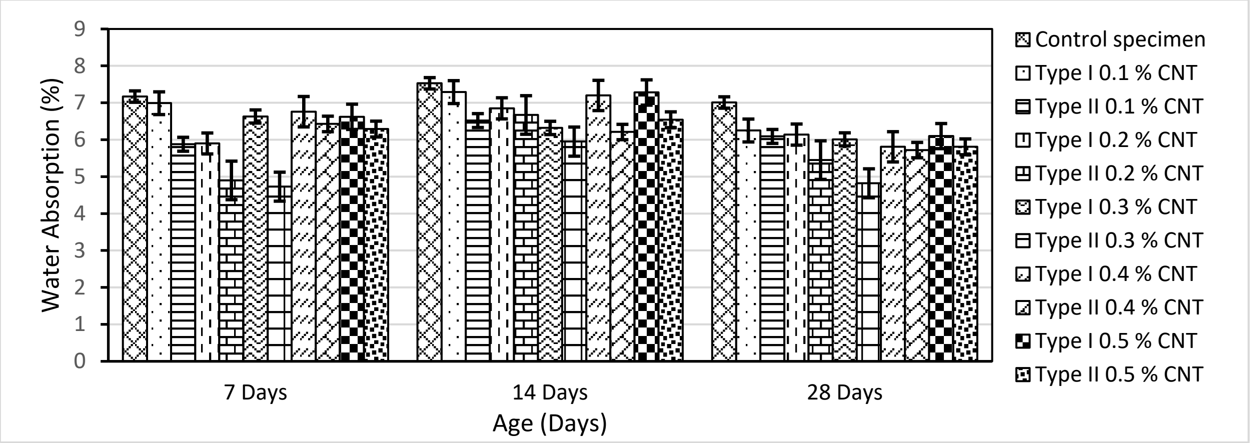


Figure (13): Water absorption of mortar specimens with different wt.% of CNTs

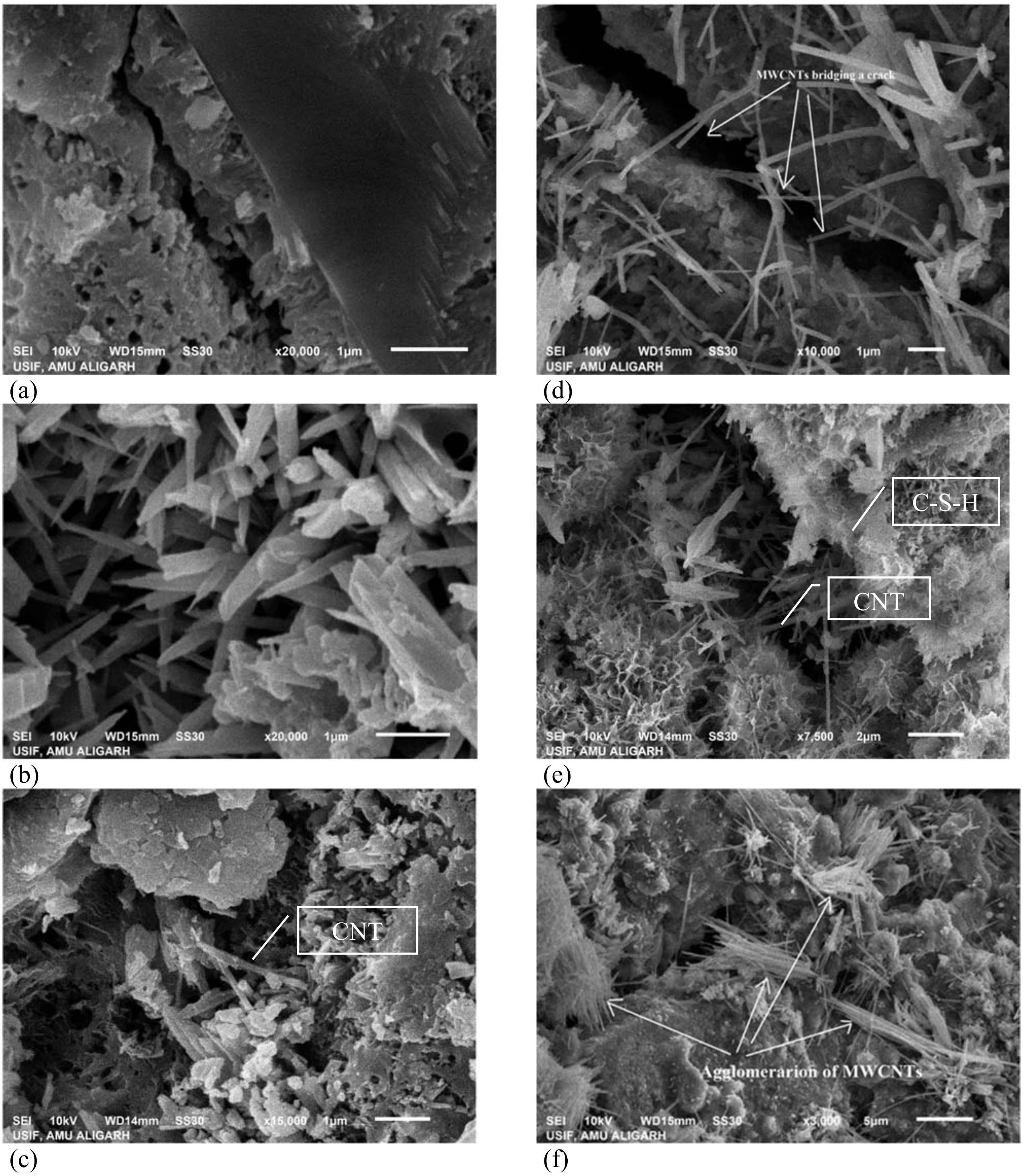


Figure (14): (a) SEM micrographs of mortars without CNTs, (b) with 0.1 (c) 0.2 (d) 0.3 (e) 0.4 and (f) 0.5 wt.% of type II- CNTs at 28 days

Fig. 12 shows a decreasing trend in the porosity of specimens at lower CNT percentages (upto 0.3%) at all ages under investigation. At higher dosage rates, a reverse trend is observed. The possible reason for this behaviour is that at low concentrations, CNTs can possibly fill the pores of hydration compounds. Consequently, porosity was decreasing due to denser microstructure in comparison to control specimens. Again, it is noted that Type II- CNT composites performed better than Type I- CNT composites.

Water absorption results for various curing periods (7, 14 and 28 days) with various wt.% of CNTs are shown in Fig. 13. It shows minimum water absorption property of mortars when the wt.% of CNTs used is 0.3%. At 7 and 28 days, water absorption results were found to decrease by 31% and 22%, respectively for specimens with 0.2 wt.% CNTs. Further, these values are reduced by 34% and 31% for 0.3 wt.% CNTs at respective ages. However, when the CNT percentage in the cement is less, an increase in absorption values was obtained. The possible reason for such phenomenon is that at low CNT- concentrations, small voids and pores are partially filled by hydration products, hence giving higher absorption values. Nevertheless, agglomeration at high concentrations (beyond 0.3%) affects well dispersion of CNTs in the cementitious matrix. Hence, these unfilled voids and pores aid in water absorption. Therefore, best performing CNT percentage for lowest water absorption values is found to be 0.3 wt.%. Again, it is evident from the graph that Type II- CNT composites performed better in relation to Type I- composites for water absorption characteristics.

Scanning Electron Microscopy Results

To elucidate and substantiate the outcomes visually, several SEM micrographs (Fig. 14 (a)-(f)) were taken for the broken specimens with Type II- CNTs at different magnifications. The image of control specimens shows several voids and cracks in their microstructure (Fig. 14 (a)). Some rod-like structures in SEM micrographs were also seen, which can be attributed to resulting hydrated compounds. Fig. 14 (c)-(e) displays that several CNTs were stretched across the fine cracks showing CNT pull out and breakage mechanism. In reality, the breakage mechanism of CNTs infers a reasonable bonding between the nano-tubes and the cementitious matrix. At higher CNT-concentration of CNTs (0.5 wt.%), uniform dispersion is difficult to achieve, resulting in agglomeration at some particular regions, as shown in Fig. 14 (f). The micrographs also confirm that CNTs are connected to the hydrated compounds and the pores seen in the control specimens are significantly reduced, thus improving the bridging phenomenon between voids and pores.

CONCLUSIONS

CNT- admixed cement mortar is a thrust area of research and cementitious composites thus developed have found applications in various civil engineering fields. From the experimental study, it can be concluded that CNT flexural specimens showed most favorable outcomes for various mechanical properties when compared to plain counterparts. This may be due to high specific surface area of CNTs, which reduces the concentration of stress at a particular point. Between 0.1 and 0.3% dosage rates, increase in mechanical strengths was observed for both Type I- and Type II- CNT specimens. Composites with CNT concentrations greater than 0.3% resulted in low strengths. More CNT addition caused insufficient dispersion and produced weaker composites. Again, if CNTs are not uniformly distributed, they agglomerate creating a weaker zone within the cement matrix. Therefore, the optimum percentage of CNTs to obtain maximum strength in cement mortar was found to be 0.3% by weight of cement. It is also observed that Type II- CNT composites produced higher strengths as compared to Type I- CNT composites at almost all percentages of CNT admixed specimens, which can be due to higher surface area of Type II- CNTs that distributes load over a large area. The compressive strengths of Type II- 0.3% CNT composites were about 33% and 22% higher as compared to control specimens at 7 and 28 days, respectively. The maximum 7- and 28-day flexural strengths with Type II- CNT composites were 22% and 17% higher than those of control specimens. The inclusion of CNTs in the cement matrix lowers porosity and water absorption capacity due to packing of fine pores in the hydrated matrix. From the foregoing investigation, it was found that when CNT content was 0.3 wt.%, water absorption registered lowest values. The pores in the matrix can be reduced by adding CNTs, which was perceived through various scanning electron microscopy images. The SEM images of nano-composites clearly show effective crack bridging, pull out and breakage mechanisms by the CNTs. Breakage of CNTs indicates a decent bonding between the matrix and the CNTs.

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