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Review

Effect of carbon nanotubes on properties of cement mortars

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HIGHLIGHTS

- Classification of carbon nanotubes.
- Uses and applications of carbon nanotubes.
- Review of synthesis of carbon nanotubes in previous researches.
- Review of various properties like, compressive strength, flexural strength.
- Review of properties like microstructure, Youngs modulus, porosity.

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ABSTRACT

Carbon NanoTubes (CNTs) are primarily elemental carbon consisting of curved graphene layer which consists of a single layer of carbon atoms in a honeycomb structure that may contain varying amounts of metal impurities, depending on the method of manufacture. After various years from its detailed characterization CNTs have grown from a material of dreams to a real world material that has already found its application fields. The production capability for carbon nanotubes is growing every year in an exponential degree and as a consequence the price is steeply descending. In addition to their remarkable strength, which is usually quoted as 100 times that of tensile strength of steel at one-sixth of the weight, CNTs have shown a surprising array of other properties. It has a wide range of its use in various applications like its use in energy sector, medicine sector, environmental sectors, electronics sectors, etc. In Civil Engineering applications CNTs are being effectively used in various research works which remarkably improves the mechanical properties of cement mortars, when added into it.

Published literature has shown that CNTs could be used in manufacturing concrete and mortars. This paper presents an overview of some of the research published on the use of CNT in concrete/mortars. Effect of CNTs on properties such as compressive strength, tensile strength, modulus of elasticity, flexural strength, porosity, electrical conductivity and autogeneous shrinkage are presented in this paper.

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1. Introduction

Until the mid-1980s pure solid carbon was thought to exist in only two physical forms, diamond and graphite, called allotropes, which have different physical structures and properties however their atoms are both arranged in covalently bonded networks. In 1985 a group of researchers led by Richard Smalley and Robert Curl of Rice University in Houston and Harry Kroto of the University of Sussex in England made an interesting discovery. They vaporized a sample of graphite with an intense pulse of laser light and used a stream of helium gas to carry the vaporized carbon into a mass spectrometer that showed peaks corresponding to clusters of carbon atoms, with a particularly strong peak corresponding to molecules composed of 60 carbon atoms, C60. This soccer ball shaped C60 molecule was named "buckerminsterfullerene" or "buckyball" for short. The unique geometric properties of this new allotrope of carbon did not end with soccer shaped molecules, it was also discovered that carbon atoms can form long cylindrical tubes also. These tubes were originally called "buckytubes" but now are better known as carbon nanotubes or CNT for short. These molecules are shaped like a tube; imagine a sheet of graphite ("graphene sheet") or chicken wire rolled into a tube. It was the Iijima observation of the multiwall carbon nanotubes in 1991 that heralded the entry of many scientists into the field of CNT, stimulated by the remarkable one-dimensional (1D) quantum effects predicted for their electronic properties, and subsequently by the promise that the remarkable structure and properties of carbon nanotubes might give rise to some unique applications. Whereas the initial experimental Iijima observation was for multi-wall nanotubes (MWNTs), it was less than 2 years before single-wall carbon nanotubes (SWNTs) were discovered experimentally by Iijima and his group. Since the first report on CNTs by Iijima in 1991, numerous attempts have been made to strengthen materials (especially polymer-based materials) with nanotubes [1–3]. In the last few years, the effect of CNT-additions to cement-based materials has also been investigated.

Carbon nanotubes can be categorized into two major forms: single walled carbon nanotubes and multi walled carbon nanotubes. Single-Walled Carbon NanoTubes (SWCNTs) are basically tubes of graphite and are normally capped at the ends, as shown in Fig. 1, although the caps can be removed [4]. The caps are made by mixing in some pentagons with the hexagons and are the reason that nanotubes are considered close cousins of buckminsterfullerene, as shown in Fig. 2, a roughly spherical molecule made of sixty carbon atoms that looks like a soccer ball and is named after the architect Buckminster Fuller. The theoretical minimum diameter of a carbon nanotube is around 0.4 nanometres, which is about as long as two silicon atoms side by side. Average diameters tend to be around the 1.2 nanometre mark, depending on the process used to create them. SWNTs are more pliable than their multiwalled counterparts and can be twisted, flattened and bent into small circles or around sharp bends without breaking. They can be conducting, like metal (such nanotubes are often referred to as metallic nanotubes), or semiconducting, which means that the flow of current through them can be stepped up or down by varying an electrical field. On the other hand multi-walled carbon nanotubes are concentric cylindrical graphite tubes made out of SWNTs. Although it is easier to produce significant quantities of MWNTs than SWNTs, their structures are less well understood than single-wall nanotubes because of their greater complexity and variety as shown in Fig. 3. MWNTs always (so far) have more defects than SWNTs and these diminish their desirable properties

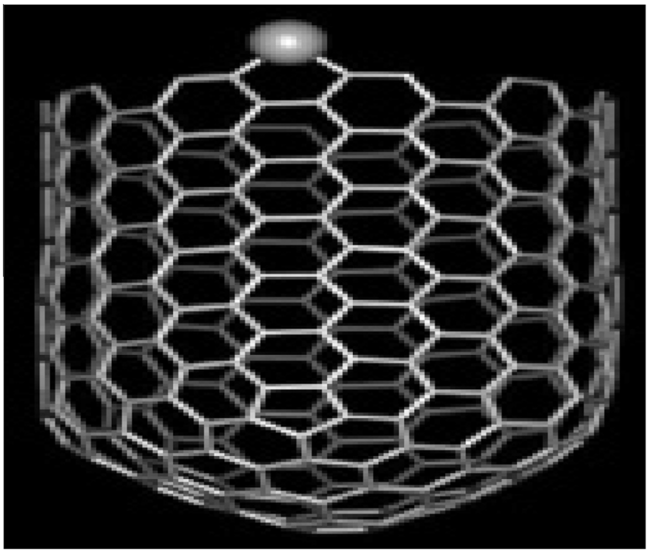


Fig. 1. Simulated structure of a carbon nanotube. Courtesy of Richard Smalley's picture gallery (http://www.cmp-cientifica.com).

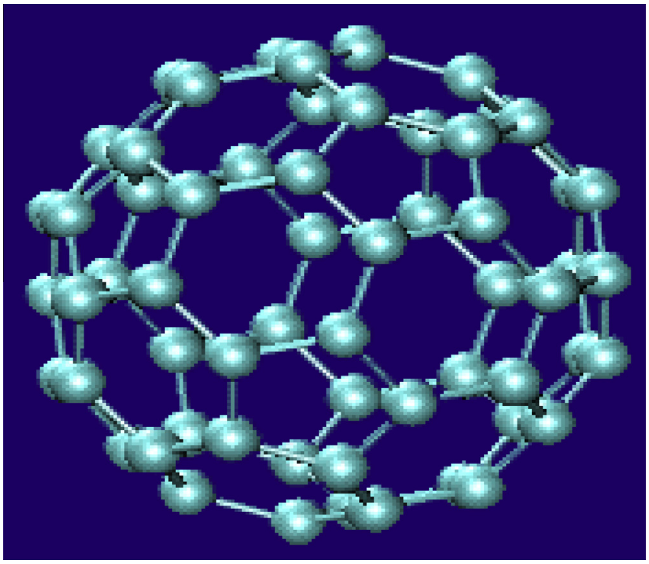


Fig. 2. Buckminsterfullerene. *Source*: Chem Library, Imperial College of Science, Technology and Medicine, UK (http://www.cmp-cientifica.com).

[4]. Many of the nanotube applications now being considered or put into practice involve multi-walled nanotubes, because they are easier to produce in large quantities at a reasonable price and have been available in decent amounts for much longer than SWNTs.

2. Properties of carbon nanotubes

2.1. Electrical properties

The unique electrical properties of carbon nanotubes are to a large extent derived from their 1-D character and the peculiar electronic structure of graphite. They have extremely low electrical resistance. Resistance occurs when an electron collides with some defect in the crystal structure of the material through which it is passing. The defect could be an impurity atom, a defect in the crystal structure, or an atom vibrating about its position in the crystal. Such collisions deflect the electron from its path but the electrons inside a carbon nanotube are not so easily scattered because of their very small diameter and huge ratio of length to diameter ratio that can be up in the millions or even higher.

2.2. Mechanical properties

The carbon nanotubes are expected to have high stiffness and axial strength as a result of the carbon–carbon sp2 bonding. The practical application of the nanotubes requires the study of the elastic response, the inelastic behaviour and buckling, yield strength and fracture. Nanotubes are the stiffest known fibre, with a measured Young's modulus of 1.4 TPa and elongation to failure of 20–30%, which projects to a tensile strength of well above 100 GPa (possibly higher), by far the highest known. For comparison, the Young's modulus of high-strength steel is around 200 GPa, and its tensile strength is 1–2 GPa.

2.3. Thermal properties

CNT have now been shown to have a thermal conductivity at least twice that of diamond. CNT have the unique property of feeling cold to the touch, like metal, on the sides with the tube ends exposed, but similar to wood on the other sides. The specific heat and thermal conductivity of carbon nanotube systems are determined primarily by phonons. The measurements of the thermoelectric power (TEP) of nanotube systems give direct information for the type of carriers and conductivity mechanisms.

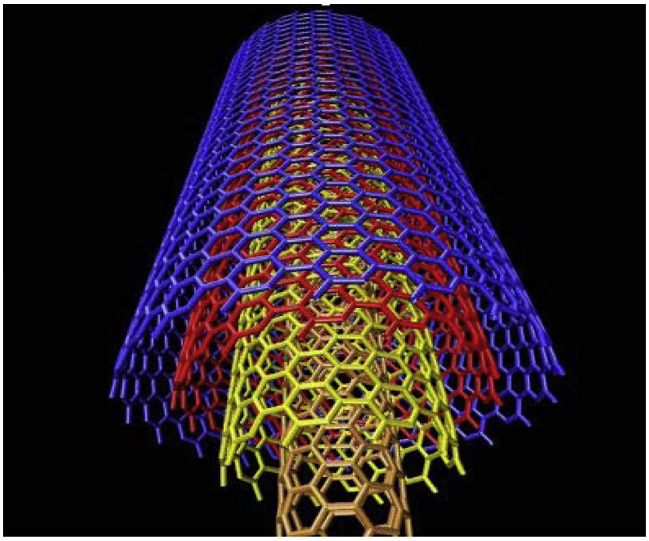


Fig. 3. Representaion of a multi-walled carbon nanotube. Courtesy of A. Rochefort, Nano-CERCA, University of Montreal, Canada (http://www.cmp-cientifica.com).

2.4. Strength

Carbon nanotubes are the strongest and stiffest materials yet discovered in terms of tensile strength and elastic modulus. In 2000, a multi-walled carbon nanotube was tested [5] to have a tensile strength of 63 gigapascals (GPa) and in 2008, gave strength of up to 100 Gpa [6], which is in agreement with quantum/atomistic models. Although the strength of individual CNT shells is extremely high, weak shear interactions between adjacent shells and tubes leads to significant reductions in the effective strength of multi-walled carbon nanotubes and carbon nanotube bundles down to only a few GPa's [7]. This limitation has been recently addressed by applying high-energy electron irradiation, which crosslinks inner shells and tubes, and effectively increases the strength of these materials to 60 GPa for multi-walled carbon nanotubes [6] and 17 GPa for double-walled carbon nanotube bundles.

2.5. Kinetic properties

Multi-walled nanotubes are multiple concentric nanotubes precisely nested within one another. These exhibit a striking telescoping property whereby an inner nanotube core may slide, almost without friction, within its outer nanotube shell, thus creating an atomically perfect linear or rotational bearing. This is one of the first true examples of molecular nanotechnology, the precise positioning of atoms to create useful machines. Already, this property has been utilized to create the world's smallest rotational motor [8]. Future applications such as a gigahertz mechanical oscillator are also envisaged.

2.6. Toxicity

The toxicity of carbon nanotubes has been an important question in nanotechnology. The data are still fragmentary and subject to criticism. Preliminary results highlight the difficulties in evaluating the toxicity of this heterogeneous material. Parameters such as structure, size distribution, surface area, surface chemistry, surface charge, and agglomeration state as well as purity of the samples, have considerable impact on the reactivity of carbon nanotubes. However, available data clearly show that, under some conditions, nanotubes can cross membrane barriers, which suggests that, if raw materials reach the organs, they can induce harmful effects such as inflammatory and fibrotic reactions [9]. Under certain conditions CNTs can enter human cells and accumulate in the cytoplasm, can cause cell death [10]. Results of rodent studies collectively show that regardless of the process by which CNTs were synthesized and the types and amounts of metals they contained, CNTs were capable of producing inflammation, epithelioid granulomas (microscopic nodules), fibrosis and biochemical/toxicological changes in the lungs [11]. Comparative toxicity studies in which mice were given equal weights of test materials showed that SWCNTs were more toxic than quartz, which is considered a serious occupational health hazard when chronically inhaled. The needle-like fibre shape of CNTs is similar to asbestos fibres. This raises the idea that widespread use of carbon nanotubes may lead to pleural mesothelioma, a cancer of the lining of the lungs orperitoneal mesothelioma, a cancer of the lining of the abdomen.

3. Applications of carbon nanotubes

Carbon NanoTubes (CNTs) have wide range of applications in various sectors like Energy, Medicine, Environment, Electronics and Civil Engineering applications. A team of researchers at Rice University have developed electrodes made from carbon nanotubes grown on graphene with very high surface area and very low electrical resistance. They have also built a solar cell that uses graphene as electrode while using buckyballs and carbon nanotubes to absorb light and generate electrons. Also using carbon nanotubes in the cathode layer of a battery that can be produced on almost any surface can be formed by simply spraying layers of paint containing the components needed for each part of the battery. Carbon nanotubes can also perform as a catalyst in a fuel cell by avoiding the use of expensive platinum on which most catalysts are based. Also researchers have developed a sensor that uses nanotubes and gold nanoparticles to detect proteins that indicate the presence of oral cancer. Tests have shown this sensor to be accurate and it provides results in less than an hour. Also it can be used in improving the healing process for broken bones by providing a carbon nanotube scaffold that new bone material can grow around, using nanotubes as a cellular scale needle to deliver quantum dots and proteins into cancer cells. An inexpensive nanotube-based sensor can detect bacteria in drinking water. When the bacteria is present it attaches to the antibodies, changing the spacing between the nanotubes and the resistance of the paper strip containing the nanotubes. Other applications includes its use in aircraft to increase strength and flexibility in highly stressed components, a lightweight, low power anti-icing system using carbon nanotubes in a layer coated onto aircraft wing surfaces, static dissipative plastic moulding compounds containing nanotubes that can be used to make parts such as automobile fenders that can be electro statically painted, strong, lightweight composites of carbon nanotubes and other materials that can be used to build lightweight spacecraft, cables made from carbon nanotubes strong enough to be used in building the Space Elevator to drastically reduce the cost of lifting people and materials into orbit.

CNTs also have tremendous range of applications in concrete structures. Depending on the size and morphology of the fibrous carbons, the application varies a lot. Researchers have found that carbon nanotubes can fill the voids that occur in conventional concrete. These voids allow water to penetrate concrete causing cracks, but including nanotubes in the mix the cracking can be stopped. Carbon nanotubes/nanofibres (CNTs/CNFs) are potential candidates for use as nano-reinforcements in cement-based materials. CNTs/CNFs exhibit extraordinary strength with modulus of elasticity on the order of TPa and tensile strength in the range of GPa, and they have unique electronic and chemical properties [12–14]. For load-bearing applications, CNT powders mixed with polymers or precursor resins can increase stiffness, strength, and toughness. Adding approx. 1 wt.% MWNT to epoxy resin can enhance the stiffness and fracture toughness by 6% and 23%, respectively, without compromising other mechanical properties. These enhancements depend on CNT diameter, aspect ratio, alignment, dispersion, and interfacial interaction with the matrix. CNTs can also be deployed as additives in the organic precursors used to form carbon fibres which have been used as reinforcements in high strength, light weight, high performance composites. Theoretical studies have suggested that SWNTs could have a Young's modulus as high as 1TPa, which is basically the in-plane value of defect free graphite. Apart from strength characteristics Nanotubes have shown promise in enhancing the mechanical performance, the resistance to chloride penetration, and the self-compacting properties of concrete and in reducing permeability and shrinkage [15,16]. The most important application of nanotubes based on their mechanical properties will be as reinforcements in composite materials. Makar et al. [17] were among the first to indicate, using hardness measurements, that CNTs can affect early-age hydration and that a strong bond is possible between the cement paste and the CNTs. The main problem is in creating a good interface between nanotubes and the polymer matrix and attaining good load transfer from the matrix to the nanotubes, during loading. The reason for this is essentially twofold. First, nanotubes are atomically smooth and have nearly the same diameters and aspect ratios (length/diameter) as polymer chains. Second, nanotubes are almost always organized into aggregates which behave differently in response to a load, as compared to individual nanotubes. The small and uniform dimensions of the nanotubes produce some interesting applications. With extremely small sizes, high conductivity, high mechanical strength and flexibility (ability to easily bend elastically), nanotubes may ultimately become indispensable in their use as nanoprobes. A lot of research has been carried out all across the globe in using nanotubes as sensors embedded in the concrete structures as crack detectors. It has a wide range of scope in health monitoring applications of concrete structures as well.

Apart from these applications the major challenges that are being faced in its usage are their availability and cost. For bulk applications, such as fillers in composites, where the atomic structure has a much smaller impact on the resulting properties, the quantities of nanotubes that can be manufactured still falls far short of what industry would need. There are no available techniques that can produce nanotubes of reasonable purity and quality in kilogram quantities. The industry would need tonnage quantities of nanotubes for such applications. The market price of nanotubes is also too high presently for any realistic commercial application. But it should be noted that the starting prices for carbon fibres and fullerenes were also prohibitively high during their initial stages of development, but have come down significantly in time. In the last 2–3 years, there have been several companies that were set up in the US to produce and market nanotubes. If these challenges can be overcome then carbon nanotubes can prove to be the most innovative and advantageous material in relation to concrete structures.

4. Synthesis of Carbon NanoTubes (CNTs)

Techniques like carbon arc-discharge, laser ablation, high pressure carbon monoxide and Chemical Vapour Deposition (CVD) are being employed to synthesize CNTs of sizeable quantities. Of these, the CVD method has shown the most promise in terms of its price/unit ratio. The arc-evaporation method, which produces the best quality nanotubes, involves applying a current of about 50 A between two graphite electrodes in a helium atmosphere. This results in graphite evaporation, part of which condenses on the walls of the reactor vessel and part on the cathode. SWCNTs are produced when Co and Ni or some other metal is added to the anode. Ijima and Ichihasti have reported the synthesis of SWCNTs with diameters of around 1 nm by using a gas mixture of 10 Torr methane and 40 Torr argon at a dc current of 200 A and a voltage of 20 V. Researchers have also used the mixture of catalysts (Ni–Co, Co–Y, or Ni–Y) in the synthesis of SWCNTs. In laser-ablation technique, intense laser pulses are used to ablate a carbon target. The pulsed laser-ablation of graphite in the presence of an inert gas and catalyst yields CNTs in the form of ropes or bundles of 5–20 nm diameter and tens to hundreds of micrometers long. Fullerenes, graphite polyhedrons with enclosed metal particles, and amorphous carbon were obtained as the by-products in an arc-discharge and a laser-ablation technique. Generally, the CVD technique involves the reaction of a carbon-containing gas (such as methane, acetylene, ethylene, and ethanol) with a metal catalyst particle (usually, cobalt, nickel, iron, or a combination of these such as cobalt/iron

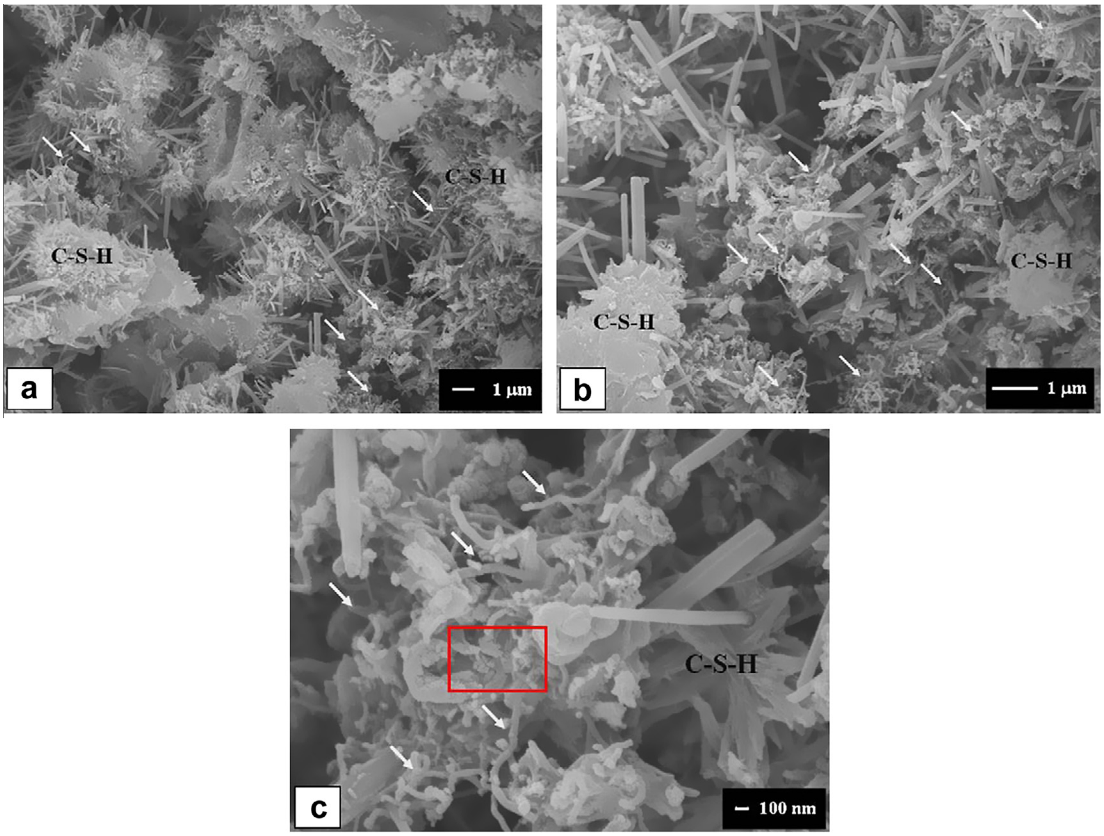


Fig. 4. SEM images of carbon nanotubes–fly ash cement composites at (a) 5000×, (b) 10,000× and (c) 30,000× [22].

or cobalt/molybdenum) at temperatures above 600 °C. Most SWCNT samples contain carbonaceous impurities such as amorphous carbon, fullerenes, nanoparticles, and transition metals introduced as catalysts during the synthesis of SWCNTs [18]. Proposed applications of SWCNTs, namely, nano-electronic devices, field emitters, gas sensors, high-strength composites and hydrogen storage demand pure SWCNT materials. Hence, one of the greatest current demands in carbon nanotube research and commercialization includes the development of effective and viable methods for obtaining SWCNTs in pure form without wall damage. The methods adopted include hydrothermal, gaseous, or catalytic oxidation, nitric acid reflux, peroxide reflux, cross-flow filtration and chromatography and chemical functionalization. A scalable purification is possible using microwave heating in the presence of air followed by treatment with hydrochloric acid. Microwave assisted purification is also used for purification of MWCNT. Various methods that are adopted in various studies have been illustrated in Table 1.

5. Properties of cement mortars containing CNTs

Due to the excellent properties of carbon nanotubes, various researches have been carried out in studying the effect of inclusion of carbon nanotubes on various mechanical properties of mortars. A brief of properties are listed in this section.

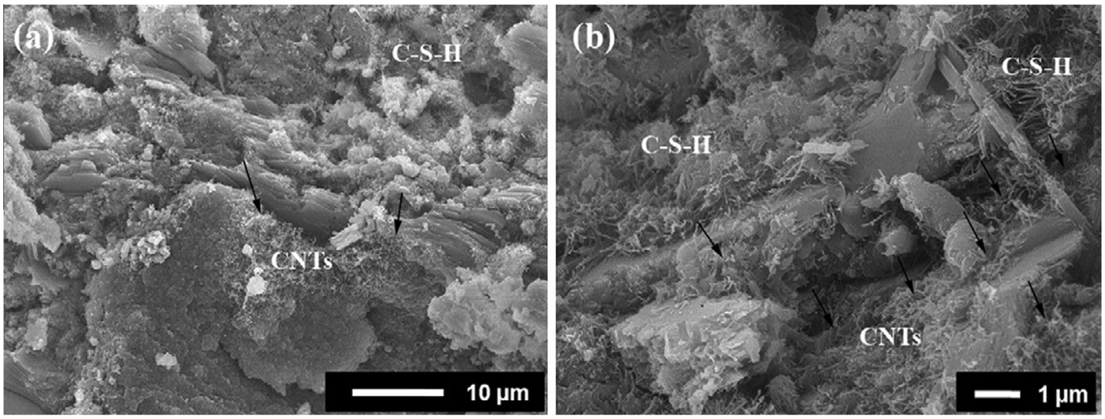


Fig. 5. SEM micrographs of 1 wt.% CNTs mix at 28 days: (a) 2000× and (b) 10,000× [23].

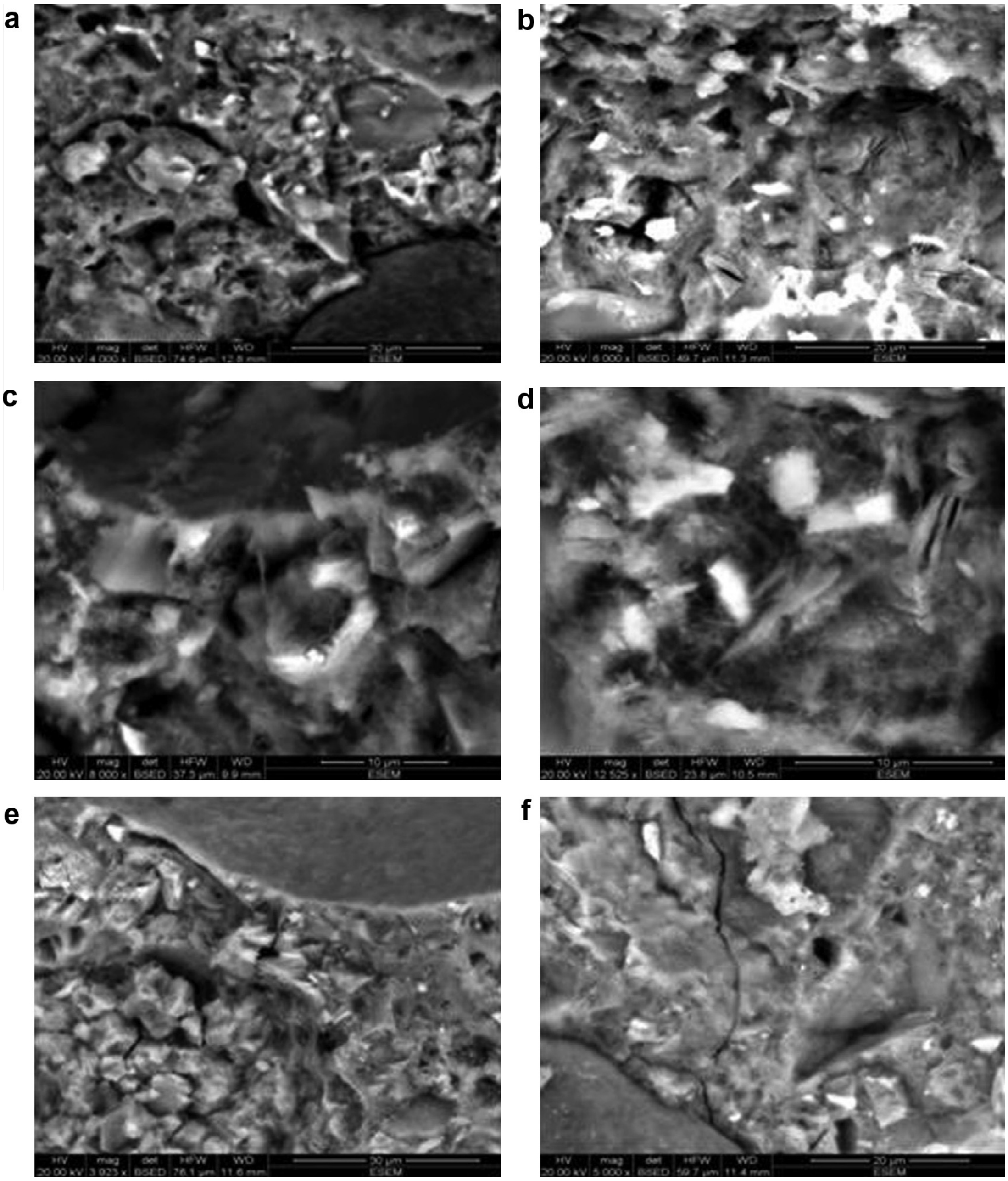


Fig. 6. SEM of ordinary Portland cement mortar; (a) control mortar, (b) mortar containing 6% NMK, (c) mortar containing 6% NMK and 0.005% CNTs, (d) mortar containing 6% NMK and 0.02% CNTs, (e) mortar containing 6% NMK and 0.05% CNTs and (f) mortar containing 6% NMK and 0.01% CNTs [25].

5.1. Microstructure

Microstructure is defined as the structure of a prepared surface of material as revealed by a microscope above 25× magnification. The microstructure of a material (which can be broadly classified into metallic, polymeric, ceramic and composite) can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, and wear resistance, which in turn govern the application of these materials in industrial practice.

Chaipanich et al. [22] studied the effect of adding Carbon NanoTubes (CNTs) with 0.5% and 1% by weight in fly ash cement matrix on the mechanical properties of CNT–fly ash cement composite. SEM analysis was done and the micrographs were studied. The results showed that CNT helped in further filling up the pores between the hydration products such as calcium silicate hydrates (CSH) and ettringite as shown in Fig. 4, where CNTs (marked by arrows) can be seen next to that of ettringite and C–S–H in some ways reinforcing the matrix where the distinguished curl of carbon nanotubes can be seen between the fly ash cement matrixes. The micrographs also showed the good interaction between carbon nanotubes and the fly ash cement matrix with carbon nanotubes acting as filler resulting in a denser microstructure and higher strength when compared to the reference fly ash mix without CNTs.

Nochaiya and Chaipanich [23] investigated the microstructure properties of Portland cement–multi-walled carbon nanotube composite. Multi-walled carbon nanotubes (CNTs) were used as an additive material, up to 1% weight of cement, synthesized by an infusion Chemical Vapour Deposition (CVD) method using nickel oxide as a catalyst. Microstructure analysis of samples of the 1% CNT mix was characterized using field emission Scanning Electron

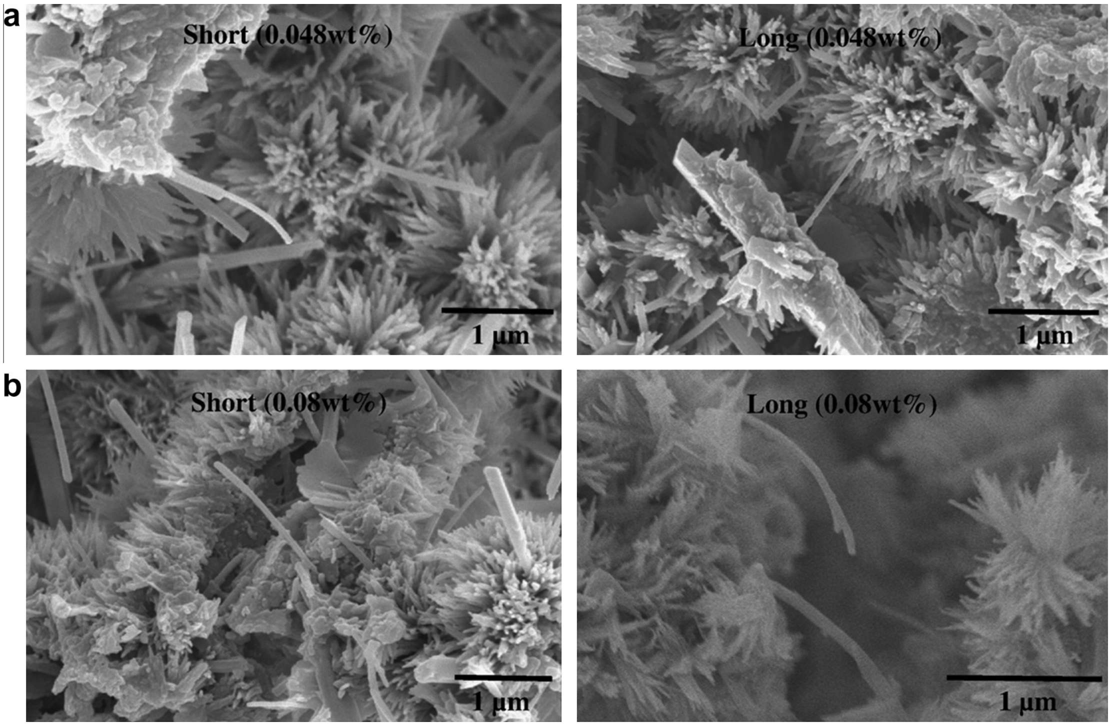


Fig. 7. Effect of different types of MWCNTs (short-long) with concentrations of (a) 0.048 wt.% and (b) 0.08 wt.% in 18 h cement paste [27].

Microscopy, microstructure shown in Fig. 5. The results showed good interaction between multi-walled carbon nanotubes and hydration products of Portland cement pastes, with multi-walled carbon nanotubes acting as filler which resulted in a denser microstructure and higher strength when compared to the control mix.

Morsy et al. [25] investigated the behaviour of cementitious matrix made from multi-walled carbon nanotubes and nano-clay materials. The OPC was substituted by 6% of NMK by weight and the mortar samples were prepared. For identification of the changes occurred in the microstructure, Scanning Electron Microscope (FEL-Spectra) was used with resolution of 4 nm. The micrographs of control, blended mortar containing NMK and CNT specimens, as shown in Fig. 6, shows that OPC mortar displayed the existence of microcrystalline and nearly amorphous, mainly as calcium silicate hydrates (CSH) whereas SEM micrographs of NMK cement mortar indicated the perfectly dense structure with the appearance of calcium hydroxide as ill-crystals. It was also illustrated that the CNTs were dispersed uniformly in the cement mortar and there was no aggregation of CNTs. The CNTs were found embedded as individual fibres in the paste and acting as bridges between hydrates and across cracks. The small size of the NMK particles compared to that of anhydrous cement particles allowed them to work their way in-between the individual CNTs which caused the CNTs to separate from one another during mixing and resulting in the separation of fibres. With the increase in CNT content, the SEM micrograph indicated the appearance of micro-cracks which suggested that at higher concentration the CNTs re-agglomerate and slide on each other which resulted in the micro-cracks formation and weak bond in the microstructure.

Konsta-Gdoutos et al. [27] investigated the effect of two different types of Multi Walled Carbon NanoTubes (MWCNTs) having the same production method, the same diameter, but different lengths, designated as short and long and for dispersion ultra-sonication technique was used. The length of the short MWCNT was in the range of 10–30 μm whereas length of the long MWCNT was in between 10 and 100 μm. Short and long fibres were incorporated into the composite at two different concentrations with lower concentration of 0.048% and higher concentration of 0.08%, respectively. The effects of different length of MWCNTs was analysed by the nanostructure of cement nano-composites as shown in Fig. 7. The figure showed that in all cases MWCNTs was well dispersed in cement paste and only individual MWCNTs can be identified on the fracture surface. Large amount of energy was expected in the mix from the method of ultra-sonication and it was cleared from the SEM imaging that these high levels of energy were absolutely necessary for adequate dispersion of nano-tubes.

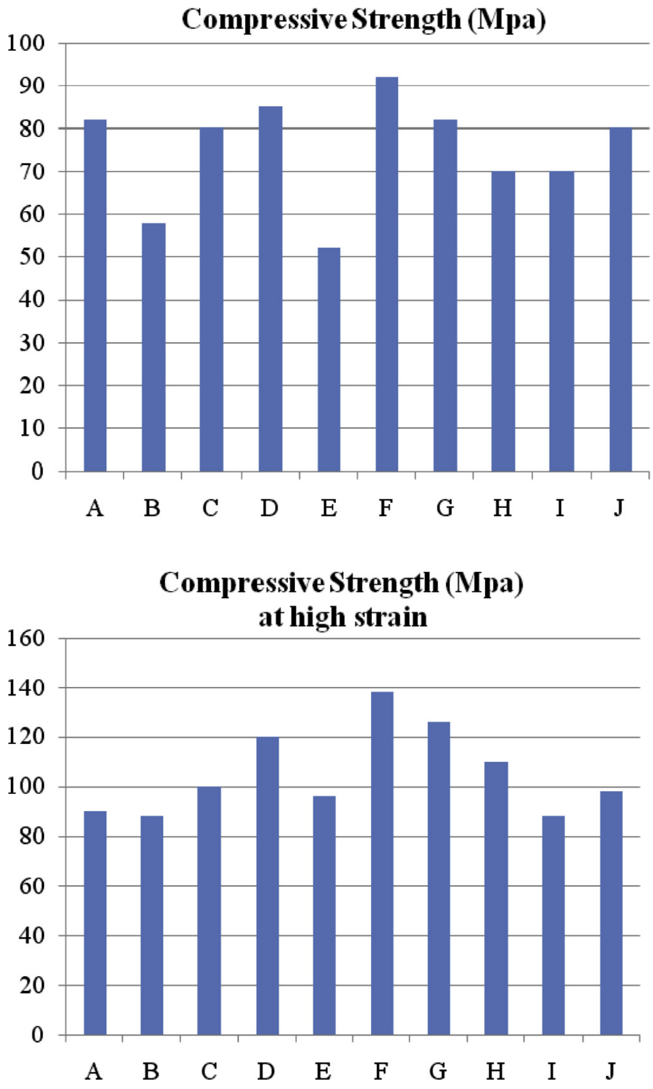
5.2. Compressive strength

The compressive strength is the capacity of a material or structure to withstand loads and the ultimate compressive strength of a material is that value of uniaxial compressive stress reached when the material fails completely. The compressive strength is usually obtained experimentally by means of a compressive test where uniaxial compressive load is applied till its failure.

Sobolkina et al. [19] investigated the dispersion of carbon nanotubes and its influence on the mechanical properties of the cement matrix with specimen preparation details shown in Table 1. Fig. 8a shows the compressive strength results for quasi-static loading. The application of SDS as a surfactant led to a severe drop in the strength of the hardened cement which was due to high porosity of the samples containing SDS caused by the formation of foam. In contrast, Brij 35 had no influence on strength and on porosity. No distinct increase in compressive strength was observed after modifying the cement paste with CNTs in a concentration of 0.05% by weight of cement in comparison with the reference sample, although these results were in disagreement with the findings of some previous investigations [28]. In contrast, the selective adsorption of SDS on N-CNT surfaces gives rise to a high concentration of surfactant in water, which leads to foam formation and, consequently, high porosity of the cement paste. An increase in the CNT content of up to 0.25% by cement weight demonstrates no positive influence on strength. At a high strain rate, the negative influence of SDS on compressive strength was reduced as shown in

Fig. 8b as the pore volume of the hardened cement paste was filled with water absorbed prior to testing. The compressive strength of the hardened cement paste containing Brij 35 was improved by 40% using the mixed CNTs and by 30% using the N-CNTs. The increase in strength in the samples where SDS was used totalled 35% and 12% for the mixed and nitrogen-doped CNTs, respectively. An increase in CNT content to 0.25% by weight of cement had no clear positive influence. Hence it was concluded that a pronounced increase in compressive strength was determined under high strain rate loading. However, no significant improvement in strength was observed for quasi-static loading and the use of SDS as a surfactant had a negative effect on strength due to foam formation during the mixing of the cement paste.

Chaipanich et al. [22] studied the effect of adding Carbon NanoTubes (CNTs) with 0.5% and 1% by weight in fly ash cement system on the mechanical properties of CNT–fly ash (FA) cement composite. The detail of mix proportions of carbon nanotubes–fly ash cement composites and its synthesis are shown in Tables 1 and 2. SEM micrographs of the materials that were used in the study were studied and the density results of Portland cement mortar, fly ash cement mortars with and without CNTs at different ages (1, 7, 28 and 60 days) were recorded and seen to be in the range of 2.17–2.29 g/cm^3. An interesting observation was made that while fly ash cement mortar (without CNTs) was lower in density compared to the control PC mortar at all ages, the fly ash mortar with CNTs was found to be significantly denser (2.29 g/cm^{3}at 28 days) than the corresponding fly ash mix without CNTs (2.19 g/cm^{3}at 28 days) and was also higher than that of PC control (2.23 g/cm^3 at 28 days). The increase in the density was most likely due to the benefit of CNTs acting as filler to the fly ash cement matrix which resulted in higher compressive strength results of fly ash cement mortars as shown in Fig. 9. The results showed that the compressive strength of fly ash mixes increases with increase in carbon nanotubes content, and the highest strength was achieved when carbon nanotubes of 1% by weight was used. At 7 days, the effect tends to reach the optimum at 0.5% CNTs level with the results of 1% showing similar strength. The strength at 28 days of 20% fly ash cement mortars however, was found to be highest with 1% carbon nanotubes addition where the compressive strength at 28 days was 51.8 MPa. This was higher than the reference mix of FA mortar without CNTs where the strength was at 47.2 MPa. It was also noticed that the strength of FA mix with 1% addition at 28 days became very close to that of the control PC mortar (52.6 MPa). Similar trend in the results were also found at 60 days where the compressive strength of FA mixes with CNTs remained higher than that of the reference FA mix without CNTs. The increment in



A	Reference
B	Reference-SDS-0.25%
C	Reference-Brij35-0.25%
D	Mixed CNTs-0.05%-SDS
E	N-CNTs-0.05%-SDS
F	Mixed CNTs-0.05%-Brij35
G	N-CNTs-0.05%-Brij35
H	Mixed CNTs-0.25%-SDS
I	Mixed CNTs-0.25%-Brij35
J	N-CNTs-0.25%-Brij35

Fig. 8. (a) shows compressive strength at quasi-static loading and (b) shows compressive strength at high strain [19].

Table 1
Description of synthesis of carbon nanotubes by various researchers.

Study	Description
Sobolkina et al. [19]	• Studied the influence of dispersion of Carbon NanoTubes (CNTs) on the mechanical properties of the cement matrix • Two types of CNTs were used, a mixture of single, double and multi-walled CNTs (labelled as mixed CNTs) and aligned, nitrogen-doped multi-walled CNTs (labelled as N-CNTs) • For mixed-CNTs Chemical Vapour Deposition (CVD) method was used for synthesis, which were sonicated for 30 min in hydrochloric acid diluted with distilled water at a ratio of 1:1 to remove the solid catalyst material (MgO and free metal catalysts). For N-CNTs, aerosol-assisted CVD method was used without any chemical treatment • Two different surfactants obtained from previous studies [20,21] were used, first, an anionic Sodium Dodecyl Sulfate (SDS) and second, a nonionic polyoxyethylene laurylether (Brij 35) used in different concentrations of 4.2 mM, 17.3 mM and 34.7 mM with minimum CNT-to-surfactant ratio of 1:0.24 for SDS and 0.01 mM, 4.2 mM and 8.4 mM with minimum CNT-to-surfactant ratio of 1:0.02 for Brij 35 • To avoid evaporation of the water during sonication, the glass container was covered and cooled and the mixtures were produced using the CNT contents of 0.05% and 0.25% by cement weight • To prepare the cement samples CNT to surfactant ratio was kept as 1:1 with a sonication time of 120 min with the water-to-cement ratio kept as 0.50 for all mixtures
Chaipanich et al. [22]	• Investigated the effect of addition of Carbon NanoTubes (CNTs) on properties of mortars in a fly ash cement system • Fly ash cement was produced with 20% fly ash and 80% Portland cement by weight and CNTs were prepared from Chemical Vapour Deposition (CVD) method by using nickel oxide as a catalyst • The CNTs were initially dispersed using ultrasonic with some part of the mix water for 10 min and then added to fly ash cement mixes of 0.5% and 1% by weight • The blends were then mixed with the remaining water and sand to produce mortar specimens with the ratio of water to cement blend to sand as 0.5:1:3 for all mixes. Paste specimens with the water to cement ratio of 0.5 was also produced
Nochaiya and Chaipanich [23]	• Investigated the fresh properties of Portland cement–Multi-Walled Carbon Nano Tube composite • Multi-Walled Carbon NanoTubes (MWCNTs) with 50 nm diameter and more than 500 nm length were used as an additive material, up to 1 wt.% of cement which was synthesized by an Infusion Chemical Vapour Deposition (ICVD) method using nickel oxide as catalyst • MWCNTs were firstly mixed with water and ultrasonicated for 1 h with further addition of Portland cement to the mixture • The water cement ratio was kept as 0.5 for the paste formation which were then poured into lubricated moulds whose surface was smoothed and further wrapped with plastic film to avoid moisture loss • All samples were de-moulded after 24 h and then cured in water at 25 °C until testing
Metaxa et al. [24]	• Studied the influence of effectively dispersed Multi-Walled Carbon Nano Tube (MWCNT) suspensions in cement based materials on their mechanical properties • Purified MWCNTs with a diameter of 20–40 nm, length of 10–30 µm, were produced by the Chemical Vapour Deposition (CVD) and used at a concentration of 0.26% by wt.% • For their effective dispersion the MWCNTs were mixed in the water which was further added in an aqueous solution containing a surfactant to MWCNTs weight ratio of 4.0 • The mixture was then ultrasonicated using high intensity ultrasonic processor with a 13 mm diameter tip, operating at 50% of its maximum amplitude. Energy was applied in cycles of 20 s to prevent the suspensions from overheating
Morsy et al. [25]	• Investigated the effect of addition of nano-metakaolin (NMK) to Carbon Nano Tube (CNT) cement composites on the mechanical properties of the mortar. • The ordinary Portland cement was substituted by 6% of nano-metakaolin (NMK) and the CNT was added by ratios of 0.005%, 0.02%, 0.05% and 0.1% of cement • The blended cement mortar was prepared using water/binder ratio of 0.5% and blended cement: sand ratio of 1:2 and the dispersant solution was prepared by adding organic ammonium chloride solution containing 7 mg/g of clay • The NMK was mixed to the dispersant solution which was covered and left for 24 h to ensure that proper homogeneity • The cement, exfoliated clay and CNTs were dry mixed for 5 min and the fresh mortar paste samples were made which were first cured at 100% relative humidity for 24 h and then cured in water for 28 days
Li et al. [26]	• Analyzed the addition of Multi-Walled Carbon NanoTubes (MWCNTs) after modified by using a H_2SO_4 and HNO_3 mixture solution on the mechanical properties of cement matrix composites • The MWCNTs were all treated firstly to attach carboxylic acid to their surfaces with the following procedure: one hundred grams of nanotubes were taken and added to one thousand millilitres of the mixed solution of sulphuric acid and nitric acid (3:1 by volume respectively) • The mixture was sonicated in a basin for 3 h at ambient temperature with further diluting the mixture with distilled water in a ratio of 1:5 by volume • After holding still for 24 h, the mixture was filtered with a filter and washed with water until no residual acid was present • Portland cement composites, sand (if needed), treated nanotubes were all mixed in a rotary mixer for 3 min followed by addition of water and water-reducing agent with mixing of another 5 min • The specimens were made and cured in water at a constant room temperature of 30 °C followed by drying in an oven at 50 ± 2 °C for 24 h before testing

Table 2
Mix proportions of carbon nanotubes–fly ash cement composites [22].

Mix	PC (%)	FA (%)	CNT (%)	*w/c*
PC	100			0.5
FA20	80	20		0.5
FA20:CNT0.5	80	20	0.5	0.5
FA20:CNT1	80	20	1	0.5

compressive strength of fly ash cement composite with the additional carbon nanotubes agreed with previously reported work on the use of CNT in pure Portland cement mixes [29,30].

Morsy et al. [25] investigated the behaviour of cementitious matrix made from multi-walled carbon nanotubes and nano-clay materials with the synthesis details shown in Table 1. The compressive strength results of control specimen and with different carbon nano-tube content from 0% to 0.1% as shown in Fig. 10 reveals that the compressive strength increased with the increase in CNTs until it reaches an optimal amount of 0.02% and then started to drop. Evidently, the replacement of OPC by 6% NMK in blended mortar increases the compressive strength by 18% in comparison to control mix. This was explained by two mechanisms, the first strengthening mechanism was the packing effect of small NMK acted as filler to fill into the interstitial spaces inside the skeleton of hardened microstructure of cement mortar which leads to increments in strength and density; the second strengthening mechanism was the pozzolonic effect that combines glass-like silicon

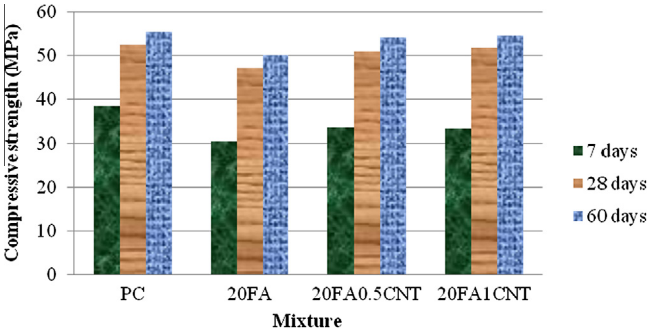


Fig. 9. Compressive strength of carbon nanotubes–fly ash cement composites at 7, 28 and 60 days [22].

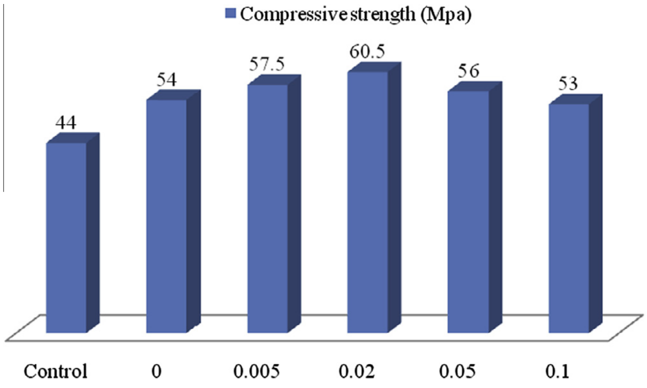


Fig. 10. Compressive strength of blended cement mortar containing exfoliated 6% NMK versus CNTs ratios at 28 days of hydration [25].

Table 3
Strengths of different mixes after 28 days curing [26].

Mix	Compressive strength (Mpa)
PCC	52.27 ± 1.4%
PCCF	47.51 ± 3.1%
PCNT	62.13 ± 2.3%

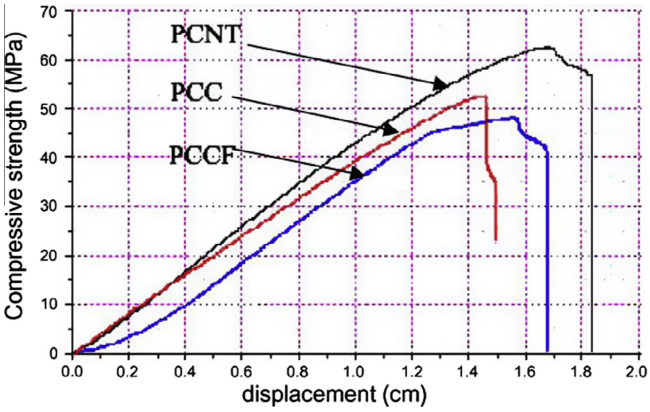


Fig. 11. Typical load–displacement curves of cement–matrix composites [26].

and alumina elements in NMK with the lime elements of calcium oxide and hydroxide in cement to add the bonding strength and solid volume, resulting in higher compressive strength of hardened cement mortar. Additionally, the improvement of cement mortar strength as CNTs loaded up to 0.02% was attributed to the crosslink of CNTs fibre with hydration product which lead to resist micro-cracks formation. Furthermore, at higher ratios of CNTs, the CNTs were agglomerated around cement grains leading to partial hydration of cement grains and producing hydrated product having weak bond. Also, the fibres may not be wetted properly thus causing fibre pullout resulting to formation and propagation of micro-cracks.

Li et al. [26] investigated the effect of addition of Multi-Walled Carbon NanoTubes (MWCNT) modified by using a mixture of H_2SO_4 and HNO_3. For comparisons carbon fibres, isotropic pitch based and of nominal length 6 mm and diameter 10–14 μm, was used in the matrix. From the compressive strength results after 28 days curing as shown in Table 3 and from the typical compressive stress–strain curves of those cement composites as shown in Fig. 11, it was observed that the use of carbon nanotubes enhances the compressive strength of cement. The compressive strength increases up to 19% but with the addition of carbon fibres, the compressive strength was reduced.

5.3. Flexural strength

Flexural strength is a mechanical parameter for brittle material, defined as a material's ability to resist deformation under load. When an object formed of a single material is bent, it experiences a range of stresses across its depth at the extreme fibres. Most materials fail under tensile stress before they fail under compressive stress, so the maximum tensile stress value that can be sustained before the beam or rod fails is its flexural strength.

Metaxa et al. [24] studied the flexural strength of Multi-Walled Carbon NanoTubes (MWCNTs) cement composites with two different suspension techniques, the swing bucket and the fixed angle rotor, both techniques differed with different configurations of rotors during ultra-centrifugation. The swing bucket rotors allow the tubes to hang on hinges so that they reorient to the horizontal as the rotor initially accelerates [31]. During ultracentrifugation, the material travels down the entire length of the centrifuge through the media within the tube; on the other hand fixed angle rotors made of a single block of metal and hold the tubes in cavities bored at a predetermined angle. The materials were forced against the side of the centrifuge tube and then slide down the wall of the tube [32]. The results of cement paste samples reinforced with the reference suspensions, without concentration and the results of the plain cement paste samples depicted in Fig. 12. The results showed that in all cases, the MWCNT reinforced nano-composites exhibited higher flexural strength when compared to the plain cement paste. The samples prepared using the swing bucket rotor show an almost identical flexural strength at all curing ages when compared with the initial reference (non-concentrated) suspensions. On the other hand, specimens prepared from the

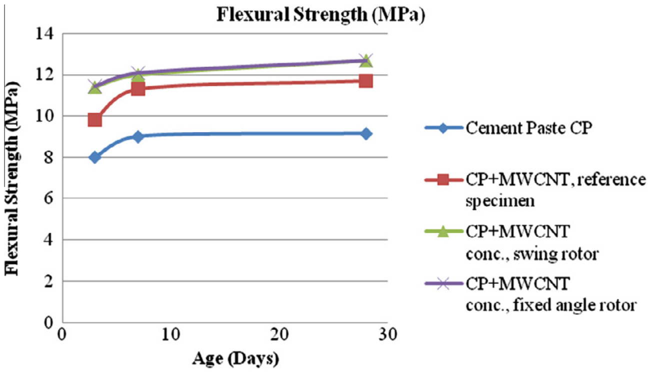


Fig. 12. Effect of admixtures prepared using different ultracentrifugation methods on the flexural strength [24].

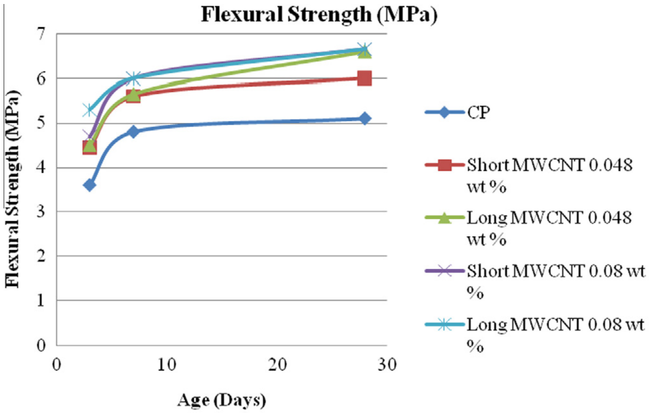


Fig. 13. Effect of different types (short and long) of MWCNTs and concentration on the flexural strength [27].

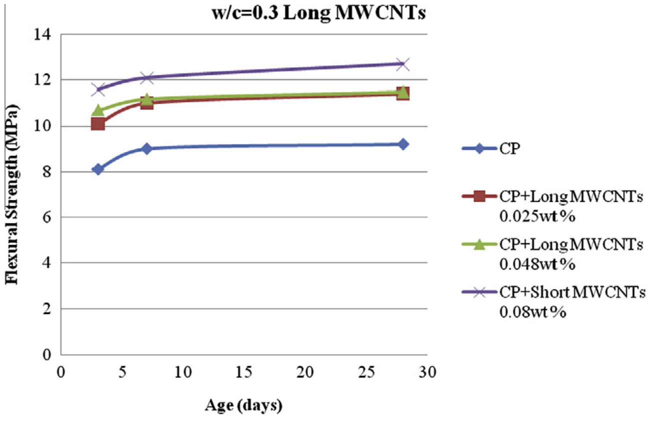


Fig. 15. Effect of long MWCNTs concentration on the flexural strength of cement paste ($w/c = 0.3$) [27].

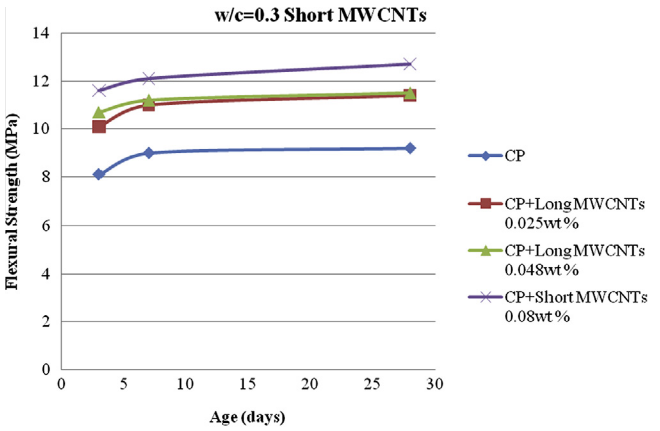


Fig. 14. Effect of short MWCNTs concentration on the flexural strength of cement paste ($w/c = 0.3$) [27].

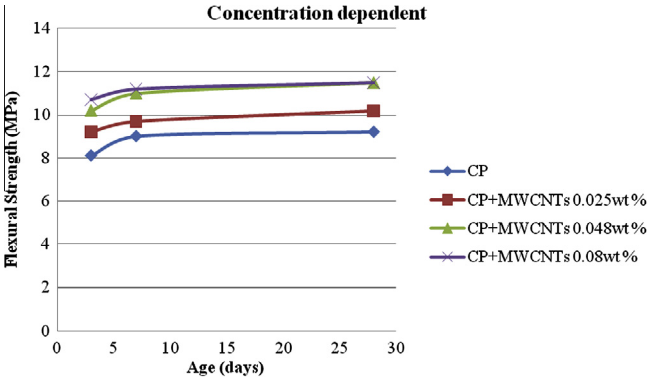


Fig. 16. Fracture mechanics test results of the flexural strength of nano-composites [27].

suspensions created using the fixed angle rotor exhibited a lower flexural strength. Also, from the absorption spectroscopy results, it was shown that the suspensions prepared using the fixed angle rotor, had a lower concentration of MWCNTs than the suspension prepared using the swing bucket rotor which concluded that the swing bucket rotor was more efficient for the concentration of MWCNT suspensions as these suspensions do not lose any CNTs during the admixture preparation process.

Konsta-Gdoutos et al. [27] investigated the effect of two different types of MWCNTs with the same diameter, but different lengths, designated as short and long, incorporated into the composite at two different concentrations with lower concentration of 0.048% and higher concentration of 0.08%. Ultrasonication technique was used to disperse CNTs into base fluids. For this samples were prepared without surfactant (CP), with surfactant (CP + SFC) and with surfactant sonicated (CP + SFC sonicated) using the exact same amounts and procedure followed for the dispersion of the MWCNTs. Results of the rate of the flexural strength through the age of 28 days of hydration shown in Fig. 13. It was observed that in all cases the samples reinforced with MWCNTs exhibit higher flexural strength than plain cement paste, at the age of 3 days the samples with short MWCNTs at an amount of 0.08 wt.% give a higher increase in the flexural strength. Comparing the response of the samples with short MWCNTs with different concentrations it was observed that the samples reinforced with a higher amount of MWCNTs exhibit higher strength. Also, samples reinforced with a smaller concentration of MWCNTs demonstrate a higher strength and samples reinforced with 0.08 wt.% short, 0.048 wt.% and 0.08 wt.% long MWCNTs gave the same 28 day flexural strength.

Konsta-Gdoutos et al. [28] investigated the effect of Multi Walled Carbon NanoTubes (MWCNTs) concentration and aspect ratio on the mechanical properties of cement paste matrix. Two types of commercially available purified MWCNTs, designated as short and long, produced by catalytic Chemical Vapour Deposition (CCVD) of carbon were used. The results of average flexural strength of cement paste samples, as shown in Fig. 14, reinforced with short MWCNTs at amounts of 0.048 wt.%, 0.08 wt.% and 0.10 wt.% by weight of cement at the age of 3, 7 and 28 days, showed that in all cases, the samples reinforced with MWCNTs exhibit higher flexural strength than plain cement paste. Samples reinforced with 0.08 wt.% short MWCNTs outperformed all other mixes, exhibiting the largest increase in flexural strength. It was observed that samples containing 0.10 wt.% MWCNTs exhibit consistently lower strength than the 0.08 wt.% mixes at all ages. This was due to the fact that effective dispersion of short MWCNTs at a concentration higher than 0.08 wt.% cannot be achieved. At concentrations lower than 0.08 wt.% the amount of the MWCNTs in the matrix were too low to arrest the nano-cracks. The results indicated that a concentration of short MWCNTs, close to 0.08 wt.% was optimal to achieve effective reinforcement under the test conditions employed. Fig. 15 shows the flexural strength results of specimens reinforced with 0.025 wt.%, 0.048 wt.% and 0.08 wt.% long MWCNTs. Similar to the specimens with short MWCNTs, it was observed that in all cases, the samples reinforced with long MWCNTs show improved mechanical performance compared to the plain cement paste. However, contrary to the results obtained with the short MWCNTs, it was observed that samples reinforced

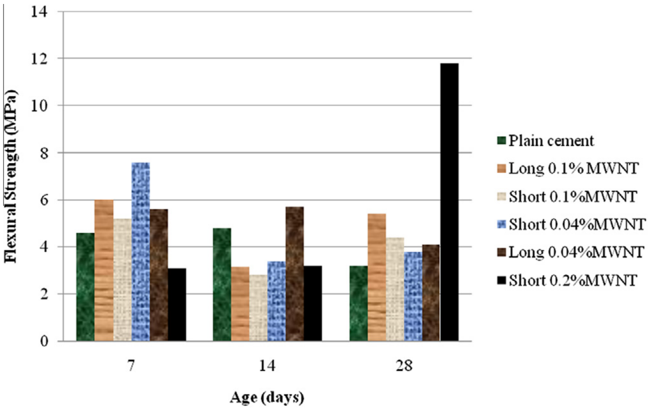


Fig. 17. Average flexural strength results for different MWCNTs composite specimens [32].

with smaller amount of MWCNTs demonstrate higher flexural strength. The results of the average flexural strength of the nanocomposites, which illustrated the best mechanical performance compared in Fig. 16. Generally, it was concluded that the optimum concentration of MWCNTs depends on the aspect ratio of MWCNTs. When MWCNTs with a low aspect ratio were used (short MWCNTs), a higher amount close to 0.08 wt.% by weight of cement was needed to achieve effective reinforcement. When MWCNTs with higher aspect ratio (long MWCNTs) were used, amounts less than 0.048 wt.% was needed to achieve a similar level of mechanical performance. These differences were attributed to the degree of dispersion of the MWCNTs, i.e., short MWCNTs exhibited a higher degree of dispersion however, because they were shorter, a higher concentration in cement paste matrix was needed to reduce the fibre free area and arrest the nano-cracks.

Abu et al. [32] investigated the effect of different concentrations of long Multi-Walled Carbon NanoTubes (MWCNTs), high length/diameter aspect ratios of 1250–3750 and short MWCNTs, aspect ratio of about 157, on the mechanical properties of cement paste. Three different batches for the short MWCNTs were made at three different concentrations; 0.04%, 0.1%, and 0.2% of the weight of cement and two batches were made at 0.04% and 0.1% by cement weight for long MWCNTs. The flexural strength of the specimens were measured and compared with that of the reference as shown in Fig. 17. At age of 7 days, most of the MWCNT/cement composites showed an increase in the flexural strength, the highest improvement in the flexural strength was shown in the short 0.04% MWCNT specimens with an increase of 66% compared to the reference specimens. The short 0.2% MWCNT specimens showed a decrease in their flexural strength by 38%, on the other hand, considerable changes in the behaviour of the composites were observed at age of 14 days. After 28 days, all of the composites retrieved their strength values to become higher than the values at 14 days; however, the short 0.2% MWCNT showed a significant large increase in the flexural strength; specifically 269% compared to the reference samples values. In addition, the long 0.1% MWCNT had also increased by 65%. It was noticed that in most cases, the strength and Young‘s modulus decreased from 7 day curing to 14 day curing and then increased Therefore, the authors believed that this observed trend was not be due to CNTs integration, but due to the curing process and the resulting properties of the cement paste matrix.

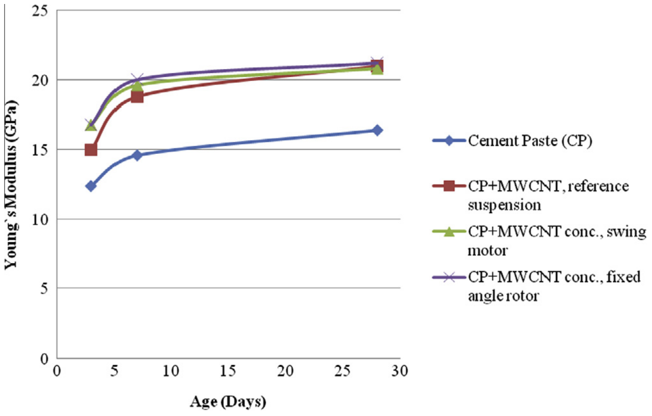


Fig. 18. Effect of admixtures prepared using different ultracentrifugation methods on the Young's modulus of cement paste ($w/c = 0.3$) [24].

5.4. Young's modulus

Young's modulus, also known as the tensile modulus or elastic modulus, is a measure of the stiffness of an elastic material and is a quantity used to characterize materials. It is defined as the ratio of the stress along an axis over the strain along that axis in the range of stress in which Hooke's law holds. It can be experimentally determined from the slope of a stress–strain curve created during tensile tests conducted on a sample of the material. In anisotropic materials, Young's modulus may have different values depending on the direction of the applied force with respect to the material's structure.

Metaxa et al. [24] studied the Young‘s modulus of multi-walled carbon nanotubes cement composites with ultra-centrifugation suspension technique with different configurations of rotors; the swing bucket and the fixed angle rotor. The results of cement paste samples reinforced with the reference suspensions, without concentration and the results of the plain cement paste samples shown in Fig. 18. The results showed that in all cases, the MWCNT reinforced nano-composites exhibit higher young‘s modulus when compared to the plain cement paste samples. It was also observed that Young‘s modulus of these specimens after 3 days of hydration was almost the same as the Young‘s modulus of the non-concentrated samples at the same curing age. However, at 7 and 28 days of hydration the samples reinforced with the highly concentrated/diluted MWCNT suspensions demonstrated slightly higher Young‘s modulus than the reference samples and the specimens prepared from the suspensions created using the fixed angle rotor exhibited slightly lower Young‘s modulus than those prepared by the swing bucket rotor.

Konsta-Gdoutos et al. [27] investigated the effect of two different types of MWCNTs of different lengths, short and long, at two different concentrations with lower concentration of 0.048% and

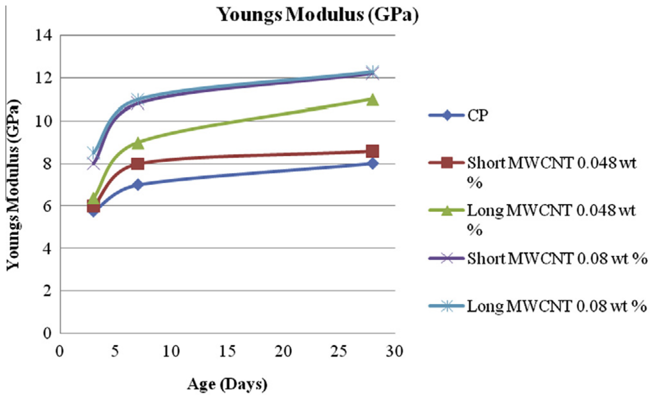


Fig. 19. Effect of different types (short and long) of MWCNTs and concentration on the Young's modulus of cement paste ($w/c = 0.5$) [27].

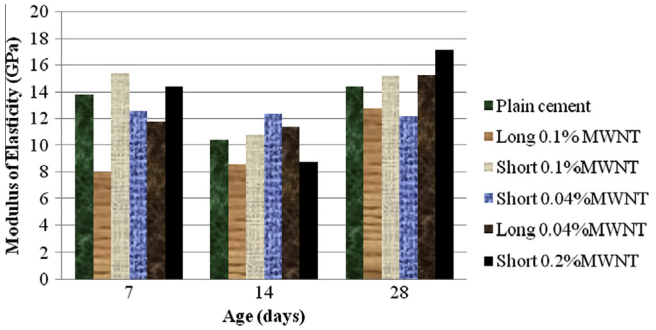


Fig. 20. Average modulus of elasticity results for different MWCNTs composite specimens [32].

Table 4
MIP analysis of Portland cement–CNTs pastes after cured at 28 days [23].

Mixes	Total intruded volume (cm^3/g)	Total porosity (%)	Total surface area (m^2/g)
PC	0.1717	27.174	31.4562
0.5% CNT	0.1494	25.5226	25.3531
1% CNT	0.1422	22.7398	24.3459

higher concentration of 0.08% respectively and were dispersed into base fluid by Ultrasonication. Young's modulus was investigated and the results, as shown in Fig. 19, shows that in all cases, the samples reinforced with MWCNTs exhibited higher Young's modulus than plain cement paste. Comparing the response of the samples with short MWCNTs at different concentrations it was observed that the samples reinforced with a higher amount of MWCNTs exhibited lower increase in Young's modulus and samples reinforced with a smaller concentration of MWCNTs demonstrated higher Young's modulus increase. Highest increase of the Young's modulus was achieved for cement paste nano-composites reinforced with 0.048 wt.% long and 0.08 wt.% short MWCNTs.

Abu et al. [32] investigated the effect of different concentrations of long Multi-Walled Carbon NanoTubes (MWCNTs) and short MWCNTs on the mechanical properties of cement paste. The modulus of elasticity for the specimens were measured and compared with that of the reference shown in Fig. 20. At age of 7 days, the modulus of elasticity values for most of the specimens was close to the reference samples. However, the short 0.1% and 0.2% MWCNT show a slight increase compared to the reference samples. On the other hand, considerable changes in the behaviour of the composites were observed at age of 14 days. At 28 days, no significant changes in the general behaviour of the composites regarding the modulus of elasticity values with respect to the reference samples was observed, but most of the specimens show decrease in the modulus of elasticity in general compared to the values at 7 days. All specimens showed an increase in their modulus of elasticity values compared to 14 days values, and the short 0.2% MWCNT had the highest increase. Therefore, from the reported results for the nano-composites at different curing periods, it was noticed that the strength and Young's modulus decreased from 7 day curing to 14 day curing and then increased. Therefore, the authors believed that this observed trend was not due to CNTs integration, but due to the curing process and the resulting properties of the cement paste matrix.

5.5. Porosity

Table 5
Porosity of different mixes [26].

Sample	Total intruded volume (ml/g)	Porosity (2 nm < d < 5 μm)	Porosity (d < 50 nm)	Porosity (d > 50 nm)
PCC	0.0737 ± 8.4%	17.76 ± 9.2%	15.09 ± 9.1%	2.67 ± 8.7%
PCCF	0.1097 ± 6.5%	23.37 ± 6.8%	13.48 ± 5.6%	9.89 ± 6.6%
PCNT	0.0445 ± 7.6%	10.8 ± 4.7%	10.13 ± 9.3%	1.47 ± 9.1%

Porosity or void fraction is a measure of the void (i.e., "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0 and 100 percent. It is controlled by various factors like grain size, pore distribution, cementation, composition, etc.

Nochaiya and Chaipanich [23] investigated the porosity of Portland cement–multi-walled carbon nanotube (CNT) composite, with CNT synthesized by an infusion Chemical Vapour Deposition (CVD) method using nickel oxide as a catalyst. Three samples, after curing in water for 28 days, were soaked in acetone for about 24 h to stop the hydration reaction, and then dried in an oven at 60 °C for 24 h, were tested using Automated Mercury Intrusion Porosimeter with a maximum pressure of 33,000 psi for pore size measurements. Total porosity and total surface area of all pastes are shown in Table 4. Total porosity of Portland cement paste was shown to be 27.2% while for Portland cement with 0.5 wt.% and 1 wt.% CNTs, the total porosities measured were 25.5% and 22.7%, respectively. Moreover, total surface areas of PC, 0.5% CNTs and 1% CNTs mixes were found to be 31.4%, 25.4% and 24.3%, respectively. Therefore, both total porosity and total surface area were found to decrease with increasing multi-walled carbon nanotube content up to 1 wt.%. This was attributed due to the fact that additional CNTs can fill in the pores between the hydration products of Portland cement. Therefore the porosity of these pastes was found to decrease, leading to a denser microstructure than that of the control mix. Also, the addition of multi-walled carbon nanotubes was found to primarily affect the mesopores of CNTs mixes, with fewer mesopores than that of the control mix.

Li et al. [26] investigated the effect of addition of multi-walled carbon nanotubes modified by using a mixture of H_2SO_4 and HNO_3. Mercury Intrusion Porosimetry (MIP), able to determine the distribution of pores from 2 to 5000 nm, was used for the measurement. The maximum pressure provided by this machine was 600 MPa. The results of porosity test for PCC, PCCF and PCNT after 28 days curing as shown in Table 5. It was observed that the use of carbon nanotubes decreased the porosity of cement and reduces the total pore volume. When containing 0.5% carbon nanotubes, PCNT had a total porosity of 10.8%, about 64% lower than that of PCC which result suggested that carbon nanotubes acted as the filler of voids. However, PCCF containing 0.5% carbon fibres had a total porosity of 23.4%, about 31% higher than that of PCC. It was concluded that due to the addition of carbon nanotubes, the porosity of the composites reduced and the pore sizes becomes more fined.

6. Conclusions

1 Carbon nanotubes (CNTs) have excellent properties which generates the wide range of applications in medical, electrical, particularly in construction fields. Lots of research has been carried out and the results showed excellent potential applications in various sectors.
2 With the inclusion of CNTs as fillers, significant effect on mechanical properties of mortars has been discovered. From the SEM micrographs it has been observed that the CNTs were dispersed uniformly in the cement mortar and there was no aggregation of CNTs. Good interaction between carbon nanotubes and the fly ash cement matrix with CNTs has been

observed which acts as filler resulting in a denser microstructure and higher strength when compared to the reference fly ash mix without CNTs.

3 The increase in compressive strength of fly ash mixes has been observed with increase in carbon nanotubes content with the highest strength achieved with CNT content of 1% by weight. Also, under high strain loading rate the compressive strength increases with the inclusion of CNTs.
4 The flexural strength found to be increased with the inclusion of CNTs when compared to the plain cement paste but with higher aspect ratio of CNTs, flexural strength found to be dependent on concentration of CNT. Also CNTs were found to be better than carbon fibres in enhancing flexure strength.
5 Young‘s modulus found to be higher than plain cement paste when the samples were reinforced with CNTs.
6 The porosity and the total pore volume of concrete/pastes made with the inclusion of CNTs found to decrease, leading to a denser microstructure than that of the control mix and also the shrinkage values were also found to be lower than that of control mixes.

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