Can Carbon Nanotubes Make Wonders in Civil/Structural Engineering?

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Abstract- **Nanoscience and nanotechnology provide enormous opportunities to engineers the properties of materials by working in atomic or molecular level. It has not only facilitated to overcome many limitations of conventional materials, but also tremendously improved the mechanical, physical and chemical properties of the materials as well. To develop high performance, multifunctional, ideal (high strength, ductile, crack free, durable) construction material, carbon nanotubes (CNTs) show promising role to modify/enhance the characteristics of the conventional construction materials such as concrete and steel. In the paper, a brief on geometry and mechanical properties, synthesis processes, possibilities and findings of different researchers on CNT reinforced composites is presented. It is also brought out that a crack free durable concrete is possible if certain issues such as uniform distribution of CNT in composite and bond behavior of CNT modified concrete can be addressed. Finally, few pre-proof of concepts are mentioned where CNTs can play the pivotal role to redefine the scope and ability of civil engineering, in general, and structural engineering, in particular.**

Keywords- Carbon Nanotubes; Concrete Composite; Durability; High Strength; Synthesis; Challenges

I. INTRODUCTION

Nanoscience has paved the way to tailor the properties of materials based on particular requirement by working in atomic or molecular level. In general, nanotechnology is not an isolated technology for certain purposes, but it is an enabling technology to achieve many goals by engineering a material at nano level. Similar to the fields like energy, medicine, electronics, etc., nanotechnology shows remarkable potentiality of its role to play by opening a new way to solve many of the perennial problems civil engineers do face every day. Aggressive development of infrastructures using conventional constructional materials will be responsible for approx. one-third of global warming. It is estimated that per ton production of cement approximately produces one ton of CO_2. Hence, there is an alarming need for developing new construction material which is smart, efficient and sustainable. The countries like India, where growth of infrastructure plays a significant role in the growth of the country, engineering of green and smart construction material will enormously help to generate public, private, strategic and societal goods. Among all the nano forms of metals and non-metals, carbon nanotubes (CNTs) seem to have the most promising role towards developing an ideal (high strength, ductile, crack free, durable) construction material like concrete. The carbon nanotubes (CNTs) attract the researchers since their discovery, because of their higher strength and relatively low weight. These nanotubes are useful for any application where robustness and flexibility are necessary. Further, nanotubes are also stable under extreme chemical environments, high temperatures and moisture as well. Use of nano engineered concrete would lead to considerable reduction in the dimensions of the structural members which could result in much less consumption of cement and thereby reduction of CO_2 release and make the world sustainable through eco-friendly products. Further, carbon nanotubes can also be used to make nano composite steel. Initial research findings reveal that they are about 50 times stronger and 10 times lighter than conventional steel. Apart from technical intricacies and lack of information, one of the main obstacles in using CNTs in construction is cost of CNTs as construction materials need to be produced in mass and should be reasonably cheap. Exorbitant cost implications in production of CNTs are diminishing very fast. For example, cost of industrial CNT was $27,000/lb in 1992, $550/lb in 2006 and $120/lb in 2011. It is also predicted that the price would be as low as $0.5/lb in 2013-14 [1]. To bring out the best from carbon nanotubes to the construction industry, specifically, in usage of construction materials, the extraordinary geometrical shape, unparallel mechanical properties, complex but challenging synthesis processes, and probable areas of applications are essential to be known. Therefore, an overview of these aspects of carbon nanotubes with the current state of knowledge is brought out in the present paper.

II. GENERAL DESCRIPTION AND GEOMETRY

Carbon nanotubes can be idealized as rolled form of graphite sheets where carbon atoms are arranged in a hexagonal array. The ends are capped by a dome shaped half fullerene molecules. Normally, the elastic properties of CNTs are assumed to be independent of the chirality due to the regular isotropic nature of hexagonal two-dimensional crystal. But, dislocation theory states that the strength mechanism is a function of the tube chirality [2]. Therefore, the mechanical properties of nanotubes greatly depend on the atomic arrangement of the nano structure. The atomic structure of nanotubes is defined by the tube chirality. Two limiting cases exist, i.e. ziz-zag shaped (chiral angle of 0^0) and armchair shaped (chiral angle of 30^0). The difference in armchair and zig-zag nanotube structures is shown in Figure 1.

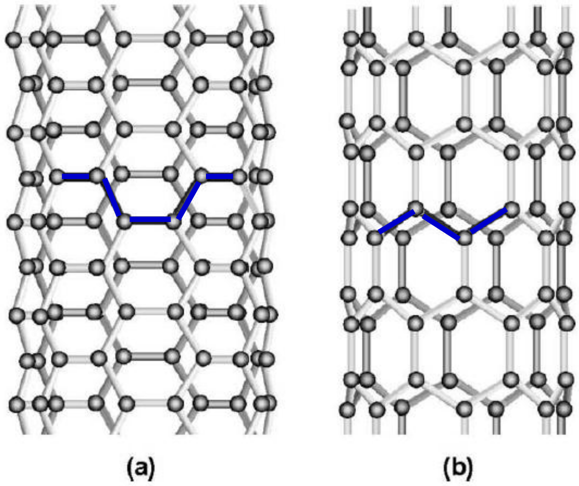

Fig. 1 Illustration of the atomic structure of (a) an armchair nanotube, (b) a zig-zag nanotube [3]

Carbon nanotubes are available mainly in two forms, viz., single-walled (SWCNTs) or multi-walled (MWCNTs). MWCNTs consist of concentric single-walled carbon nanotubes (SWCNTs) with different chirality and van der Waals forces are responsible to keep the concentric nanotubes in place. Due to purity in the basic form, single-walled nanotubes are primarily used in fundamental investigations on preparation, characterization of carbon nanotubes as the geometry and mechanics of multi-walled carbon nanotubes further complicate to evolve their mechanical properties. Therefore, the geometry aspects allow for manipulation of various properties according to the requirements.

III. MECHANICAL PROPERTIES (STRENGTH AND STIFFNESS)

The first closed, convex structure formed was the C60 molecule and was named as Fullerene. In the mid-1980s, chemistry of fullerenes was developed by Kroto et al. [4]. Fullerenes are geometric cage-like structures of carbon atoms that are composed of hexagonal and pentagonal faces. Further, in 1991, carbon nanotubes (CNTs) were synthesized by Ijima [5]. The mechanical property of CNT mainly depends on their bonding nature of atoms. This system is similar to that of graphite. A strong σ covalent bond that binds the atoms in plane, results in the stiffness and high strength of a CNT whereas the π-bond determines the interlayer interaction between atoms on neighboring layers, which is normally weaker than the atoms within the layers.

The unparallel mechanical properties of CNT have drawn intense interest among the research communities. The chirality of the CNT has significant implications on the mechanical and electronic properties since the bonding configuration plays a key role in defining mechanical and conductance properties. It has been reported that nanotubes can be either metallic or semiconducting, depending on tube chirality [6]. Owing to the symmetric structures, these cage-like well-knitted forms of carbon have exhibited exceptional material properties. Therefore, CNTs are quickly becoming one of the most promising nano-materials due to their unique mechanical properties. These materials are promising candidates for the next-generation high performance structural and smart composite materials [7-9]. The SWCNT is about 100 times stronger than steel, yet one-sixth of its weight [10]. Its hollow center structure makes it very light, being one-sixth the weight of copper, and about half the weight of aluminum. Treacy et al. [11] and Walters et al. [12] investigated the influence of chirality on the mechanical properties of CNTs. CNT can be used as fibers in material applications to improve the strength of material. The small diameter of CNTs also has an important effect on their mechanical properties compared with traditional micron-size graphitic fibres [13]. Yakobson et al. [14], Yakobson and Samsonidze [15] had analytically shown that though carbon nanotubes are instable beyond linear response, they are remarkably resilient with extreme strain resisting capacity. Analytical/theoretical studies on the mechanical properties of CNTs are more advanced than experimental measurements, mainly due to the technological challenges to handle specimens in nano level. However, using sophisticated instruments viz., transmission electron microscopy (TEM) and atomic force microscopy (AFM)), it is possible to evaluate the mechanical properties of CNTs [16, 17]. Salvetat et al., [17] reported that the Young’s modulus of CNTs was approximately 1 TPa. Hence, the direct information on the strength of molecular structures inspires the development of new materials with a higher strength to size ratio. Yu et al. [18] found out that the yield strength of single walled CNT is between 20-60 GPa and yield strain of CNTs is found to be up to 10% [12]. In addition to their high strength and elastic constant, CNTs have extremely high aspect ratios (> 1000:1) and reaching to a level as high as 2,500,000:1 [19]. In spite of availability of sophisticated instruments, intricacies in handling and interpretation of the results have led to wide discrepancies among the reported mechanical properties of CNTs.

Yakobson and Avouris [20] distinguished the CNTs (usually less than 20 nm) from carbon nanofibers (CNFs with diameter can be as large as 200 nm). Like CNTs, CNFs have recently achieved significant scientific attention owing to their extraordinary and useful properties, such as exceptional tensile strength, elastic modulus and electrical and thermal conductivity [21, 9]. Ozkan et al. [22] performed direct mechanical measurements on carbon nanofibers (CNFs) and brought out that the tensile strength of CNFs is between 2 and 5 GPa with an average modulus of elasticity of 300 GPa. Experimental tests on CNFs have shown that Young's modulus of CNFs is found to be as high as 400 GPa with a tensile strength of 7 GPa [23]. CNTs/CNFs are the strongest and stiffest materials on earth, in terms of tensile strength and elastic modulus respectively. Unlike graphite fibers, CNTs and CNFs possess both high flexibility and high strength along with high stiffness. These properties of CNTs pave the way for generation of high performance composites. Unfortunately, investigation on usage of CNTs/CNFs in construction industries is extremely occasional and inadequate [24, 25] and convincing results [7, 26, 27] are yet to be achieved.

IV. SYNTHESIS

To apply carbon nanotubes in composites, large quantities of nanotubes need to be produced economically which is extremely challenging. Since the discovery, variety of techniques has been developed for producing carbon nanotubes. Iijima [28] first observed multiwalled nanotubes, and a few years later Iijima and Ichlhashi [29] and Bethune et al. [30] independently reported the synthesis of single-walled nanotubes. Primary synthesis methods for single and multi-walled carbon nanotubes include arc-discharge [28, 31] and laser ablation technique [32-34]. The main limitations of the arc-discharge and laser ablation techniques are their prohibitive cost of operation and CNTs cannot be produced continuously. During nanotube synthesis, impurities in the form of catalyst particles, amorphous carbon, and other impurities are also produced. Thus, subsequent purification steps are required to separate the tubes. For both the arc-discharge and the laser-ablation techniques, purification steps are necessary to separate the CNTs from undesirable by-products.

These limitations have been overcome in chemical vapor deposition (CVD) technique [35, 36] where nanotubes are formed by the decomposition of a carbon-containing gas. Since the carbon source is continually replaced by flowing gas, amount of impurities are also considerably less than arc-discharge and laser ablation techniques. One of the unique aspects of CVD techniques is its ability to synthesize aligned arrays of carbon nanotubes with controlled diameter and length. The synthesis of well aligned, straight carbon nanotubes on a variety of substrates has been accomplished by the use of plasma enhanced chemical vapor deposition (PECVD) [36-39]. It is reported that the growth rate under the plasma enhancement was 40 times faster than the thermal CVD. It is suggested by Thostenson et al. [3] that CVD technique provides immense potential for the large scale nanotube production. One major drawback in CVD is that catalysts used in this technique need to be prepared and calcinated well before they are used for the growth of CNTs. To overcome this, Nasibulin et al. [40] developed a CVD reactor enabling continuous feeding of the catalyst particles. It is worth noting that SiO_2, MgO and Al_2O_3 are known to be good supporting materials for the growth of CNTs [41-43].

V. CARBON NANOTUBES AS REINFORCING MATERIALS IN COMPOSITES

Concrete is the most commonly used construction material in the world. However, very low tensile strength and strain capacity limit the usage of concrete. Witnessed the advancement of nanotechnology in general and CNTs in particular, researchers are attempting to incorporate materials engineered at nano level, like CNTs, as a means to overcome these well-reported limitations of cementitious materials used in concrete [26, 44]. Towards this, it is necessary to understand the mechanics (of both macro- and micro- level) of CNT modified composites. In a broad sense, keeping aside the scale, the concepts of fiber reinforced composites can also be applied to CNT modified composites Chou [45]. Researchers [46-52] used discrete macro- to micro- fibers as a means to control crack growth in cementitious materials.

As mentioned before, the majority of research on CNT composites has focused on polymer matrices and brought out the promising results such as significant improvements in fracture toughness, hardness and strength [53, 54]. Further, due to their remarkable mechanical, chemical, electrical, and thermal properties, carbon nano-fibers are used in reinforcing polymer-based materials [55-57]. These nano-fibers, both carbon nanotubes (CNTs) and carbon nanofibers (CNFs), may prove to be superior alternatives to traditional fibers, and promising candidates for the next-generation of high performance and multi-functional cement-based materials. In order to realize the potential applications of these composite materials, it has been suggested to continue further investigations which would lead to developing more economical ways for mass production techniques of CNTs [58].

Unlike other important matrix materials, limited work has been done on the use of cements to produce CNT composites, with only very preliminary work being reported [59, 60]. Different mechanical tests on CNT modified cement/concrete (with varying concentration of CNT) were conducted by few researchers [25, 61-65]. As far as the integration of CNFs in cementitious materials is concerned, even fewer studies have been conducted as compared to that of CNTs. Recently, Sanchez [66] has studied the effect of CNFs on the mechanical properties of nano engineered materials. Studies have been carried out focusing on the effect of CNFs–CNTs on the mechanical properties of cementitious composites [67-70, 64, 44].

Many researchers [71, 72, 25, 63] utilized ozone gas or sulphuric or nitric acid treated CNTs, for enhancing the reinforcement efficiency between the hydrated cement and CNTs. Li et al. and Shah et al. [25, 73] investigated the flexural strength of nanocomposite based cementitious materials. For industrial applications, instead of cement, clinker particles may also be used to make CNT-cement composite manufacturing cheaper and chemically stable [74]. Metaxa et al. [75] performed nanoindentation tests on 28 days cement paste samples reinforced with MWCNTs and reported the increase in the Young's modulus of the composite. The studies have shown that CNFs–CNTs can improve properties such as tensile and compressive strength of concrete, although marginally in most cases. A major problem that arises when CNFs–CNTs are used to reinforce any kind of material is dispersion. CNFs–CNTs strongly attract each other due to van der Waals forces. This attraction results in the formation of agglomerations in the form of entangled ropes and clumps that are very difficult to disentangle.

Schematic representation of the general concept of the incorporation of CNTs/CNFs into composite material by their direct growth on the surface of matrix particles is shown in Figure 2. These structures provided a good dispersion of the CNTs in the cement matrix, which is essential for obtaining the improved properties of CNT modified concrete composites [40].

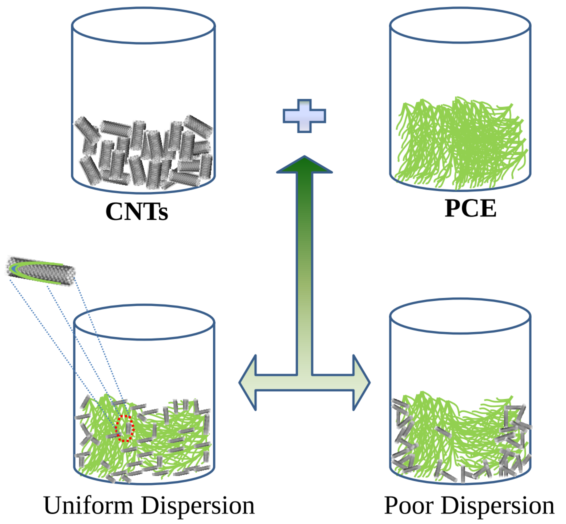

Fig. 2 Incorporation of CNTs/CNFs into composite material by their direct growth on the surface of matrix particles

A. Problems in Achieving CNT Modified Concrete

Few well-reported problems toward developing CNT modified concrete are discussed here. Typically, time-consuming steps are required of carbon nanomaterial purification, functionalization and mixing with matrix. On the other hand, interfacial bonding between CNTs and the binder matrix is another grey area that needs more attention for developing advanced cementitious materials using CNTs [27]. To develop CNT modified concrete, one of the major drawbacks is to attain uniform dispersion of CNTs in cement-based materials [27, 76]. Due to enormously large surface area of CNT, they tend to agglomerate and cannot be homogenously dispersed in a cement matrix by simple mixing procedure. It leads to the formation of many defect sites in the nanocomposites and limits the efficiency of the CNTs in the matrix. Although previous investigations have shown encouraging results in dispersing both CNTs and CNFs within aqueous solutions [77, 78], most of these techniques have limitations in using for cementitious materials because if large amount of surfactant is used as dispersant (as proposed by few researchers) it will retard the hydration process of cement [64]. Further, Tyson et al. [79] suggested that the size of the cement grains also plays a crucial role in the dispersion of CNTs within the cement matrix (as shown in Figure 3).

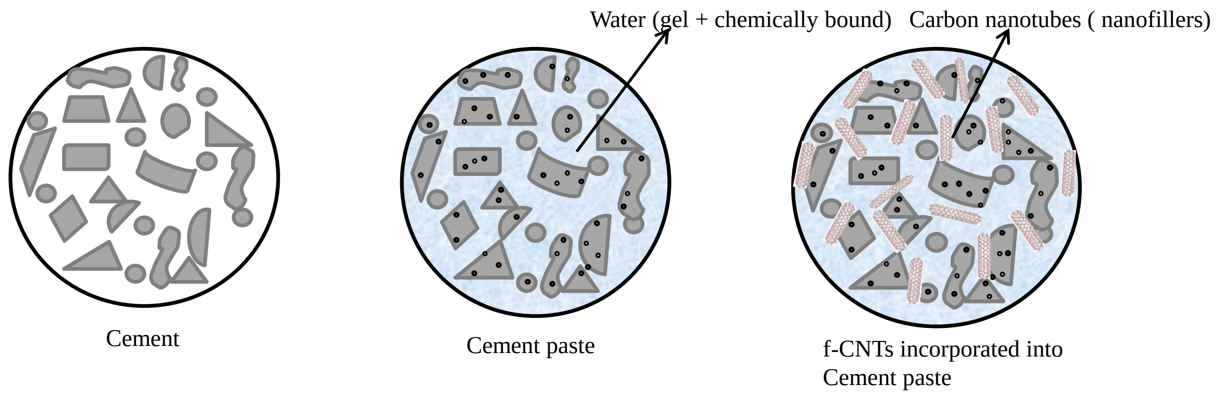

Fig. 3 Illustration of the effect of cement grains on dispersibility of CNTs/CNFs

B. Promising Ways out to Counter the Problems

To overcome the problem mentioned above, several attempts are being made. Bandyopadhyaya et al. [80] was able to disperse up to 15% wt of (by weight of water) CNTs into an aqueous solution containing Gum Arabic and mixing in an ultrasonic mixer. These techniques have been, to a reasonable extent, successful in dispersing CNTs in polymeric materials. Zhao et al. [26] demonstrated a procedure to reach aqueous concentration of CNTs up to 5 mg/ml. Use of surfactants for dispersion of CNFs–CNTs in liquids may lead to other problems; they can retard or prevent hydration, entrap substantial air in the paste, or undergo reactions with water-reducing admixtures, resulting in re-agglomeration [44]. Hence, these techniques may not always be appropriate for cementitious materials. Wang et al. [81] used microwaves to functionalize SWCNTs in a solution of nitric and sulfuric acid. Grunlan et al. [78] has conducted research on the use of poly acrylic acid as well as polyallylamine hydrochloride as a means to control the dispersion of non-functionalized carbon nanotubes based on the pH of the solution. Some investigators have first dispersed CNTs in water by using surfactants and sonication, and then added the dispersion to cement for mixing [64] where CNTs were dispersed in water by sonication while using polyacrylic acid polymers as a surfactant.

Nasibulin et al. [40] proposed a new simple approach to grow CNTs/CNFs directly on the surface of matrix particles providing an exceptional dispersion of the carbon nanomaterial in the matrix. Mudimela et al (2009) [59] also proposed a method to solve the problem of creating a good dispersion of CNTs and CNFs in a matrix by growing carbon nanomaterial on the surface of matrix particles (silica fume and cement particles). It is observed that along with good dispersion, the method provides good bonding between the carbon nanomaterials and matrix. Konsta-Gdoutos et al. [82] also proposed another innovative technique to achieve a highly dispersed CNTs reinforced cementitious materials. Tyson et al. [79] showed that superplasticizers which are hydration-compatible surfactants, can enhance the distribution of CNFs in water and cement paste.

VI. DURABLE CONCRETE

Cementitious materials are typically characterized as quasi-brittle and susceptible to cracking. Strength, ductility, creep and shrinkage, fracture behavior and durability of cementitious construction materials greatly depend on the micro- and nano- scale formation of the material. Hence, along with the effort to develop new construction material, it is also similarly important to investigate the nano-scale properties like fracture properties and durability. In past two decades, various attempts are made [83, 73] to incorporate fibers (organic, steel, plastics etc) into cementitious matrices to control cracks by bridging the cracks during loading and transferring the load. Effectiveness of discrete macro- to micro- fibers as a means to control crack growth in cementitious materials is reported by several researchers [46, 50, 51]. The use of discrete fibers results in a more uniform distribution of stress within the matrix. It is reported [84] that microfibers and hybrid fiber systems have led to significant improvement of the mechanical properties of cement-based materials.

Considerable improvement in restricting cracks in cementitious matrices was observed by addition of CNTs [54]. It is worth noting that the distribution of the CNT in the hydrated samples can provide addition bridging in the cracked zone (as shown in Figure 4). Due to their remarkable mechanical, chemical, electrical, and thermal properties, and excellent performance in reinforcing polymer-based materials, performance of carbon fibers in cement is also investigated by Marrs et al. [56]. The incorporation of fibers and CNTs at the nanoscale will allow the control of the matrix cracks at the nanoscale level and essentially create a new generation of a “crack free material” [83, 73, 85].

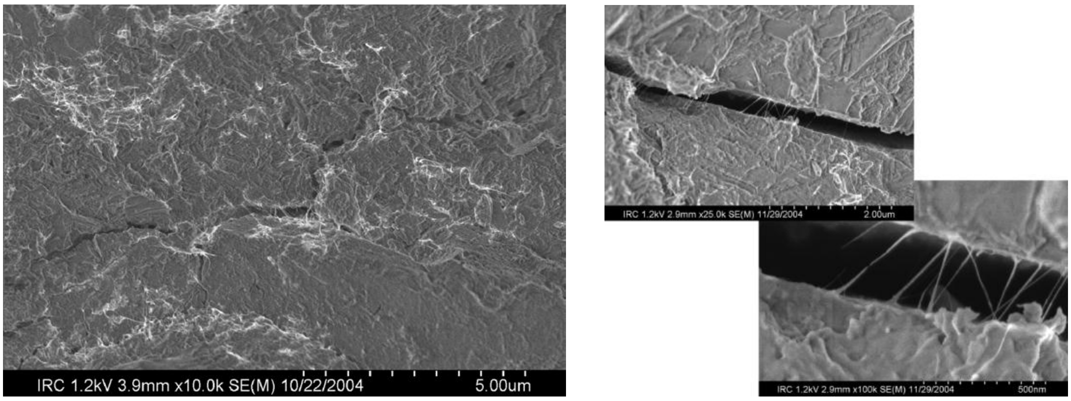

Fig. 4 Image of fracture surface of group 3 sample (3 days hydration) (b) Crack bridging across group 3 sample (3 days hydration) [86]

Crack in cement matrix can also be formed due to shrinkage. Hence, reduction in shrinkage would also help in controlling the crack in concrete. Studies on autogenous shrinkage of plain cement paste and CNT reinforced cement paste are presented in [75]. It is observed that the samples reinforced with CNTs exhibit lower shrinkage than the plain cement paste. It is important to mention here that shrinkage development is proportional to the amount of the fine pores in the binder at early ages [87]. Due to small size of CNTs, they will reduce the amount of fine pores which leads to the reduction of the capillary stresses, resulting in lower autogenous strains. Hence, CNT reinforced matrix would reduce the length and width of crack in concrete and it expected to produce significantly stronger and tougher composites than traditional reinforcing materials. Thus, promises are being envisaged in CNT reinforced matrix for the next-generation of high performance and multi-functional cement-based materials and structures.

VII. APPLICATION IN SENSORS

Concrete structures undergo damage processes manifested in the form of cracks due to fatigue loading and environmental effects. In order to achieve long-term durability and performance, continuous health monitoring systems are needed for the concrete structures to make critical decisions regarding operation, maintenance and repairs. Traditional strain sensors such as strain gages, widely used for structural health monitoring, are sensitive, stable, of low cost and easy to use. However, stain gages can only measure the strains on the structural surface in a particular directions and locations. Hence, there is a need to develop new types of strain sensors which can be applicable in both the micro- and macro- scale, either on the surface or embedded in the structure, and will be able to make extra contributions such as structure strengthening or structure damping as well, i.e. behave as multifunctional materials/components.

As mentioned before, depending on their precise structure, conductance of CNT changes [88]. Changes in structure along the length of tube through defects or diameter changes can produce changes in conductivity. CNTs are also believed to be the best thermal conductors known [89]. Rolling up a graphene sheet on a nano-meter scale has dramatic consequences on the electrical properties [90]. Because of the symmetry and unique electronic structure of graphene, the structure of a nano-tube strongly affects its electrical properties. CNTs can have conductivity up to eight times higher than that of copper. It can carry a current density achievable by any known conventional metallic wire, thus making them as potential candidates as nano-scale wires [91].

Several researchers have brought out the use of piezoresistivity and electrical conductivity of CNTs for sensing purposes [92, 2, 93] and proved to be efficient. It has paved the way to conduct extensive research in the area of self-sensing/self-monitoring/self-diagnosing of carbon-based system. The extremely high aspect ratio of CNTs makes them easy to form a conductive network and reinforcement network with doping level as low as 0.1% wt of CNTs [94-96]. Pham et al. [97] developed carbon nanotube polymer composite films that can be used as strain sensors with tailored sensitivity. The films were fabricated by either melt processing or solution casting of poly (methyl methacrylate) (PMMA) with MWNT.

Utilization of carbon nanotubes as strain sensors for health monitoring are described by Frogley et al [98], Dharap et al [99], Kang et al [100], Thostenson and Chou [101], Park and Kim [102], Neng-Kai et al. [103], Li and Chou [104]. To monitor the health of civil structures, Loh et al [105] developed surface mounted single walled carbon nanotube- polyelectrolyte (SWNT-PE) composite sensors to measure strain in concrete structures. CNTs were also used to detect damage initiation in composite materials such as matrix microcracking and delamination. Thostenson and Chou [101] processed glass-fiber-epoxy composites with embedded CNTs to evaluate the onset and evaluation of damage. It is further demonstrated that by combining load and strain measurements in real-time with the direct current electrical resistance measurement of the CNT network, evolution and accumulation of damage in composite structures can be predicted [106]. These researchers also used CNTs for health monitoring of mechanically fastened composite joints [107] where CNTs were integrated into the joints to detect local damage such as delamination, cracking and fastener loosening. Gao et al [108] coupled CNTs and acoustic emission (AE) monitoring for sensing damage development in composites. They used the relationship between the resistance change and the AE signal cumulative counts to sense the damage initiation in the laminated composite specimens. Saafi and Kaabi [109] discussed the concept of using wireless and embedded nanotube sensors in concrete structures for structural integrity monitoring. Carbon nanotube networks were embedded into a cement matrix and used to develop an in situ, wireless and embedded sensor for damage detection in concrete structures.

VIII. OTHER PROBABLE AREAS OF APPLICATION OF CNTS

In addition to the exceptional mechanical properties associated with carbon nanotubes, they also possess superior thermal and electric properties: *thermally stable* up to 2800^0C in vacuum, thermal conductivity about twice as high as diamond, *electric-current-carrying* capacity 1000 times higher than copper wires [110]. Due to high electrochemically accessible surface area of porous CNTs arrays, combined with their high electronic conductivity, these materials can be used as smart structural materials [111-113] which would redefine the horizon of civil/structural engineering.

Super-hydrophobicity is an important criteria for developing *self-cleaning* surfaces [114-116]. Conventionally, super-hydrophobic surfaces are generated by conjunction of high surface roughness and low surface energy materials [117, 118]. A unique and versatile technique to impart super-hydrophobicity to stainless steel by surface modification using a carbon nanotube (CNT)-mesh structure is proposed by [87, 119]. These coatings are environmentally stable, thermally robust, and conductive. The exceptional properties of carbon nanotubes have been investigated for devices such as microelectronic devices [120, 121, 1].

There are many ideas being floated to create wonders in civil engineering by taking the advantages of nanotechnology. For example, (i) CNTs technology gives a new avenue for developing storage units for *solid hydrogen storage* at room temperature. (ii) A space elevator consists of a climber on a cable connecting Earth and space. The centrifugal force at space would counter gravity and the cable would stand by itself [122]. For designing such an elevator, it is required to invent new high performance materials to withstand tremendous forces. Only a carbon nanotube cable might be the answer for that [5]. (iii) Suspension bridges with few kilometers of unsupported span seem to be possible by taking greatest advantages of carbon nanotube cables.

IX. CHALLENGES AND WAY FORWARD

Though application of CNTs in civil engineering is being explored by few researchers, adequate attention has not yet been paid. For achieving the breakthrough in this area, it is not only a field of challenge and utmost importance, but it also needs a well-coordinated, multi-disciplinary and systematic approach. Advantages and drawbacks of using nanotechnology in construction industry have been brought out by Torgal and Jalali [123]. Advancements in nanoscience and nanotechnology need to be applied to develop a new material which can either be a high performance cementitious material or high strength, high stiffness cables. First of all, the knowledge in laboratory stage has to be brought to the field. Enormous efforts have to be made to develop technology for mass production of CNTs which is cheap and fast; similarly the product is with less impurity. Along with the well-reported problems like uniform dispersion in matrix, bond behavior, certain issues like long-term behavior, fracture toughness, ductility, energy absorption capacity of CNT reinforced cement have to be investigated. In other applications such as to develop self-cleaning steel or ultra high strength cables, though show enormous potentiality towards developing less energy and high efficiency materials, much more research is required before it can be brought to practice [124-127]. Cement is commonly used in engineering construction all around the world. However, cement has poor EMI protective properties. It is possible to shield or absorb some electromagnetic waves through conductive introductions. By incorporating MWCNT, various cement mortar samples were prepared and their electro-magnetic wave absorbing properties were investigated by Wang et al. [128]. The influence of the MWCNT content and sample thickness on the electromagnetic wave reflectivity was investigated in the frequency ranges of 2–8 GHz and 8–18 GHz. Wang et al. [129] discussed the effect of imcorporation of CNTs in flexural toughness of the cement composites and it was found that the addition of treated nanotubes significantly improved both the fracture energy and flexural toughness index of Portland cement pastes. The porosity and pore size distribution of the composites were also measured and it was found that cement paste containing MWCNTs had lower porosity and a more uniform pore size distribution. Transport properties of carbon-nanotube incorporated cement composites were investigated by Han et al. [130].

Finally, with the rise of nanotechnologies and their alluring promises, the extent of health hazard by using nano materials has also to be investigated. Unlike macro- or micro- particles, nanoparticles are capable of entering cells and disrupting cellular metabolism. Nanoparticles may also be able to enter the brain via the nasal mucous membrane. There is less clarity regarding the extent to which they are capable of entering the body through the skin [131]. Before bringing nanotechnology into mass usage like in construction, parallel research needs to assure the safety of the technology or safety of those who wish to make use of this technology.

A. Research Studies at CSIR-SERC on Possible Application of CNT in Civil Engineering – The Way Forward

(1) Atomistic simulation of CNT and cement-CNT composites for evaluation of the mechanical properties in multi-scale [132, 133];

(2) Numerical simulation of nano-micro mechanical properties of cementitious composites modified using CNT [134];

(3) Cement replacement and enhancement of mechanical strength and physical properties of nano engineered cementitious material [135], high performance concrete HPC (for enhanced durability or self-sensing or for making concre-tenna i.e (in-built antenna for health monitoring the structures), high strength concrete HSC (for enhanced elastic modulus and high tensile strength) and self compacting concrete SCC (for reducing the high bleed) as well [136, 137];

(4) Epoxy modification by CNT for maintaining the efficient and high fracture energy of FRP-composites during various type of loading;

(5) Co-guest moiety for highly challenged and efficient corrosion inhibitor with effective inhibitor loading. making high performance of the anti-corrosion paint is one of the most challenging R&D thrust area.

As a first level, the research team at CSIR-SERC has taken a significant research effort to achieve the above mentioned area. The following issues are specially emphasized during executing the investigations:

a) Identification of proper force field and parameters for CNT and cement composites for realistic modeling of the same at atomic level;

b) To find suitable dispersion agent, process, optimisation level, mixing procedure, rheology, effect on hydration and their appropriate mechanism, and long-term effect, i.e durability effect;

c) Most important part is how to make sure the Form-Structure-Function relationship of the CNT modified composites;

d) Proper characterisation, appropriate procedures for test or test protocols;

e) Last but not least, the thundering question i.e What will happen to the health of environment and mankind? and how about the cost effectiveness? - Though, we do not have direct answers for these questions, various researchers are putting their effort to convey the reality to society.

Hence it is concluded that, by-passing the last gap which is identified, it is sure CNT will make enormous changes in the civil engineering with the concerted effort by all the researchers.

X. CONCLUSIONS

In the paper, an overview on usage of carbon nano tubes (CNTs) in construction materials, their extraordinary geometrical shape, unparallel mechanical properties, complex and challenging synthesis processes is discussed. It is observed that the research on synthesis, characterization and usage of CNTs in construction materials as a reinforcing material is not so intense and competitive like the research on mechanics, mathematical modeling and evaluation of properties of CNTs. Hence, this paper will provide the initial information, state-of-the-art knowledge and limitations of usage of CNTs in construction materials. Finally, few pre-proof of concepts are mentioned which can redefine the boundaries of civil engineers. The transfer of concepts observed on materials at nano level to field remains a big challenge in civil engineering. However, engineering of nano structural features into material development could lead to significant breakthrough in civil/structural engineering. Towards this, a concerted, systematic, cross disciplinary and futuristic approach among the research communities from both science and technology is required. Further, social, economical and environmental concerns of usage of nanotechnology in mass applications like civil constructions need much more care, judicious approach and time tested observations.

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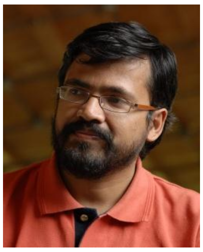

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