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Application of Nonconventional Materials, CNTs, in Road Maintenance-A Review

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ABSTRACT:

Concrete is considered a composite with conventional components such as cement, aggregate, and water. The tendency of using unconventional components in the concrete mix has been increased over the last few years. Maintenance of concrete is one of the most significant concerns for all Departments of Transportation (DOTs) across the nation for concrete pavement prone to crack propagation. With periodic advances in nanotechnology, nanomaterials have captured more attention from researchers (Isfahani et al. 2016) and (Etemadi et al. 2018). Carbon nanotubes (CNTs) is one of the best nonconventional additives to reduce roadway maintenance due to low permeability, low shrinkage, and high mechanical properties. This paper briefly reviews the impact of using CNTs in cement paste for road maintenance application, as well as mechanical properties and other attributes that make it a versatile alternative for coating and rehabilitation purposes. Additionally, this paper summarizes Colorado DOT results on using CNTs by the City and County of Denver Maintenance Department.

1 INTRODUCTION

Over the last century, significant effort has been made to increase concrete performance and strength by adding or replacing various components. Many studies have been conducted on adjusting major concrete elements such as cement, coarse and fine aggregate. However, little to no research has been performed on the replacement of water with carbon nanotubes (CNTs) as an admixture, especially for highway materials (M. M. Patel et al. 2016). Currently, all nanomodified materials for the construction industry are in the laboratory stage. However, application of nanomaterial products is a growing market to address a variety of concrete issues (if not all) in terms of durability and performance. Recently, applications of CNT are more feasible due to a reduction in the cost of CNTs in recent years to as low as \$0.20/g (TimeNano, China) (X. Yu and E. Kwon, 2012). According to BCC Research Market Report, "The global market for CNT primary grades was \$158.6 million in 2014. This market is projected to reach \$167.9 million in 2015 and \$670.6 million in 2019, with a compound annual growth rate (CAGR) of 33.4% from 2014 to 2019.". The CNT composites market is rapidly growing, but the knowledge of CNT usage is developing more gradually.

The first time CNTs were used by the construction industry was in 2011; e.i. EdenCrete produced CNT additive to increase concrete strength. The Colorado DOT in the county of Denver used CNT-mixture from EdenCerete to solve the maintenance issues faced in a specific road and published initial satisfactory results. The pioneer practice of CDOT demonstrated CNT mixture as a promising nanomaterial. The CDOT also provided limited suggestions to introduce CNT as an alternative solution for concrete pavement repair. However, the long-term impact of CNTs haven't been investigated yet (M. M. Patel et al. 2016).

2 CARBON NANOTUBES DEFINITION

A CNT is a miniature cylindrical carbon structure with hexagonal graphite molecules attached at the edges. CNTs are very thin and long. The diameter is one nanometer (one billionth of a meter) and the length is up to several nanometers. Nanotubes look like powder or black soot, but they are in fact rolled-up sheets of graphene that form hollow strands with walls that are only one atom thick (X. Yu and E. Kwon, 2012). Nanotubes with an aspect ratio >>1 are an alternative to reinforce and improve the mechanical properties of concrete (Nadiv et al. 2016).

3 MAIN TYPE OF CNT

The two main types of CNTs are Multi-Walled Carbon Nanotubes (MWCNTs) and Single-Walled Carbon Nanotubes (SWCNTs). SWCNTs are tubes of carbon atoms and came into production less than two years after the discovery of MWCNTs (Siddique, R., & Mehta, A. 2014), (Nojoomizadeh, M., & Karimipour, A. 2016), and (Yoo, D., You, I., & Lee, S. 2018). The MWCNTs can consist of up to ten shells of carbon. "The diameters and length of CNTs are 1~20 µm, and 0.2~5 µm, respectively (X. Yu and E. Kwon, 2012).

According to the US National Library of Medicine (NLM) and the National Institute of Health (NIH), the tensile strength of SWCNT is, amazingly, one hundred times greater than steel. SWCNTs perform very well, even under enormous amounts of pressure. When SWCNT is under a high compressive load, it bends, twists, kinks and buckles, but returns to the original structure because of high SWCNT elasticity (R. Jazaei, 2018). However, among all nanoparticles, multi-walled carbon nanotubes have outstanding mechanical properties, such as a Young's modulus of 0.45 TPa and tensile strength of approximately 3.6 GPa (Xie et al. 2000 & Styonski 2015).

4 GRAPHENE ROLLED METHODS

Three distinct ways in which graphene can be rolled into tube are known: Armchair, Zig-Zag and Chiral (Eftekhari, M.et al, 2016). Multi-Walled Carbon Nanotubes can be rolled using two different structural methods: The Parchment model and the Russian Doll model in Figure 1. When a carbon nanotube has an interior carbon nanotube nested inside, the outer tube has a larger diameter, referred to as the Russian Doll model. The other structural method is like rolling up paper. The Parchment model is shown below (Etemadi, A. 2014).

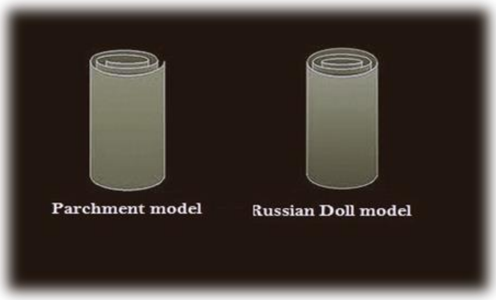

Fig. 1. Structural Rolling Graphene sheet methods (Etemadi, A. 2014).

5 CNT POTENTIAL IN CONSTRUCTION INDUSTRY

CNTs were discovered by S. Iijima in 1991(X. Yu and E. Kwon, 2012), and have been used in a variety of applications because of their superior mechanical, thermal, and electrical properties compared to other reinforcements that are compatible with concrete. Additionally, CNTs have the ability to bridge nano-scale cracks, while other reinforcements such as microfibers poorly binds cement crystals to provide strong paste for concrete (R. Jazaei, 2018).

Current applications of carbon nanotubes are varied in other fields. Among many applications, CNTs are used in water purification, air pollution filters, solar cell production, fire protection, polyethylene, sports equipment, synthetic muscles, gene therapy, tissue regeneration, cancer treatment, and textiles, and have the potential to be used in the tether of a proposed space elevator. Due to the high strength-to-weight ratio of CNTs, they are extensively used in the aerospace, military, medicinal and automotive industries. The use of CNTs has extended to become an alternative for rehabilitation of existing construction, bridges, cellular phone antennas as well as repairing damage, fatigue or loss of cross section due to corrosion, for both concrete and steel structures. CNTs are cost-effective solutions in the preceding fields but are not currently applied to cement composites. This is due to a lack of research in this area. Thus, the benefits of CNTs are currently out of reach. Potential applications of CNTs could be innumerable if combined with typical cementitious products (R. Jazaei, 2018).

However, there are some drawback to fabricating CNTs into cementitious materials. The tendency of CNTs to bundle and adhere together due to Van der Waals forces is problematic. The second problem is that CNTs are considered hydrophobic material, and water is the main contributor of all types of cement-based composites. Thus, CNTs do not disperse well in water because they are not capable of generating adequate interfacial bounds with cement matrices (Konsta-Gdoutos et al. 2010). Therefore, the challenging part of producing cementitious nanocomposite is dispersion of carbon nanotubes in water, so that water and carbon atoms create a homogeneous liquid for the cement matrix (R. Jazaei, 2018). The contemporary method to achieve high quality dispersion and deagglomeration includes the ultrasonic technique (Konsta- Gdoutos et al. 2010 & Musso et al. 2009) and use of functionalized CNTs (Li et al. 2005 & Muss et al. 2009). However, excessive use of ultrasonic energy may damage the carbon nanotube structure and decrease the beneficial properties of CNTs (Rausch et al. 2010).

Many researchers used Carboxylate acid functionalized carbon nanotubes; various solvents; stirring CNTs in a centrifuge, and heating after sonication of CNTs to increase dispersion effectiveness and enhance dispersion quality. In fact, covalent bonds between CNT sidewalls and chemical functionalization increases bonding with CNTs and the composite matrix. Cementitious nanocomposite is an emerging field with limited laboratory research. Thus, the procedure for dispersion of CNTs has not developed yet. CNT fabrication is conducted with various methods and sonication processes (Li et al. 2013 & Bhari et al. 2014 & Wang et al. 2013 & Jiang et al. 2003)

Overall, CNTs considerably increase mechanical, thermal, and electrical properties of cement-based composites. This review paper objective is only to shed a light on two major applications addressing DOT's issues; strength and structural health monitoring in highways and bridges.

6 CNT APPLICATION AS WATER REDUCER

All Departments of Transportation (DOT) are seeking a cost-effective sustainable solution for street/highway material maintenance. Colorado Department of Transportation (CDOT) conducted a research on the effect of carbon nanotube admixture as unconventional repair material for concrete pavement deterioration in Denver (M. M. Patel et al. 2016).

Continuous cyclic load in highway structures including concrete pavements and bridges has resulted in cracking and other concrete pavement deteriorations. It causes low service life and major delay in traffic flow due to repairing strategies. However, non-conventional materials such as CNT additives with as low a dosage as 1% CNT by weight of cement offers promising enhancement in concrete mechanical properties (X. Yu and E. Kwon, 2012) and (M. M. Patel et al. 2016). CNT contributes as a water reducer due to quick setting time and low permeability. Therefore, the CNT-concrete products are more durable and long-lasting as highway materials or repair materials (R. Jazaei 2018). G. Y. Li et al. 2005 research demonstrated that adding 0.5% CNT by weight of cement resulted in a 19% increase in compressive strength and a 25% increase in flexural strength.

CNTs were first used by the construction industry in 2011 (A. Al-Dahawi et al. 2016). The CNT-admixture was from EdenCrete. The Colorado DOT in the county of Denver used CNT-mixture from EdenCerete for the maintenance issues faced by a specific road and published initial satisfactory results (Figure 2). The pioneer practice of CDOT demonstrated CNT mixture as a promising nanomaterial. Additionally, limited suggestions were provided for CDOT to introduce CNT as an alternative solution for concrete pavement repair. However, the long-term impact of CNTs hasn't been investigated, yet (M. M. Patel et al. 2016).

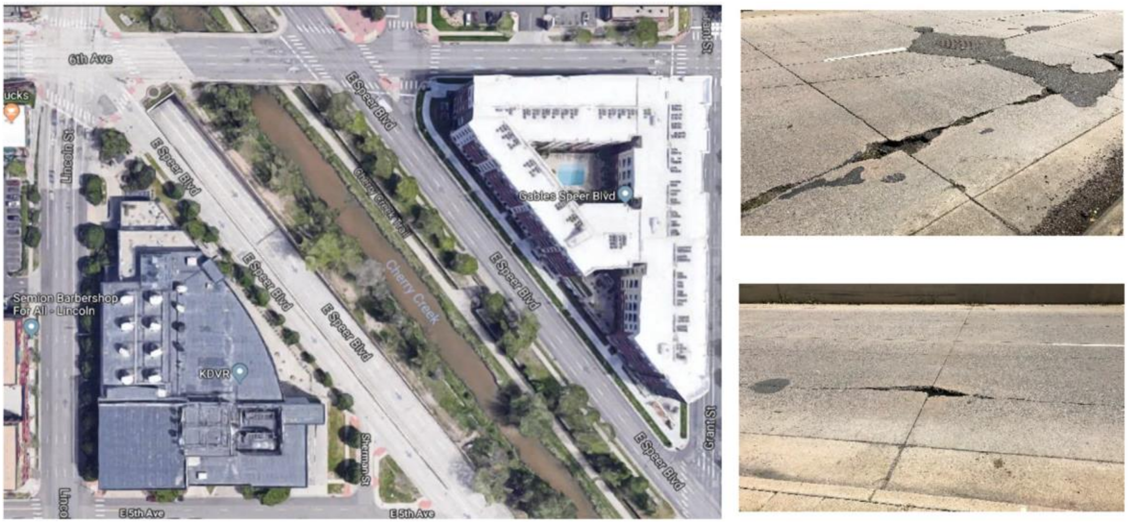

Fig. 2. Site location and condition of concrete pavement to be replaced by City and County of Denver Maintenance Department (M. M. Patel et al. 2016).

The CDOT report presented that CNT-admixture reduces required water-to-cement ratio, provides low permeability, decreases shrinkage, and, most importantly, decreases freeze-thaw resistance. Freeze-thaw resistance is a major issue for the Wisconsin Department of Transportation (WisDOT) and other states in similar severe environments. The highest priority of WisDOT is to complete road repair with minimal interruption for traffic flow and lane closures, which is 6-8 hours of nighttime. Consequently, CNT-admixture might be a good alternative due to its rapid setting and durability (Wisconsindot website, 2019).

7 CONCRETE MIX SAMPLES

CDOT research addressed three major deteriorations specific to cracks in concrete pavement; heavy loads from running vehicles, freeze-thaw cycles, and de-icing salts with $MgCl_2$ component. The mix design is presented in Table 1 (M. M. Patel et al. 2016).

Table 1. Mix design of CDOT Class E 12 h mix (reference mix) (M. M. Patel et al. 2016)

Material	Source	Description	ASTM	Spec. Gravity	Oz/cwt	Weight (lb)
Coarse Aggregate	Aggregate Industries	Aggregate Industries Morrison 57/67	C-33	2.64		1690
Sand	Aggregate Industries	Aggregate Industries Platte Valley Sand	C-33	2.62		1225
Cement	Mountain Cement	Mountain Cement Type I/II	C150	3.15		600
Air Entrainer	BASF	MB-AE 90	C 260	1.00	0.40	0.2
Type C	BASF	Pozzolith NC534	C 494	1.00	30.00	14.7
Water Reducer	BASF	MASTER GLENIUM 7920	ASTM C	1.08		2.2
Class F Fly Ash	Boral	Boral Class F Craig		2.225		150
		Water	C-94	1.00		263
					Total	3945
Specified F'c:		4500	PSI			
Specified Slump:		3.00 To 6.00	In.	Designed Unit Weight:	144.0	lbs./cu.ft.
Specified Air:		4.00 To 8.00	%	Designed W/C + P Ratio:	0.35	
Designed Air:		5.0	%	Designed Volume:	27.45	cu.ft.

A compressive test with a 4-in and 8-in diameter cylinder was performed, and the results reported. As seen in Figure 3 from CDOT, the data for three samples including a control sample, 2GPY (9.9 l/m3), and 3GPY (14.85 l/m3) were presented. GPY is acronym for gallon per yard of CNT mixture that was purchased from EdenCrete. The trend indicates that 3GPY compressive strength is 8.9% more than 2GPY, while 2GPY compressive strength is 19.9% greater than the control sample with zero CNT-admixture (M. M. Patel et al. 2016). As other experimental research on the effect of CNT additive has demonstrated, small dosage of CNTs dramatically increases mechanical properties of concrete. On the other hand, after a specific amount (that is still debatable in the progressive current research) (R. Jazaei 2018) and (M. M. Patel et al. 2016). M. Mayank at el, 2018 suggested 3 GPY mix for Colorado department of transportation due to higher slump for GPY (Figure 4). The low workability of CNT-admixture is due to strong Van der Waals forces among

CNTs (M. M. Patel et al. 2016) (R. Jazaei, 2018) and (Yin X., et al. 2018). In Figure 5, the field observation of test mixes shows the quality of concrete pavement before and after six months in the County and City of Denver (M. M. Patel et al. 2016).

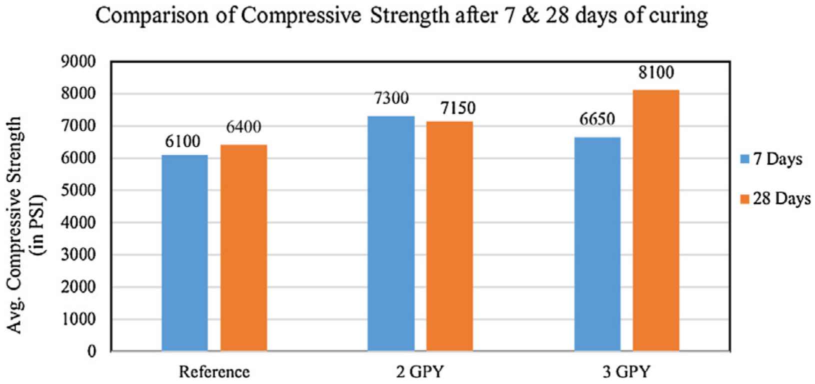

Fig. 3. Compressive strengths using carbon nano-tube replacements (M. M. Patel et al. 2016).

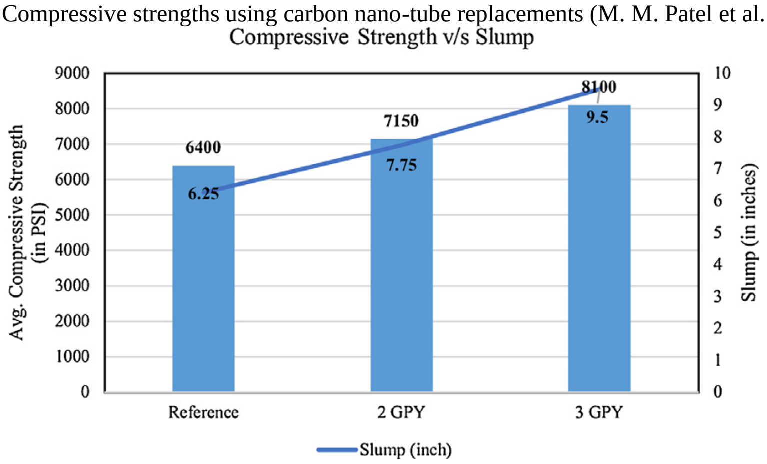

Fig. 4. (28 day) Compressive strength versus Slump (M. M. Patel et al. 2016).

Fig. 5. Field observations of test mixes: Reference mix after five years (left), sample mixes after six months, and one winter (right).

8 CNT APPLICATION AS SELF-SENSING SENSOR

Research was conducted by University of Minnesota Duluth and was funded by Federal Highway Administration (FHWA) of the U.S. Department of Transportation (USDOT). The main objective of this research was to evaluate CNT as a self-sensing material for Pavement Structural Health Monitoring. CNT has piezoresistive property that allows stress and strain (crack development inside the pavement is monitored or detected). Therefore, CNT not only increases concrete pavement strength, but also provides the stress/strain level with periodic change in electrical resistivity of the cement-based composites (X. Yu and E. Kwon, 2012).

Highway structural health monitoring is a crucial issue because progressive cracks result in damaged infrastructure and are a risk to public safety. At the present, some common methods use embedded sensors inside the concrete pavement such as electric-resistance strain gauges, optic sensors and piezoelectric ceramic sensors. However, these sensors are not a cost-effective or durable solution. Another drawback for using such sensors is low compatibility with concrete, while CNT-admixture is highly compatible with cement (X. Yu and E. Kwon, 2012) and increase the compressive and flexural strength (G. Y. Li et al.. 2005). CNT cost has been extremely high since their discovery due to advanced manufacturing process (R. Jazaei 2018). However, the cost of CNTs has rapidly dropped in recent years to as low as \$0.20/g (TimeNano, China) (X. Yu and E. Kwon, 2012). Therefore, CNT has high potential to be an alternative for current sensor products with development of the mix procedure for DOTs. The MWCNT (X. Yu and E. Kwon, 2012) physical and electrical properties is presented (Table 2). Figure 6 illustrates the process of fabricating MWCNT in water with one of the methods discussed by X. Yu and E. Kwon, 2012, then mixing the CNT-admixture with cement. Two sets of tests were performed in the lab and in the field. For the lab test setting, two electrodes were positioned in the specimen to measure the electrical conductivity due to applied compressive load (Figure 6). For quality control of proper CNT dispersion in the sample, a Scan Electron Microscope was used (X. Yu and E. Kwon, 2012) and (R. Jazaei, 2018). CNT-to-cement ratio was 0.05%, 0.1%, and 1% in three samples with constant water-to-cement ratio of 0.45. CNT-admixture needs higher w/c ratio compared to conventional cement-based composites (R. Jazaei, 2018).

Table 2. Properties of carboxyl multi-wall carbon nanotubes (X. Yu and E. Kwon, 2012)

Parameters	**Values**
Outside diameter	<8nm

Inside diameter	2~5nm
-COOH content	3.86 wt.%
Length	10~30μm
Purity	>95%
Ash	<1.5 wt.%
Special surface area	>500 m2/g
Electrical conductivity	>102 s/cm
Density	~2.1 g/cm3

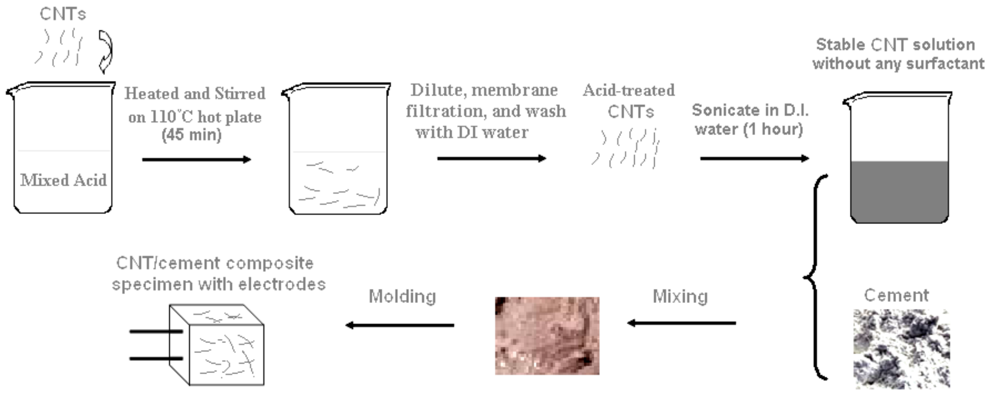

Fig. 6 Illustration of the CNT/cement fabrication process based on the acid treatment of CNTs (X. Yu and E. Kwon, 2012)

In the first picture of lab test setting, the CNT/cement composite sample and electrode are illustrated. In the second picture of the lab test setting, the applied compressive load and resistivity was measured continuously. In the third picture of field test setting, road testing of self-sensing CNT concrete is shown (Figure 7-8) (X. Yu and E. Kwon, 2012).

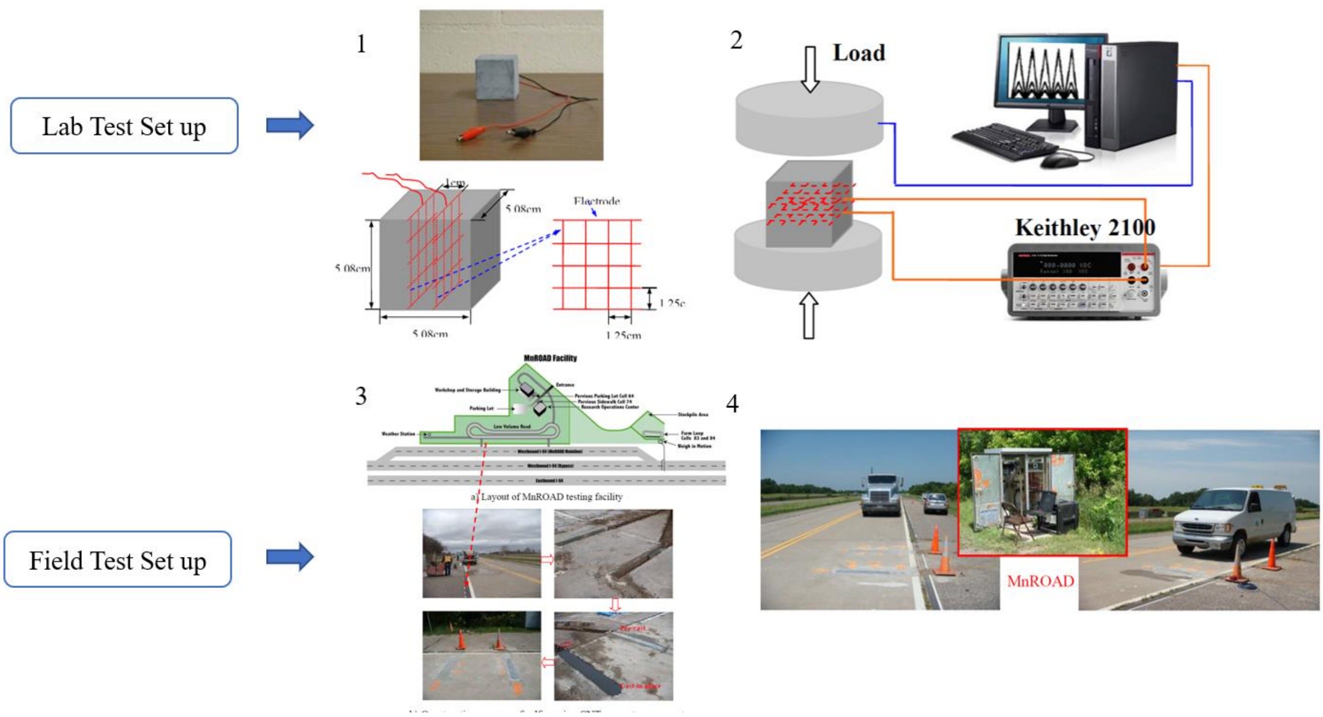

Fig. 7. Lab test setting and field test setting (X. Yu and E. Kwon, 2012).

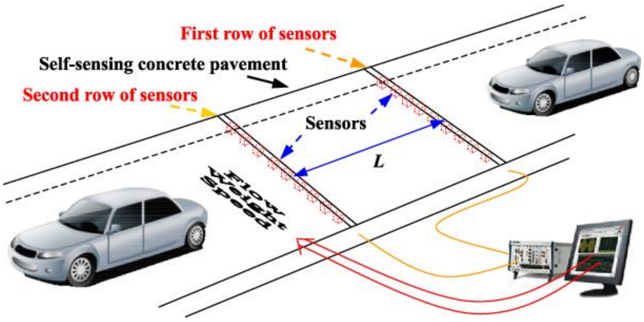

Fig. 8. Schematic self-sensing concrete pavement tested by traffic flow (Baoguo Han et al.., 2009)

The change in amplitude of electrical resistance as compressive load was applied on samples described the effect of CNT/Cement verses resistance (Ω). The result depicts in Figure 9 indicates that 0.1% (sample#2) performed the best under a compressive stress of 6 MPa. Other experimental research presented the same phenomena in CNT cement-based composites.

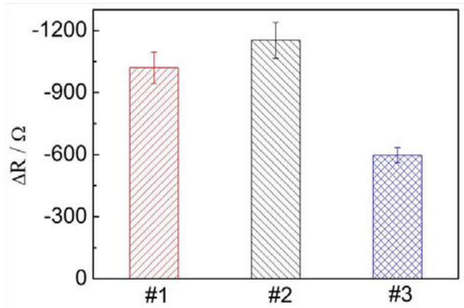

Fig. 9. Comparison of electrical resistance changes of CNT/cement composites with different MWNT concentration levels (#1: 0.05 wt. %, #2: 0.1 wt. %, #3: 1 wt. %) (X. Yu and E. Kwon, 2012)

H. K. Kim et al, 2014, reported that adding 0.1, 0.3, 0.5% CNTs to cement mortar and decreasing water/cement ratio will improve the stability of piezoresistivity (conductivity resistance) under a cyclic load. The mixture included cement, silica fume, crushed sand, water, super-plasticizer and CNTs (Figure 10).

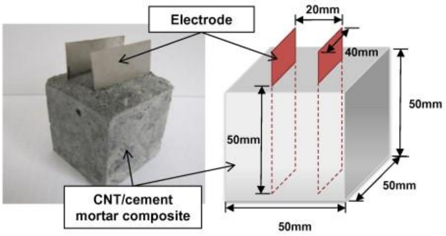

Fig. 10. Conductivity test (H. K. Kim et al, 2014)

G.M. Kim et al, 2016, investigated the effect of CNT additive to cementitious composite in terms of heating element. In this study, 0.1, 0.3, 0.6, 1 and 2% CNT, silica fume, and poly-carboxylic acid base super-plasticizer were mixed. The results showed up to 0.6% of CNTs improves heating conductivity. Additionally, the electrical resistivity of CNT-embedded cementitious materials related to heat generation capacity. Beyond 0.6% of CNTs, additive electrical resistivity rapidly decreased (Table 3).

Table 3. Summary of test results in previous studies on electrically conductive concretes (G.M. Kim et al, 2016)

Conductive filler	Steel fibers and steel shavings	Steel fibers	Carbon products	Stainless steel fibers and graphite	CNT 0.6%	CNT 2%
Electrical resistivity (Ω cm)	7500	748.33	5100	400	145.2	68.1
TI (°C)*	38.7	41.3	47	25	34.6	67.8
Heating rate (°C/min)	0.83	1.8	1.2	0.41	2.41	7.98

TI (°C): temperature increase from ambient temperature to terminal temperature within 1 h

Heyong-Ki Kim, 2015, indicated that use of CNTs in cement composite and RC decreases chloride penetration. The mixture included cement, water, silica fume, super-plasticizer and 0, 0.3 and 0.6% CNT tested in saturated and dry conditions. The results showed that 0.6% CNT mixture in dry conditions has minimum conductivity (Figure 11-13) (Heyong-Ki Kim, 2015).

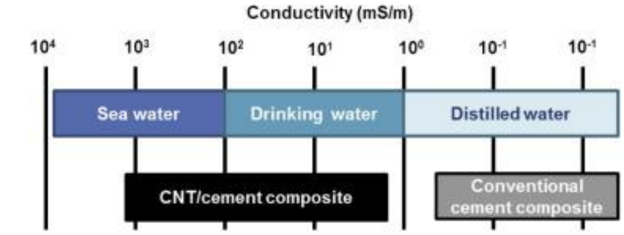

Fig.11. Conductivity ranges of various types of water and cement composites (Heyong-Ki Kim, 2015).

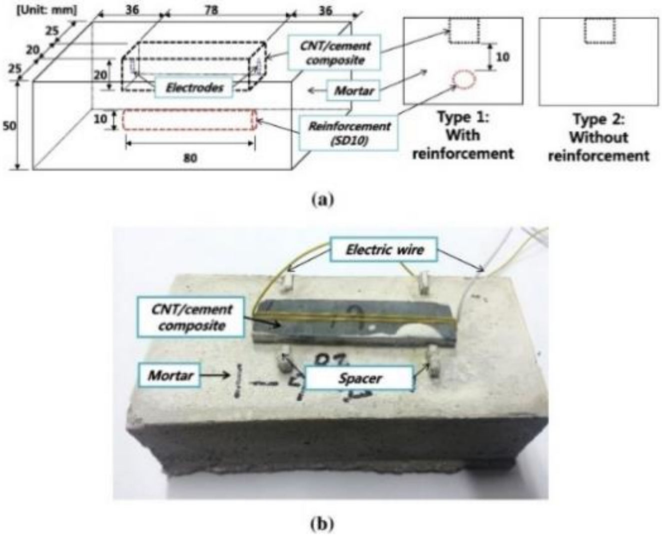

Fig. 12. Specimens for evaluating the effect of reinforcement on conductivity of CNT/cement composites in concrete structure: (a) schematics and (b) actual shapes (Heyong-Ki Kim, 2015).

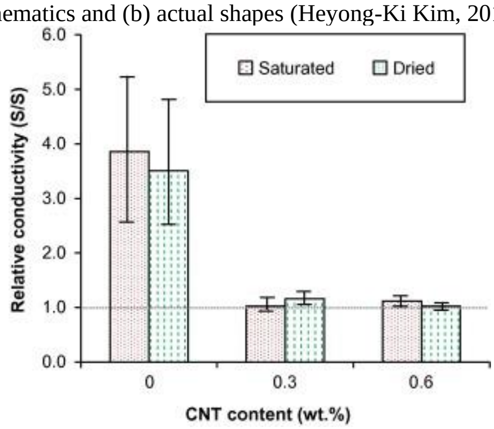

Fig. 13. Relative conductivities of CNT/cement composites embedded in cement mortar with reinforcement (Heyong-Ki Kim, 2015).

H.K. Kim, 2014, conducted research on the effect of improving dispersion of CNTs by adding silica fume. The findings indicated an enhancement in mechanical and electrical properties in cement composite. The mixture contains CNTs that were 0, 0.15, 0.3% wt of cement and 0, 10, 20 and 30% silica fume by weight cement (H.K. Kim, 2014).

9 SUMMARY AND CONCLUSION

The aim of using CNTs in concrete pavement is to provide a safe and durable surface which is subjected to traffic load and severe environmental conditions. Application of CNTs increase not only longevity and performance of concrete pavement, but also sensitivity of concrete pavement to load or environmental changes. The objective of this review is to shed light on two important types of CNT application in civil engineering infrastructure. The usage of CNTs was discussed with emphasis on DOT applications and the need to invest in such research.

CNTs improve mechanical properties of concrete pavement under heavy traffic loads as well as resistance to damage caused by environmental factors such as moisture and temperature. Therefore, concrete consisting of CNTs has better resistance to applied load in severe environments. The unique properties of CNTs enable them to be a multifunctional material. Low doses of CNTs (<1%) improve mechanical, electrical properties of concrete pavement considerably.

- improve the compressive and flexural strength of concrete significantly and improve concrete ductility. CNTs
- reduce the short-term and long-term shrinkage of fresh and solid concrete.
- are water reducers, offering lower permeability.
- can be used as a compatible sensor due to binding strongly with cement.
- can sense traffic flow and collect data as needed.

However, further research should be performed to confirm the results in different application. The optimum percentage of CNT is still varied. The procedure of dispersion of CNT has not been developed fully. The mechanical tests manual needs to be approved by civil and mechanical engineering associations with the proper scale for CNT composites.

REFERENCES

- Malay Mayank Patel, Caroline M. Clevenger, Moatassem Abdallah, Carbon nano-tube as water reducer in CDOT Class E 12 hr concrete mix, Case Studies in Construction Materials, Volume 9, 2018, e00207, ISSN 2214-5095, https://doi.org/10.1016/j.cscm.2018.e00207.
- https://www.bccresearch.com/market-research/nanotechnology/carbon-nantubes-global-markets-technologies-report.html
- Mukhopadhyay, Anal K, Kasthurirangan Gopalakrishnan, Bjorn Birgisson, Peter Taylor, and Nii O Attoh-Okine. "Next-Generation Nano-based Concrete Construction Products: A Review." Nanotechnology in Civil Infrastructure: A Paradigm Shift. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011. 207-23. Web.
- Yu, X., & Kwon, E. (2012). Carbon Nanotube Based Self-Sensing Concrete for Pavement Structural Health Monitoring. Final Report, Department of Civil Engineering, University of Minnesota, Duluth.
- Torabian Isfahani, F., Li, W., & Redaelli, E. (2016). Dispersion of multi-walled carbon nanotubes and its effects on the properties of cement composites
- Nadiv, R., Shtein, M., Refaeli, M., Peled, A., & Regev, O. (2016). The critical role of nanotube shape in cement composites
- S. Xie, W. Li, Z. Pan, B. Chang, L. Sun, (2000) Mechanical and physical properties on carbon nanotube, J. Phys. Chem. Solids, 6, pp. 1153-1158
- Stynoski, P. Mondal, C. Marsh (2015) Effects of silica additives on fracture properties of carbon nanotube and carbon fiber reinforced Portland cement mortar, Cem. Concr. Compos, 55, pp. 232-240
- M.S. Konsta-Gdoutos, Z.S. Metaxa, S.P. Shah, (2010) Highly dispersed carbon nanotube reinforced cement-based materials, Cem. Concr. Res., 40 , pp. 1052-1059
- M.S. Konsta-Gdoutos, Z.S. Metaxa, S.P.Shah (2010), Highly dispersed carbon nanotube reinforced cement based materials, Cem. Concr. Res., 40 , pp. 1052-1059
- Y. Li, P.M. Wang, X. Zhao (2005), Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes, Carbon, 43, pp. 1239-1245
- S. Musso, et al. (2009) Influence of carbon nanotubes structure on the mechanical behavior of cement composites, Compos. Sci. Technol., 69 (11), pp. 1985-1990
- J. Rausch, R.C. Zhuang, E. Mäder, (2010) Surfactant assisted dispersion of functionalized multi-walled carbon nanotubes in aqueous media, Compos Part A, 41, pp. 1038-1046
- C. Li, H. Zhu, M. Wu, M. Yan, (2013) Effect of dispersity of multi-walled carbon nanotubes on compression strength of cement, Fourth International Conference on Digital Manufacturing & Automation
- J. Bharj, S. Singh, S. Chander, R. Singh, Experimental study on compressive strength of cement-CNT composite paste, Indian J. Pure Ap Phy, 52 (2014), pp. 35-38
- B. Wang, Y. Han, S. LiuEffect of highly dispersed carbon nanotubes on the flexural toughness of cement-based composites, Constr. Build. Mater, 46 (2013), pp. 8-12
- L. Jiang, L. Gao, J. Sun, Production of aqueous colloidal dispersions of carbon nanotubes, J. Colloid Interface Sci., 260 (2003), pp. 89-94
- Yin, X., Li, S., He, G., Feng, Y., & Wen, J. (2018). Preparation and characterization of CNTs/UHMWPE nanocomposites via a novel mixer under synergy of ultrasonic wave and extensional deformation
- Baig, Z., Mamat, O., Mustapha, M., Mumtaz, A., Munir, K. S., & Sarfraz, M. (2018). Investigation of tip sonication effects on structural quality of graphene nanoplatelets (GNPs) for superior solvent dispersion.
- Siddique, R., & Mehta, A. (2014). Effect of carbon nanotubes on properties of cement mortars. Construction and Building Materials, 50, 116-129.
- Nojoomizadeh, M., & Karimipour, A. (2016). The effects of porosity and permeability on fluid flow and heat transfer of multi walled carbon nanotubes suspended in oil (MWCNT/Oil nano-fluid) in a microchannel filled with a porous medium
- Yoo, D., You, I., & Lee, S. (2018). Electrical and piezoresistive sensing capacities of cement paste with multi-walled carbon nanotubes
- Jazaei, R. (2018). Preliminary investigation of tensile strength and impact characterization of cementitious composite incorporating carbon nanotubes (Order No. 10838959). Available from Dissertations & Theses @ University of Nevada Las Vegas; ProQuest Dissertations & Theses Global. (2124052875). Retrieved from

http://ezproxy.library.unlv.edu/login?url=https://search.proquest.com/docview/2124052875?accountid=3611

- Eftekhari, M., & Mohammadi, S. (2016). Molecular dynamics simulation of the nonlinear behavior of the CNT-reinforced calcium silicate hydrate (C–S–H) composite. Composites Part A: Applied Science and Manufacturing, 82, 78-87.
- Eatemadi, A., Daraee, H., Karimkhanloo, H. et al. Nanoscale Res Lett (2014) 9: 393. https://doi.org/10.1186/1556-276X-9-39
- R. Jazaei; M. Karakouzian; B. O'Toole; J. Moon; S. Gharehdaghi, "Energy Absorption of Cementitious Composite Incorporating Carbon Nano-tubes (CNTs) Under Low-Velocity Impact Test", Submitted to ASCE 8thForensic Engineering Congress, Austin, Texas, USA, November 29–December 2, 2018, pp. 717 – 725, https://doi.org/10.1061/9780784482018.069.
- G. Y. Li, P. M. Wang, and X. Zhao, "Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes," Carbon, vol. 43, pp.1239-1245, 2005.
- R. Jazaei; M. Karakouzian; B. O'Toole; J. Moon; S. Gharehdaghi, "Failure Mechanism of Cementitious Nanocomposites Reinforced by Multi-Walled and Single-Walled Carbon Nanotubes Under Splitting Tensile Test". ASME. ASME International Mechanical Engineering Congress and Exposition, Volume 9: Mechanics of Solids, Structures, and Fluids http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=2722328 (): V009T12A012. doi:10.1115/IMECE2018-88512.
- Ali Al-Dahawi, et al. Electrical percolation threshold of cementitious composites possessing self-sensing functionality incorporating different carbon-based materials, Smart Mater. Struct. 25.10 (2016) 105005.
- https://wisconsindot.gov/Pages/about-wisdot/research/rigid-pave.aspx
- Yin, X., Li, S., He, G., Feng, Y., & Wen, J. (2018). Preparation and characterization of CNTs/UHMWPE nanocomposites via a novel mixer under synergy of ultrasonic wave and extensional deformationhttps://doi-org.ezproxy.library.unlv.edu/10.1016/j.ultsonch.2017.12.039
- Baoguo Han, Xun Yu1, and Eil Kwon, 2009. A self-sensing carbon nanotube/cement composite for traffic monitoring. Nanotechnology, 2009, Vol.20(44), p.445501 (5pp), https://doi.org/10.1088/0957-4484/20/44/44550.
- R. Jazaei; M. Karakouzian; B. O'Toole; J. Moon; S. Gharehdaghi, "Effect of Dispersion and Quality Control of Multi-Walled Carbon Nanotubes on Cementitious Nanocomposite Subjected to Impact Load", International Road Federation (IRF) Conference, Las Vegas November 7-9, 2018.
- Kim, H. K., Park, I. S., & Lee, H. K. (2014). Chloride penetration monitoring and stability of CNT/cement mortar composites with low water–binder ratio. Composite Structures, 116, 713-719.
- Kim, G. M., Naeem, F., Kim, H. K., & Lee, H. K. (2016). Heating and heat-dependent mechanical characteristics of CNT-embedded cementitious composites. Composite Structures, 136, 162-170.
- Kim, H. (2015). Chloride penetration monitoring in reinforced concrete structure using carbon nanotube/cement composite. Construction and Building Materials, 96, 29-36.
- Kim, H. K., Nam, I. W., & Lee, H. K. (2014). Enhanced effect of carbon nanotube on mechanical and electrical properties of cement composites by incorporation of silica fume. Composite Structures, 107, 60-69.