**Wireless Carbon Nanofiber Aggregate Sensor System for Real-Time Water Level Monitoring and Flood Warning**

1. **Introduction**

Today, concrete is the second most used building material across the globe. It is a mixture of cement gel matrix with granular coarse-fine aggregates and water with the necessary amount of additive and mineral materials in the proper ratio. The researchers in this field of study have been working to improve the technical functions and performance of concrete by using a different proportion of its ingredients and different types of additives. Hydrated cement as a major constituent of concrete in itself is a brittle material, and the tensile strength is typically only one-tenth of its compressive strength. To compensate for this weakness, a reinforcement of rebars and fibers are added to concrete.

Increasing the strength of concrete has been one of the key fields of investigation. On the other hand, enhancing the sensing ability of concrete is another vast field of concrete research. The sensing ability of concrete that responds its environment and the changes in strain, temperature, moisture, pH, and electric or magnetic fields is an area of interest for a big fraction of scientists and researchers in the concrete study. These sensing abilities make the concrete smart enough to be used to monitor its health regarding stress-strain, temperature, pH, moisture, electrical/magnetic responses. The concrete can even obtain an awareness of damage on itself and its surroundings. This property is utilized in Structural Health Monitoring (SHM). The technology of structural health monitoring helps in providing the capability of non-destructive flaw detection allowing concrete to be repaired before it is too late. This evaluation of safety and the durability of a structure is essential during its lifetime.

The field of fiber reinforced concrete research has been much enthusiasm for the development of the self-sensing structural system with major implementation as a structural sensor. Short electrically conducting fiber pull-out that aids the slight and reversible crack opening which enables the short fiber composites to behave as a strain sensor. Mortar or concrete reinforced with well-dispersed fibers of a diameter smaller than crack width and conductance higher than that of the matrix have strain sensing ability independent of their orientation and contact with one another The electrical conductivity of the added fibers enables the magnitude of direct current in the composite to change in response to strain variation, allowing sensing.

1. **Goal and Objectives**

The objectives of this research can be shortened as follows:

1. Develop CNFAs and investigate its’ behavior in DC vs AC Circuit
2. To optimize the CNFs content and AC frequency for CNFAs implementation
3. Investigate the waterproofing of CNFAs and implement them for real-time water level monitoring.
4. **Materials and Methods**

The material properties used in the mix are as follows:

1. Fine Aggregate: Quikrete ® premium play sand
2. Cement: Martin Marietta’s ASTM Type III Portland cement
3. Carbon Nanofibers: PR-19-XT-LHT-OX by Pyrograf ®-III Product Inc.
4. High Range Water Reducer (HRWR): Master-Glenium 3400
5. Silica Fume: Master-Life SF 100
6. Waterproofing Admixture: Krystol internal membrane (KIM)
7. Steel wire mesh
8. Wire: Commercial 24 gauge stranded speaker wire
9. External waterproofing agents: MasterSeal 581 (MS-581), MasterSeal 500 (MS-500), Xypex Concentrate and quick setting professional epoxy.

**Methods**

1. Scanning and analysing 4-probe and 2-probe mesh structure with DC circuit using Keithley Source-meter.
2. Scanning and analysing 2-probe mesh structure and waterproofing with AC circuit using Keysight E4980AL Precision LCR Meter and CHI660E Electrochemical Workstation.
3. Uniaxial compression using INSTRON 5960 Series Universal Testing Systems up to 50 kN to detect maximum response to optimize frequency and CNFs concentrations.
4. **Results**
5. Stable response in 2-probe AC circuit over either of 4-probe or 2-probe DC circuit.
6. Frequency optimized in a range of 100Khz to 200Khz for CNFA.
7. CNFA sample with 0.8% concentration of CNFs by the weight of cement produced higher response at peak load.
8. Kim Krystol is inefficent in waterproof, so are MasterSeal 581 (MS-581), MasterSeal 500 (MS-500), Xypex Concentrate. However, quick setting epoxy was useful in waterproof CNFA.
9. **Summary and Conclusions**

A carbon nanofiber aggregate (CNFA) with two and four meshes was developed. The development of CNFAs with CNFAs’ response in DC and AC circuits were investigated. The study was further extended with the optimization of AC frequency and carbon nanofiber (CNF) content of CNFAs for practical implementation. The optimized CNFAs were then tested to develop waterproof CNFAs with the external coating for real-time water level monitoring.

CNFA with 2-probe in AC circuit has more stable response in the frequency range of 100Khz to 200Khz in the both case of loading the sample with stress and without any stress. CNFA with 0.8% CNFs concentration produced maximum response among tested samples with different concentrations at its peak load. The electrical impedance variation (EZV) ranged from 24% to 30% in a frequency band between 500Hz and 300Khz. The scanning of optimized, externally epoxy coated, CNFA sample showed only 12% drop in response, whereas, other agents used for externally coating were inefficient as the drop in response was around 90%.

1. **List of publications, posters and presentations**

* Carbon Nanofiber Aggregate Sensors for Sustaining Resilience of Civil Infrastructures to Multi-Hazards

**7. List of students, postdocs and other research personnel involved in project**

* Avinash Gautam (Student)
* Bhagirath Joshi (Student)
* Jinghong Chen (Advisor, University of Houston)
* Yuhua Chen (Advisor, University of Houston)
* Y.L. Mo (Advisor, University of Houston)
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**8. Proposals submitted**

**9. Proposals awarded**

**10. References cited**

ACI Committee 318. (2011). Building Code Requirements for Structural Concrete. American Concrete Institute, Farmington Hills, Michigan.

Avinash G, Mo YL, Yuhua C, Jinghong C, Bhagirath J (2019). “Carbon Nanofiber Aggregate Sensors for Sustaining Resilience of Civil Infrastructures to Multi-Hazards”. Adv Civil Eng Tech .3(1).

Baughman, R. H., Cui, C. X., Zakhidov, A. A., Iqbal, Z., Barisci, J. N., Spinks, G. M., G, W. G., Mazzoldi, A., de Rossi, D., Rinzler, A. G., Jaschinski, O., Roth, S., and Kertesz, M. (1999). “Carbon Nanotube Actuators.” Science, 284, 1340–1344.

Baughman, R. H., Zakhidov, A. A., and de Heer, W. A. (2002). “Carbon nanotubes—the route toward applications.” Science, 297, 787–92.

Bontea, D.M., Chung, D. D. L., and Lee, G. C. (2000). “Damage in carbon fiber reinforced concrete, monitored by electrical resistance measurement.” Cement and Concrete Research, 30(4), 651–659.

Cao J, Chung DDL (2004) “Electric polarization and depolarization in cement-based materials, studied by apparent electrical resistance measurement.” Cem Concr Res 2004;34(3):481–5.

Chang, C., Ho, M., Song, G., Mo, Y.-L., and Li, H. (2009). “A feasibility study of self-heating concrete utilizing carbon nanofiber heating elements.” Smart Materials and Structures, 18(12), 127001.

Chen, B., Wu, K., and Yao, W. (2004). “Conductivity of carbon fiber reinforced cement based composites.” Cement and Concrete Composites, 26(4), 291–297.

Chen, P.-W., and Chung, D. D. L. (1993a). “Concrete reinforced with up to 0.2 vol% of short carbon fibres.” Composites, 24(1), 33–52.

Chen, P.-W., and Chung, D. D. L. (1993b). “Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection.” Smart Materials and Structures, 2(1), 22–30.

Chen, P.-W., and Chung, D. D. L. (1996). “Concrete as a new strain/stress sensor.” Composites Part B: Engineering, 27(1), 11–23.

Chen, P.-W., Fu, X., and Chung, D. D. L. (1997). “Microstructural and mechanical effects of latex, methylcellulose, and silica fume on carbon fiber reinforced cement.” ACI Materials Journal, 94(2), 147–155.

Chung, D. D. L. (1995). “Strain sensors based on the electrical resistance change accompanying the reversible pull-out of conducting short fibers in a less conducting matrix.” Smart Materials and Structures, 4, 59–61.

Chung, D. D. L. (1998). “Composite material strain/stress sensor.” US Patent 5,817,944, United States of America.

Chung, D. D. L. (2000). “Cement reinforced with short carbon fibers: a multifunctional material.” Composites Part B: Engineering, 31, 511–526.

Chung, D. D. L. (2004). “Self-heating structural materials.” Smart Materials and Structures, 13(3), 562–565.

Chung, D. D. L. (2005). “Dispersion of short fibers in cement.” Journal of Materials in Civil Engineering, 17(4), 379–3831

Dotelli G, Mari CM (2001) “The evolution of cement pastes hydration process by impedance spectroscopy”. Mater Sci Eng A 2001; 303:54–9

Dume, B. (2007). “Nanofibres under control.” nanotechweb.org, <http://nanotechweb.org/cws/article/tech/32055> (Oct. 8, 2012).

F. Reza, Jerry A. Yamamuro, Gordon B. Batson, (2004) “Electrical resistance change in compact tension specimens of carbon fiber cement composites.” Cement & Concrete Composites 26 (2004) 873–881

Gao, D., Sturm, M., and Mo, Y. L. (2009). “Electrical resistance of carbon-nanofiber concrete.” Smart Materials and Structures, 18(9).

Han, B., Zhang, L., and Ou, J. (2010). “Influence of water content on conductivity and piezoresistivity of cement-based material with both carbon fiber and carbon black.” Journal of Wuhan University of Technology-Mater. Sci. Ed., 25(1), 147–151.

Hilding, J., Grulke, E. a., George Zhang, Z., and Lockwood, F. (2003). “Dispersion of Carbon Nanotubes in Liquids.” Journal of Dispersion Science and Technology, 24(1), 1–41.

Hong, Xinghua and D.D.L.Chung (2017),” Carbon nanofiber mats for electromagnetic interference shielding”, Carbon, Volume 111, January 2017, Pages 529-537

Howser, R. N., Dhonde, H. B., and Mo, Y. L. (2011). “Self-sensing of carbon nanofiber concrete columns subjected to reversed cyclic loading.” Smart Materials and Structures, 20(8), 085031.

Howser, R. N., and Mo, Y. L. (2013). “Development of Carbon Nanofiber Aggregate.” Structures Congress 2013, American Society of Civil Engineers, Pittsburgh, Pennsylvania, 12.

Iijima, S. (1991). “Helical microtubules of graphitic carbon.” nature, 354(November 1991), 11–14.

Konsta-Gdoutos, M., Metaxa, Z., and Shah, S. (2010a). “Multiscale Fracture Characteristics of Cement Based Materials Reinforced with Carbon Nanofibers.” ECF18, Dresden 2010, 1–8.

Konsta-Gdoutos, M. S., Metaxa, Z. S., and Shah, S. P. (2010b). “Highly dispersed carbon nanotube reinforced cement based materials.” Cement and Concrete Research, Elsevier Ltd, 40(7), 1052–1059.

Konsta-Gdoutos, M. S.; Metaxa, Z. S.; and Shah, S. P., (2008) “Nanoimaging of Highly Dispersed Carbon Nanotube Reinforced Cement-Based Materials”, Proceedings of Seventh International RILEM Symposium on Fiber Reinforced Concrete: Design and Applications, R. Gettu, ed., RILEM Publications S.A.R.L., 2008, pp. 125-131.

Li, G. Y., Wang, P. M., and Zhao, X. (2005). “Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes.” Carbon, 43(6), 1239–1245.

Li, G. Y., Wang, P. M., and Zhao, X. (2007). “Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites.” Cement and Concrete Composites, 29(5), 377–382.

Li, H., Xiao, H., Yuan, J., and Ou, J. (2004). “Microstructure of cement mortar with nano-particles.” Composites Part B: Engineering, 35(2), 185–189.

Li, H., Zhang, M., and Ou, J. (2007). “Flexural fatigue performance of concrete containing nano-particles for pavement.” International Journal of Fatigue, 29(7), 1292–1301.

Li, V. C. (2002). “Large volume, high performance applications of fibers in civil engineering.” Journal of Applied Polymer Science, 83, 660–686.

Liao, W. C., Chao, S. H., Park, S.-Y., and Naaman, A. E. (2006). Self-Consolidating High Performance Fiber Reinforced Concrete: SCHPFRC. High Performance Fiber, 76.

Makar, J., and Beaudoin, J. (2004). “Carbon nanotubes and their application in the construction industry.” 1st International Symposium on Nanotechnology in Construction, National Research Council Canada, Paisley, Scotland, 331–341.

Makar, J., Margeson, J., and Luh, J. (2005). “Carbon nanotube/cement composites–early results and potential applications.” 3rd International Conference on Construction Materials: Performance, Innovations and Structural Implications, National Research Council Canada, Vancouver, British Columbia, Canada, 1–10.

Mondal, P., Shah, S. P., and Marks, L. (2007). “A reliable technique to determine the local mechanical properties at the nanoscale for cementitious materials.” Cement and Concrete Research, 37(10), 1440–1444.

Naaman, A. E. (1985). “Fiber Reinforcement for Concrete.” Concrete International, 7(3), 21–25.

Roco, M. (2007). “National nanotechnology initiative-past, present, future.” Handbook on Nanoscience, Engineering and Technology, CRC Press, Boco Raton, 3.1–3.26.

Salvetat, J.-P., Bonard, J.-M., Thomson, N. H., Kulik, A. J., Forró, L., Benoit, W., and Zuppiroli, L. (1999). “Mechanical properties of carbon nanotubes.” Applied Physics A: Materials Science & Processing, 69(3), 255–260.

Sanchez, F., and Sobolev, K. (2010). “Nanotechnology in concrete – A review.” Construction and Building Materials, Elsevier Ltd, 24(11), 2060–2071.

Shah, S. P., and Naaman, A. E. (1976). “Mechanical Properties of Glass and Steel Fiber Reinforced Mortar.” ACI Journal Proceedings, 73(1), 50–53.

Tzeng, Y., Huang, T., Chen, Y., Liu, C., and Liu, Y. (2004). “Hydration properties of carbon nanotubes and their effects on electrical and biosensor applications.” New Diamond and Frontier Carbon Technology, 14(3), 193–201.

Wen, S., Chung DDL “The role of electronic and ionic conduction in the electrical conductivity of carbon fiber reinforced cement.” Carbon 2006; 44:2130-8

Wen, S., Chung DDL (2001) “Electric polarization in carbon fiber reinforced cement.” Cem Concr Res 2001; 31(2):141–7

Yang, X., and Chung, D. D. L. (1992). “Latex-modified cement mortar reinforced by short carbon fibres.” Composites, 23(6), 453–460.