

Carbon Nanotube-Cement Composites in the Construction Industry: 1952-2014. A State of the Art Review

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Abstract— Carbon nanotubes have extraordinary properties and thus they are considered as major candidates for diverse applications in nanotechnology.

The main disadvantages they present are a lack of solubility and intricacies in handling. In fact, carbon nanotubes are insoluble in all organic solvents and aqueous solutions, and thus they require to be dispersed by using surfactants or chemical agents, in addition to vigorous agitation by sonication. Carbon nanotubes have been widely used with polymers in composite materials in order to improve their mechanical and electromagnetic properties.

They are also known to be adequate for the development of structural materials, and can be used in cement and reinforced concrete. Carbon nanotubes have been shown to reduce the occurrence of cracks, decrease their porosity, and improve their mechanical properties, thus lengthening their durability. To date the construction sector has not experienced a significantly large growth due to, among other factors, the competitiveness of the market, in which a high adjustment in the material cost is required, and the scarce knowledge of new materials, which limits their degree of actual implementation on site.

The present study comprehensively reviews the feasibility of developing new cements with a maximum carbon nanotube content of 0.5% in order to provide large increases in flexural strength and in compressive strength, along with a reduction in porosity. The paper analyzes different research cases that have been carried out with cementitious materials to date and reviews the current state of the art and some future trends for these composites.

Keywords—Carbon nanotubes, cement composite, concrete, dispersion, fiber reinforcement, mechanical properties.

I. INTRODUCTION

CARBON nanotubes (CNTs) are molecular carbon allotropes whose structure can be visualized as cylinders made up of rolled graphene layers [1]. Two types of CNTs are differentiated depending on whether they consist of a single graphene wall (SWCNTs, Fig. 1a), or of multiple walls concentrically arranged (MWCNTs, Fig. 1b). The typical diameters of SWCNTs and MWCNTs range from 0.4 to 10

nm and from 4 to 100 nm, respectively, while their lengths usually reach the micrometer range, although centimeters-long CNTs have been synthesized [2], [3]. Thus CNTs have very large aspect ratios (length to diameter ratio), typically higher than 1000 and reaching up to 2,500,000, which render their nanostructure quasi-one-dimensional (1D). Their ends can be open or capped by a half of a molecule of a fullerene [1], a carbon allotrope with a convex, approximately spherical shape that was first discovered in 1985 [4]. MWCNTs can have from tens to hundreds of walls, with typical adjacent walls separations of 0.34 nm [5]. Infinite forms of SWCNTs can exist, each one being uniquely characterized by its chiral angle, which defines the rolling direction of a hypothetical graphene layer, its diameter, and its length, along with the characterization of its terminations or caps, while the different possible combinations of walls a MWCNT can have give rise to infinitely more forms of CNTs [6].

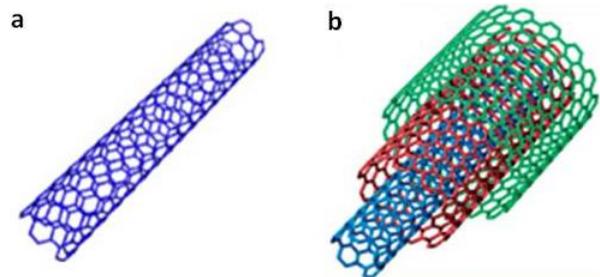


Fig. 1 Representation of a SWCNT (a) and a MWCNT (b)

Although it is reported that CNTs were identified as early as 1952 [7], it was not until the publication in 1991 of a paper on Nature by Iijima [8] that they received worldwide attention and intense research began into their characterization, synthesis, and applications for a wide variety of fields. CNTs have exceptional mechanical, thermal, electrical, and optical properties which are being studied for promising applications as field emitters, composites materials for radio wave reflection and electrostatic discharge protection, biomolecular and chemical sensors, hydrogen storage media, fuel cell and catalyst supports, and composites with enhanced mechanical properties, among others [9]-[11]. Several uses have been successfully commercialized, such as reinforcing material for the carbon electrodes of lithium ion batteries, electrical

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conductive fillers in plastics, and polymeric-CNT composites for sporting goods.

The outstanding combination of properties of CNTs makes them potential candidates as a reinforcing material in concrete. They are among the strongest and stiffest materials known (Fig. 2), and they are also very ductile. MWCNTs, which are usually preferred as concrete reinforcement versus SWCNTs because they are less expensive to synthesize [12], have a tensile strength of 11 to 63 GPa, about 100 times greater than that of steel—the most widely used reinforcing material for concrete [13]—while being 6 times lighter, a Young's modulus of 0.3 to 0.9 TPa, up to 5 times greater than steel, and an elongation at break of up to 12%, 60 times greater than that of steel [14]; SWCNTs have even higher Young's modulus and ductility, while having similar to slightly lower tensile strengths [15]. Thus integration of CNTs has the potential to remarkably increase not only concrete strength and stiffness but also its ductility. In addition, the high aspect ratios and surface areas of CNTs, along with their exceptional mechanical properties, means they can greatly aid in reducing concrete porosity and in resisting crack propagation by being finely distributed throughout the cement matrix, filling pores and acting as bridges across voids and cracks [16]. Furthermore, harnessing the superior piezoresistivity and electrical conductivity properties of CNTs [17] can lead to design of multifunctional concrete in applications such as strain and damage sensing concrete, radio wave reflecting concrete, and cathodic protection of steel reinforcement in concrete [18]-[21].

While considerable advancement has been attained to date on research into advanced CNT-polymer composite materials and several of these applications have been commercialized [11], research into CNT-concrete composites is still at an early stage and actual civil engineering applications have yet to be put into practice. Improvement of concrete properties by incorporation of CNTs has been demonstrated [16], [23], but more research is needed into optimal means of functionalization and dispersion of CNTs, as poor interfacial bonding between CNTs and the cement matrix as well as poor dispersion of CNTs into the matrix are predominant challenges reported throughout the literature. These problems stem from the difficulty in handling CNTs, their hydrophobicity and lack of solubility, and their tendency to agglomerate [24], [25]. In addition to effective integration of CNTs into the cement matrix, more research is required to achieve economic scale-up of CNT synthesis in order to make large-scale applicability of CNT-reinforced concrete feasible [12]. With an annual production of 25 billion tons [26], concrete is the most widely used construction material in the world, and this is in part due to its low cost, in addition to its high compressive strength. However, it is expected that increased demand of CNTs and continued research into their synthesis and applications will lower their industrial cost [12]. According to Eklund *et al.* [10], successful research into large-scale production of CNTs is viable with the current state of the art and technology, and an increased demand of CNTs

would spur investment onto such investigation. Cost of CNTs has decreased from \$1200/kg in 2006 and \$260/kg in 2011 to less than \$100/kg in 2014 [11], [27].

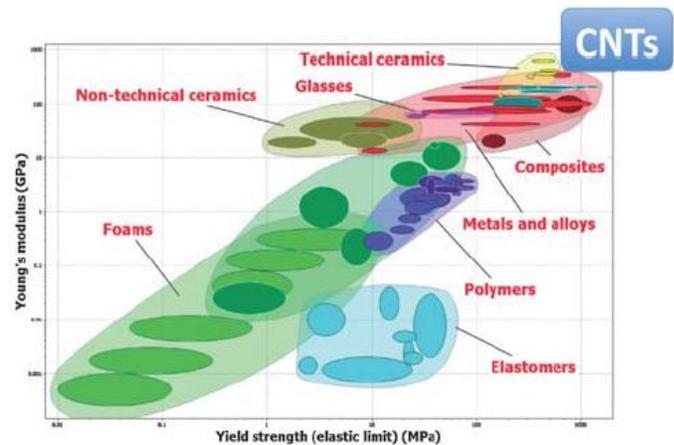


Fig. 2 Ashby plot showing Young's modulus plotted against tensile for many engineering materials [22]. Note the axis scales are logarithmic

The present paper reviews research carried out to date on CNT cement-based composites and comprises the following sections:

- Fabrication of CNT-reinforced cementitious composites, focusing on functionalization and dispersion of CNTs in cementitious matrixes and a description of results obtained by several authors.
- A study of the microstructure and porosity of fabricated CNT-reinforced cementitious composites.
- A summary of reported mechanical properties of CNT-reinforced cementitious composites, with a discussion of the variables that influence them.

II. FABRICATION OF CNT-REINFORCED CEMENTITIOUS COMPOSITES

A. Synthesis of CNTs

For fabrication of CNT cement-based composites, CNTs with typical purity values of 90 – 97% can be bought directly from a distributor. CNTs are synthesized by chiefly three methods: electric arc-discharge, laser ablation, and thermal- or plasma-assisted chemical vapor deposition (CVD) [12], [22]. Thermal CVD is the most suitable method for up-scale to industrial production because it is less costly than the other methods and because a reactor can be readily designed to operate in continuous mode [12], [28]. Other advantages of thermal CVD include higher yield and purity and the possibility of synthesizing long CNTs of controlled diameter, length, and alignment [22]. On the other hand, the relatively low operation temperatures associated with CVD, compared to those of arc discharge and laser ablation, lead to synthesis of CNTs with a larger number of lattice defect sites, which degrade to some extent their properties and also provide reactive sites for formation of functional groups [29], [30].

Nevertheless, a subsequent annealing treatment can be applied to correct these defects [31], [32].

Commercial synthesis of CNTs via thermal CVD typically involves flowing a preheated hydrocarbon gas (commonly ethylene, methane, or ethylene), along with oxidizing or reducing gases, through a fluidized bed reactor containing transition metal (Fe, Co, Ni) catalyst particles at temperatures ranging from 700 to 900 °C; when deposited on the catalyst surface, the hydrocarbon decomposes into carbon atoms and CNTs are formed [22]. Design of optimal reactors for CNT large-scale production poses a challenge stemming from the incomplete understanding of CNT growth mechanisms, in addition to the wide range of parameters that commonly require analysis in process design (flow composition and rates, catalyst and support material selection, temperature for each step, etc).

B. Dispersion of CNTs in cementitious matrixes

Having synthesized CNTs or acquired them from a distributor, CNTs then need to be adequately dispersed in cement. Given the large widespread surface area of CNTs, they tend to form agglomerates and bundles maintained by Van der Waals forces [24]. This, along with the hydrophobicity, lack of solubility, and nanodimensions of CNTs, makes their handling and dispersion into cement very difficult. Bundles of CNTs in a cement paste are readily revealed by Scanning Electron Microscopy (SEM) [25]. In order to maximize the enhancement of the nanocomposite properties, it is essential to attain both a fine distribution of individual CNTs throughout the cement matrix and proper adhesion between the CNTs and the matrix, as the strength of interfacial bonding is directly related to the efficiency of load-transfer from the matrix to the CNTs. Poor adhesion between the cement matrix and CNTs even when these are well dispersed has been evidenced by easily having pulled MWCNTs off the matrix under tension [33].

Successful investigated techniques for dispersion of MWCNTs into cement have usually consisted of the application of ultrasonication in combination with either treatment of CNTs with group functionalizing agents or with addition of dispersing agents prior to mix into cement. The effect of ultrasonic energy on dispersion of CNTs for addition in cement has proved to be in effect an essential step for adequate dispersion [25], [34]. Typical functionalizing agents for CNT dispersion are aggressive oxidizing chemicals, commonly strong acids [16], although other compounds such as ozone gas [18] have been used, while potential dispersing agents encompass a large range of common surfactants such as sodium dodecyl sulfate [35] and gum Arabic [36], superplasticizers such as those based on modified acrylic polymers [37], and cement admixtures.

Chemical treatment of CNTs with agents for formation of functional groups on their surface can improve their dispersion and create strong, covalent-type interfacial bonding through reaction of the CNT superficial groups with cement products. Li *et al.* [16] treated MWCNTs with a strongly oxidizing acid mixture solution of sulfuric acid (H₂SO₄) and nitric acid (HNO₃) under sonication at ambient temperature

for three hours, leading to the formation of oxygen-containing functional groups on the surface of CNTs, mostly carboxylic acid and hydroxyle groups. After washing the treated MWCNTs, they were added in the amount of 0.5% of weight by cement in a mortar, attaining a 19 % increase in compressive strength, a 25% increase in flexural strength, and a 64% reduction in porosity. Inspection by SEM revealed good dispersion of CNTs, while Fourier-transform infrared (FT-IR) spectra suggested covalent bonds between CNTs' superficial functional groups and cement hydration products, including calcium silicate hydrate (C-S-H) and calcium hydroxide (Ca(OH)₂), had been formed.

Cwirzen *et al.* [33] functionalized MWCNTs and coated them with polyacrylic acid polymeric surfactants under sonication. Adding the treated CNTs in very small amounts into cement (0.045 - 0.15 weight % by cement), he obtained a homogeneous dispersion, good workability, and a significant increase in the compressive strength of cement, of nearly 50%. A strong matrix-CNT adhesion was again found to be the result of covalent bonds formed between CNT functional groups (hydroxyle) and products of the cement matrix. The low percentage of CNTs used is attractive in terms of cost material.

Konsta-Gdoutos *et al.* [38] also studied dispersion of MWCNTs added in small amounts but did not esteem functionalizing of CNTs necessary. They dispersed CNTs in water using a commercially available surfactant and ultrasonication and added CNT loads of only 0.048 weight % by cement, attaining a 45% increase in the Young's modulus and a 25% increase in the flexural strength. The authors observed that addition of CNTs into cement increased the proportion of high stiffness C-S-H phases as opposed to low stiffness, porous C-S-H phases and decreased total porosity. Li *et al.* [16] had required ten times as much amount of CNTs to produce the same relative increase in the flexural strength of a mortar. This result led authors to conclude that when fine dispersion of CNTs is ensured, a very low percentage of CNTs is needed to achieve a remarkable enhancement of the properties of the cementitious composite.

Abu Al-Rub *et al.* [39] compared the reinforcing effects of surface-functionalized CNTs with those of unfunctionalized CNTs on cement properties and found the latter to be superior, with the disadvantage of producing worsened workability. They used a mixture solution of H₂SO₄ and HNO₃ as the functionalizing agent, and a polycarboxylate-based commercial superplasticizer for dispersion of unfunctionalized CNTs. The inferior mechanical properties of cement reinforced with functionalized CNTs were attributed to the excessive formation of needle-like ettringite crystals which could have resulted from the presence of left-over sulfate ions incorporated into the acid-treated CNTs. Additions of untreated CNTs in the amount of 0.1 weight % and 0.2 weight % by cement produced excellent results, with an increase in flexural strength of up to 60%, an increase in Young's Modulus of up to 25%, an increase in ductility of up to 73%, and an increase in fracture toughness of up to 170%. The excessive formation of ettringite in acid-treated CNT cement composites reported by Abu Al-Rub *et al.* [39] and the resulting degradation of mechanical properties may be

neutralized by addition of nanosilica (nano-SiO_x), which participates in the generation of cement hydration product C-S-H [40].

Li *et al.*'s experiments [16], in which the method of dispersion was chemical functionalizing treatment combined with sonication, seemed to produce the most modest improvements in the mechanical properties of the composite. It is worth noting, however, that the material they tested for reinforcement was a mortar, whereas in the other experiments it was cement. In fact, when Li *et al.* used the same dispersion method to reinforce a cement, he obtained a higher increase in compressive strength, 27%, versus 19% for the mortar. However, the individual effect of CNT addition cannot be assessed in the case of Li *et al.*'s cement experiment because nano-SiO_x was also added into the mixture. Further research into the chemistry and properties of CNTs and cement needs to be conducted in order to reach precise conclusions as to what method of dispersion is optimal and yields a cementitious material with more desirable properties.

Konsta-Gdoutos *et al.* [25] studied the effect of the ratio of surfactant-CNT on the mechanical properties of a CNT-cement composite, observing an optimum value existed. Surfactant-CNT weight ratios in the range of 1.5 to 8 were studied for dispersion of 10-100 μm long CNT content of 0.08 weight % in a cement paste with a water-cement ratio of 0.5, obtaining an optimum ratio of 4 for their particular case. At surfactant amounts lower than the optimum value, dispersion is thought not to be complete. At amounts higher than the optimum value, the authors suggest bridging of CNTs by extra surfactant molecules may occur, causing CNT flocculation [41]. An additional factor may be that surfactant molecules beyond the amount required for efficient dispersion make up part of the composite without contributing to its strength and therefore overall composite strength is lowered. The optimum value of surfactant-CNT ratio is expected to increase with the length of CNTs, as longer CNTs are more difficult to disperse due to their stronger tendency to agglomerate and entangle [25]. Sonication amplitude and time can also be critical factors that can affect CNT dispersion and the ultimate properties of the CNT-cement composite, since long CNTs have been reported to break under excessive sonication amplitude and time [42].

C. Direct synthesis of CNTs on cement particles

Yet another novel approach has been investigated by Nasibulina *et al.* [43]. CNTs were synthesized directly on the surface of clinker particles by thermal CVD. Two types of reactor schemes were studied: screw feeders and fluidized bed reactors, with the latter producing a higher yield, and gas feedstocks were acetylene, CO, and CO₂. The compressive strength of the "cement hybrid material" (CHM) increased by two times. One of the inherent advantages of this method is that it reduces the number of stages of composite fabrication—CNT synthesis, purification, and pre-treatment—to one. In addition, the cement itself contains catalysts for CNT synthesis as well as appropriate catalyst support materials. Thus it could become an economic alternative for large-scale production of CNT-reinforced cement.

Consideration should be given to determine whether integrated or separated synthesis is more efficient.

III. MICROSTRUCTURE AND POROSITY OF CNT-REINFORCED CEMENTITIOUS COMPOSITES

A. Microstructure

Properties of materials at the macroscopic level are directly related to their structure at the micro and nanoscale level. Li *et al.* [16], among other authors, analyzed the enhancement of the mechanical and electrical conductivity properties of CNT-reinforced mortar in relation to its microstructure. Important aspects to consider in the microstructure of CNT-reinforced cement are the homogeneity of the CNT dispersion, interfacial bonding between CNTs and the cement matrix, crack bridging, and pore size distribution.

As discussed earlier, interfacial bonding between CNTs and cementitious matrixes has been achieved by mainly two strategies: formation of covalent bonds between functional groups of the CNT surfaces and hydration products of the cement matrix; the reaction scheme between a carboxylic acid (-COOH) group on the surface of a CNT and a C-S-H cement product is shown in Fig. 3; the other strategy is through the use of surfactants and admixtures, which does not produce covalent interfacial bonding but rather physical interactions. Fig. 4 shows a comparison between the microstructures of cement nanocomposites with chemically treated CNTs and untreated CNTs, from where Li *et al.* [23] could observe that the former are wrapped up by C-S-H and the latter display a glossy surface and form a three-dimensional meshwork with a great number of contact points between them. However, composite microstructures vary widely depending on the specific procedure of dispersion employed and the characteristics and amount of CNTs. As mentioned earlier, Konsta-Gdoutos *et al.* [38] suggested CNTs may act as nucleating sites of high stiffness C-S-H phases.

Crack bridging has been readily observed in CNT cementitious composites (Fig. 5) and accounts for another essential advantage of incorporating CNTs into concrete, since concrete by itself is a brittle material [13] and increasing its resistance to cracking through CNT bridging of voids and cracks will lengthen its durability. The connecting effect of CNTs also increases flexural strength by increasing load transfer under stress. Fiber reinforcements have already been widely studied and used in concrete as a way to resist crack propagation and increase flexural strength [44], but CNTs move the connecting effect from the macro- and micro- to the nanoscopic level and have the potential to act as fillers of voids and pores [16], thereby resulting in a more intrusive and efficient kind of reinforcement which withholds crack propagation at the very onset, whereas microfibers could only delay crack development but could not inhibit it once it had started [45]. Li *et al.* [16] compared the performance of CNT-versus carbon-fiber-reinforced mortars and found that, while both reinforcing materials cause a similar increase in flexural strength, the latter decreased its compressive strength and

increased its porosity. The traditional reinforcing mechanism of fiber pull out has also been observed in CNT-reinforced cementitious composites by SEM [46], [47].

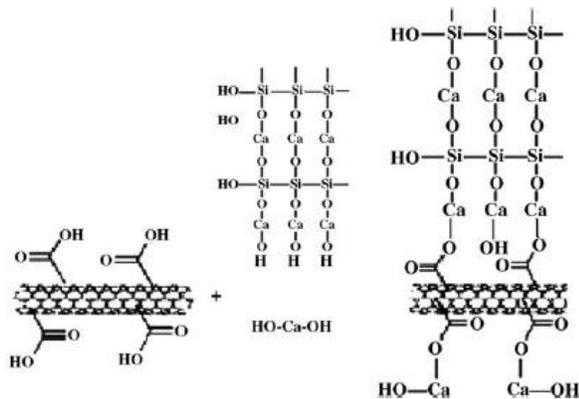


Fig. 3 Reaction scheme between carboxylated nanotubes and cement hydration products ($\text{Ca}(\text{OH})_2$ and C-S-H) [16]

B. Porosity

Porosity of concrete has a direct effect on its strength, its vulnerability to permeation of aggressive species such as water, chlorides, and sulfates, and the extent of autogenous shrinkage [48], [49]. Micropores (pores with radii smaller than 1.25 nm, according to the International Union of Pure and Applied Chemistry classification) and mesopores (pores with radii of 1.25-25 nm) of small size constitute the majority of gel pores and do not affect strength and permeability significantly; they are directly related, however, to the extent of autogenous shrinkage. The concrete permeability is mainly due to the existence of macropores (pores with radii between 25 nm and 5 μm), air voids, and microcracks.

The porosity of a CNT-reinforced mortar with a CNT content of 0.5 weight % by cement was measured by Li *et al.* [16] with mercury intrusion porosimetry (MIP), finding it decreased dramatically, by 64%, in relation to the standard mortar, and the resulting total porosity was 10.8% by volume. Pore size distribution also decreased, with the total volume of macropores and voids decreasing by 82% and the mean pore radius decreasing from 15 nm to 8.7 nm. Thus reinforcement with CNTs filled the larger pores to a great extent and produced a more compacted mortar, which leads to higher strength as well as decreased potential for damage by permeation of aggressive species, which in turn greatly influences durability. Han *et al.* [50] determined the water sorptivity, water permeability, and gas permeability transport coefficients of plain cement and reinforced cement with 0.2 weight % by cement of COOH-MWCNTs and found the latter were indeed noticeably lower.

The porosity measured by Li *et al.* encompassed pores only larger than 2 nm in radius as limited by the maximum pressure of mercury applied. Therefore micropores and mesopores with radii shorter than 2 nm were not taken in.

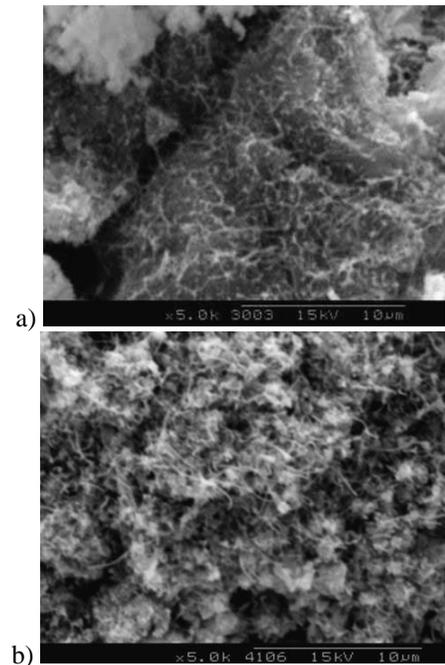


Fig. 4 SEM images of cement paste reinforced with acid-treated CNTs (a) and untreated CNTs (b) [23]

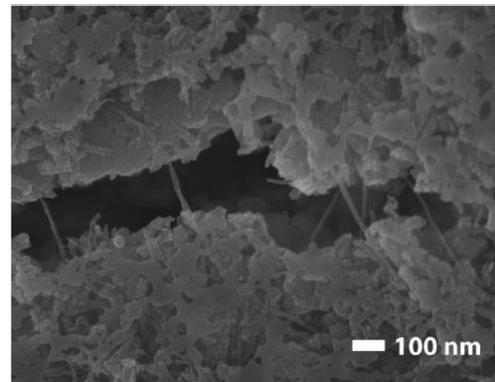


Fig. 5 Untreated CNTs embedded in cement paste bridging a nano-sized crack [39]

A decrease in the total volume of fine pores was indicated by Konsta-Gdoutos *et al.*'s results [45], who observed reductions in autogenous shrinkage of about 30% for a cement reinforced with 0.028-0.048 weight % of unfunctionalized CNTs (Fig. 6) and took into account that the extent of autogenous shrinkage is directly proportional to the amount of pores of radius sizes lower than 20 nm [45], [51]. From Fig. 6., it is observed that autogenous shrinkage is reduced with increased CNT content, which is an indication of the relation between fine porosity and CNT content. Lower shrinkage also has a significant effect on the durability of cement, as the development of microcracks due to volumetric changes during its early age is reduced.

Because there has not been reported sufficient data to date on reduction of macroporosity for unfunctionalized CNT-cement composites, it is early to conclude whether functionalized CNTs' strong interaction with the matrix results in a greater filling of pores.

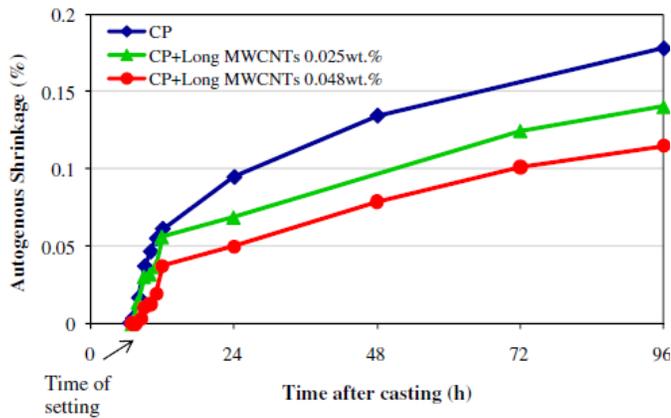


Fig. 6 Autogenous shrinkage of cement paste (water/cement = 0.3) and cement paste reinforced with 0.025 wt.% and 0.048 wt.% of 10-100 μm long MWCNTs [45]

IV. MECHANICAL PROPERTIES OF CNT-REINFORCED CEMENTITIOUS COMPOSITES

Owing to the exceptional mechanical properties of CNTs and their high aspect ratios, their embedment into concrete has the potential to overcome its inherent limitations (low values of tensile strength, fracture toughness, and ductility), while enhancing all its mechanical properties as a whole, and consequentially contributing also to lengthening its durability. Table I summarizes the results of some of the most significant research to date into successful enhancement of mechanical properties of cementitious composites through inclusion of CNTs. As it is observed, relative increases in properties vary widely from study to study. These variations depend on several factors, among which the most important are the method of dispersion, CNT content, and length and aspect ratio of CNTs. While dispersions with both physically dispersing agents and chemical functionalizing agents are reported to have produced a great enhancement of mechanical properties, there is not sufficient reported data about the effect of physically-dispersed CNTs on the porosity of the composites, which is an important factor to consider as it has affects the composite durability.

Since the variables related to the method of CNT dispersion have been discussed in detail in Section 2, a brief discussion of the influence of the other variables mentioned will be presented here. In view of the level of improvement of the composites' mechanical properties in the experiments shown in Table I, it seems that only a small amount of CNTs, in the approximate range of 0.05-0.2 % by weight of cement, is needed for effective reinforcement if efficient dispersion has been achieved. However, significant reductions of porosity for such low additions have not been reported.

The studies of Sha *et al.* [38], who compared the Young's modulus of cement reinforced with short (10-30 μm) and long (10-100 μm) CNTs of the same diameter, indicated that a higher content of CNTs was required (0.08 weight %) when short CNTs were used to achieve the same level of reinforcement that was achieved with 0.048 weight % CNT

content of long CNTs. Abu *et al.*'s results [47] also suggest that greater length of CNTs produces more effective reinforcement. It is expected longer CNTs can better withstand the stress of bridging cracks and voids, since they are anchored more deeply inside the matrix. For example, to bridge a 500 nm wide microcrack, a 1 μm long CNT would have half its length anchored, while a 10 μm long CNT would have 95% of its total length anchored.

On the other hand, higher increases in ductility are associated with shorter CNTs [47], and dispersion of longer CNTs is more challenging [25]. Care must be exercised during sonication not to break long CNTs [42].

Fig. 7 shows the typical compressive strain-stress curve of mortars studied by Li *et al.* [16]. The curves show an increase in the compressive strength and failure strain of the CNT-reinforced mortar relative to the standard mortar. While reinforcement with carbon fibers also produced an increase of the failure strain of the mortar to a lesser extent, it was accompanied by a decrease of its compressive strength.

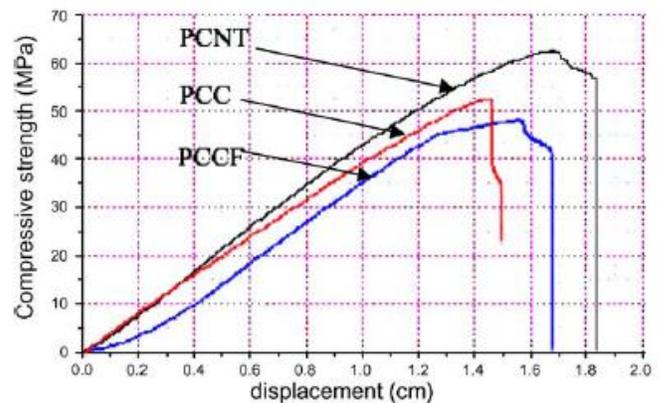


Fig. 7 Typical compressive strain-stress curve of mortars with CNT reinforcement (PCNT), carbon fiber reinforcement (PCCF), and no reinforcement (PCC) [16]

V. CONCLUSIONS

Reinforcing cement with low additions of MWCNTs, ranging from 0.05 to 0.5 weight %, can produce a remarkable enhancement of the mechanical properties of cement. Incorporation of CNTs into concrete thus has the potential to overcome its mechanical limitations, i.e., low tensile strength, low strain capacity, and brittleness. This enhancement could be particularly applicable in building structures and civil works in which the own weight of the structure is one of the main loads they have to bear during their service life. By using concrete of higher strength, the weight of the structure could be reduced, which would lead to a saving of resources and may compensate economically for the currently high cost of CNT synthesis.

In order to realize the potential of CNTs in the construction industry, further research needs to be carried out on mortars and concretes in real scale structures, as to date most tests have been performed on cement in laboratory scale. In addition, most studies have heavily relied on empirical tests, with limited theoretical understanding of the chemistry of

CNT-cement composites. There are many gaps that need to be overcome in understanding how the selected method of CNT dispersion in cementitious matrixes affects the microstructure and ultimate mechanical and permeation-resistant properties of the composite.

TABLE I
SELECTION OF RESEARCH STUDIES INTO ENHANCEMENT OF MECHANICAL PROPERTIES OF CEMENT THROUGH ADDITION OF CNTS

Research study	Dispersion method	CNT dimensions ^a	CNT content (wt.% by cement)	Compressive strength increase (%) ^b	Flexural strength increase (%) ^b	Young's modulus increase (%) ^b	Fracture toughness increase (%) ^b	Ductility increase (%) ^b
Li <i>et al.</i> , 2005 (16) ^f	Chemical treatment	d = 10-30 nm l = 0.5-500 μm	0.5	19	25	-	-	-
Li <i>et al.</i> , 2007 (23) ^d	Chemical treatment	d = 10-30 nm l = 0.5-500 μm	0.5	27	-	-	-	-
Cwirzen <i>et al.</i> , 2009 (33)	Chemical treatment + Surfactant	-	0.045-0.15	-	50	-	-	-
Konsta-Gdoutos <i>et al.</i> , 2010 (25)	Surfactant	d = 20-40 nm l = 10-100 μm	0.048	-	25	45	-	-
Konsta-Gdoutos <i>et al.</i> , 2010 (45)	Surfactant	d = 20-40 nm l = 10-30 μm	0.08	-	35	35	-	-
Nasibulina <i>et al.</i> , 2009 (43)	Direct CNT synthesis	-	-	200	-	-	-	-
Abu <i>et al.</i> , 2011 (38)	Surfactant	d = 60-150 nm l = 30-100 μm	0.1 - 0.2	-	60	25	170	73

^a d = CNT diameter; l = CNT length.

^b Values indicated are after 28 days curing.

^c Nanocomposite: mortar.

^d The tested cement nanocomposite incorporated nano-SiO_x in addition to CNTs.

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