

SELF-SENSING EVALUATION USING MULTI-FUNCTIONAL COMPOSITES FOR HEALTH MONITORING OF CRITICAL INFRASTRUCTURES

Khandaker Hossain¹, Mohammad Hossain², Tanvir Qureshi³

¹ Professor, Dept. of Civil Eng., Toronto Metropolitan University, Toronto, Canada,
(ahossain@torontomu.ca)

² Post-doctoral Researcher, Dept. of Civil Eng., Toronto Metropolitan University, Toronto, Canada
(mohammadali.hossain@ryerson.ca)

³ Senior scientist (R&D Civil Eng.), Canadian Nuclear Laboratories Limited, Chalk River, ON, Canada
(tanvir.qureshi@cnl.ca)

ABSTRACT

This paper presents self-sensing capability of specimens made of multi-walled carbon nanotube (MWCNT) incorporated multi-functional composites (MFCs) (such as engineered cementitious composite ‘ECC’ and alkali-activated engineered composite ‘AAEC’) simultaneously instrumented with traditional strain gauges subjected to static monotonic loading to failure. Self-sensing behaviour of the composite was investigated during loading comparing the two-probe electrical conductivity/resistivity (ER) change with time and strain development measured by strain gauges. Test results show that the MWCNT incorporated MFCs can detect/sense events (such as crack initiation, progressive cracking, failure etc.) in specimens at the time of occurrence by indicating changes in ER or capacitance. These events also synchronized very well with the change in strain readings recorded at critical locations through strain gauges validating the sensing ability of structures made of MWCNT incorporated MFCs. The self-sensing ability is expected to detect intrinsic changes or damages during service life of structures and hence, leading to effective monitoring and maintenance. This study confirms the viability of using MWCNT-incorporated MFCs as self-sensing material for construction and health monitoring of critical infrastructure such as those related to nuclear reactors.

INTRODUCTION

A critical aspect of the civil structures such as nuclear power plants (NPPs) is ensuring and improving their safety and serviceability by controlling and monitoring structural loads, vibration, and health. One of the best alternatives to address this issue is incorporating intrinsic self-sensing multifunctional composites (MFCs) to construct such critical structures (Han et al. 2015a). Self-sensing is the ability of structural materials to sense changes in strain, stress, damage, and temperature. Such self-sensing concrete composites can be fabricated by incorporating well dispersed functional fillers, such, carbon nanotube (CNT), carbon black, graphene nanomaterials etc creating an electrically conductive medium. This medium changes its electrical properties (such as conductivity) due to the deformation or stress development under external forces or environmental actions, which can be sensed and identified for health monitoring (Zhu & Chung, 2007).

The application of smart concrete with self-sensing ability in the structural health monitoring (SHM) system has been developed over the last decades. The self-sensing ability of was achieved by a change in the conductive network of the conductive material inside the concrete (Al-Dahawi et al., 2017; Yıldırım et al., 2020). Research has focused on exploring the self-sensing potential of conventional OPC-containing conductive fillers, such as short carbon fibres (Chen et al. 2004). Additionally, carbon nanotubes (CNTs)

have been employed as conductive fillers to enhance the electrical conductivity of ordinary Portland cement (OPC) for self-sensing purposes (Gao et al., 2009; Yoo et al. 2018). Previous works measured geopolymers' electrical conductivity, considering different alkaline-to-fly ash ratios (L/A), showing values of approximately 10^{-3} S m^{-1} and $5 \times 10^{-4} \text{ S m}^{-1}$ for L/A ratios of 0.4 and 0.7, respectively. Smart multifunctional concrete composites including engineered cementitious composites (ECCs) or geopolymer/alkali-activated engineered composite (AAECs) were developed by adding carbon nanotube and other functional fillers, graphene (Siad et al. 2018; Lee et al., 2020; Hossain and Hossain 2025).

This paper presents an investigation on the self-sensing properties of zero-cement based low-carbon AAECs and ECCs incorporating polyvinyl alcohol fibre having strain hardening and micro-cracking characteristics. The piezoresistive behaviour (to assess self-sensing ability) of the multifunctional AAEC/ECCs was examined by monitoring the electrical resistivity development during compression testing of cube specimens as well as simultaneous monitoring of electrical resistivity and strain development under compressive loading of cube specimens.

EXPERIMENTAL PROGRAM

Self-sensing performance of AAEC/ECC was assessed by measuring electrical conductivity/resistance of cube/prism samples/specimens without loading and monitoring piezoresistive response in terms of electrical conductivity under flexural loading (relating various events such as crack initiation and propagation) of cube specimens as well as simultaneous measurement of conductivity and axial strains at strategic locations during axial compression loading to failure.

AAEC mixes were formulated by incorporating Polyvinyl alcohol (PVA) fibres, powder-based alkali activators, silica sand, and multiwall carbon nanotubes (MWCNT) as self-sensing agents along with binary combination of source materials including Ground Granulated Blast Furnace Slag (GGBFS) and class C Fly Ash (FA-C) (Hossain and Hossain 2025). ECC mixes were formulated by incorporating PVA fibres, MWCNT along with Portland cement, FA-C and silica sand (Hossain and Hossain 2025).

Test methods and testing procedures for self-healing assessments of AAEC/ECC

Self-sensing performance of ECCs/AAECs with and without MWCNT was assessed by using three methods. Method 1: used measurement of electrical conductivity/resistance by passing a direct current through the dry cube samples/specimens without applying load. Method 2: determined piezoresistive response in terms of measuring electric conductivity, cracking and cracking propagation during loading history to failure of cube specimens subjected to compression. Method 3: is similar to Method 2 by measuring piezoresistive response involving the measurement of conductivity and axial strains at strategic locations (using electrical strain gauges) simultaneously during axial compression test to failure of cube specimens.

Fig. 1(a) shows a cube (50 mm x 50 mm) specimen with embedded copper probes installed at the two ends for electrical resistance measurement. A constant direct 5-volt current (DC) electrical field was applied for electrical resistance/conductivity measurement during testing. Ammeter/Multimeter was used to record conductivity data for cube specimens with and without loading condition. Fig. 1(b) shows the test set-up of cube samples (installed with copper electrodes at the two opposite faces) in Method 2 to measure resistivity during compression loading to failure using data acquisition system to get piezoresistive effect for self-sensing property assessment. The same test set-up was used simultaneously to measure the resistivity and axial strains (from installed copper probes and strain gauges) of cube specimens subjected to axial loading to failure in Method 3. Simultaneous recording of resistivity and strain data with time was synchronized in the same time domain using data acquisition system.

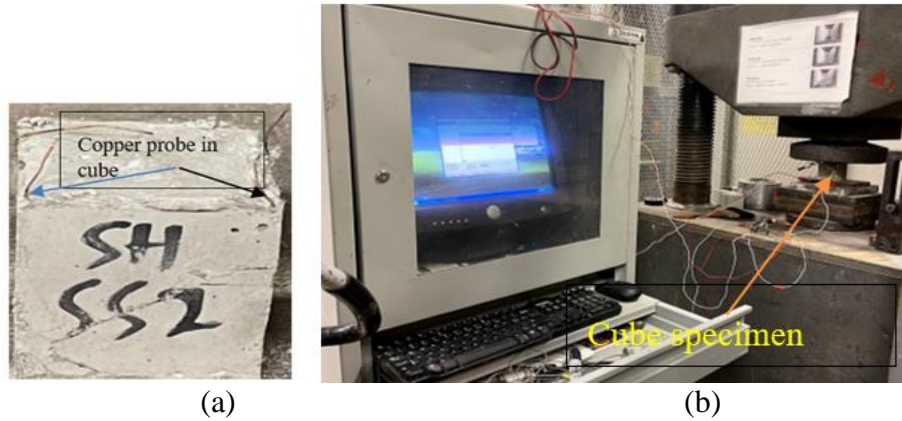


Figure 1. (a) Cube specimen with copper probes and (b) Test set-up for conductivity test on cube specimen, and simultaneous measurements of conductivity and strain under compression loading

RESULTS AND DISCUSSION

The self-sensing behaviour of AAEC cube specimens without and with loading conditions were used through measuring electrical resistivity (Method 1) or evolution of electrical resistivity with time (Method 2) or simultaneous evolution of electrical resistivity and strains in Method 3. This is to investigate the impact of events/conditions in the specimens during loading captured by tandem at a particular time in order to assess the self-sensing performance. Sensitivity, an essential factor in evaluating the sensing property of the AAECs, can be characterized by parameters such as change in electrical conductivity/resistivity. The sensing capability is related to materials electrical conductivity as any change (such as crack initiation, progressive cracking, reinforcement yielding, fibre-crack bridging and failure) within the matrix or specimen expected to change the conductivity. Such conductivity change can be considered as a sensing capability of the material and only the conductive or semi-conductive materials can effectively signal this change.

Electrical conductivity values of MWCNT incorporated AAEC and ECC mixes

The electrical conductivity values of MWCNT incorporated AAEC and ECC mixes derived from dry cube specimens without loading (Method 1) are summarized in Table 1. Samples from AAEC/ECC mixes without MWCNT did not show electrical conductivity in dry conditions. MWCNT addition introduced electrical conductivity and a piezoresistive behaviour into the AAEC/ECCs.

Table 1: 28-day electrical conductivity of AAEC mixes of cubes and prisms without loading

AAECs Mix ID	Electrical conductivity (τ) ($\times 10^{-3}$ S/m)*
AAEC/ECC	0
AAEC-MWCNT	18.72
ECC-MWCNT	18.93

* Average value of two cube specimens considered– deviation from the mean is 1 to 2%

It can be noted that the AAEC/ECC with 0%MWCNT exhibited a non-conductive medium showing very low/zero conductivity. The conductivity values of $18.72 \times 10^{-3}\text{S/m}$ and $18.93 \times 10^{-3}\text{S/m}$ were observed for AAEC and ECC with 0.3% MAWCNT additions, respectively (Table 1). MWCNT-AAECs showed close conductivity value compared to its MWCNT-ECC counterpart suggesting their potential as self-sensing material. Previous research studies also showed MWCNT addition induced electrical conductivity in concrete composites as well dispersed MWCNTs bridge hollow spaces and micro-cracks and improved matrix connectivity (Jittabut & Horpibulsuk, 2019).

Self-sensing capability through measurement of Piezoresistive and strain characteristics under loading

Figures 2(a-b) show the variation of %change in electrical conductivity ($\Delta\rho/\rho\%$) with progressive compressive stress in cube specimens during loading as an indicator of self-sensing performance of MWCNT-AAEC/ECC. The variation of $\Delta\rho/\rho\%$ shows similar distinctive pattern with progressive compressive stress characterized by state of balance (no change), decrease and increase during loading history. These states corresponded to specific stages or events: the $\Delta\rho/\rho\%$ decrease was associated with crack formation representing reduction of conductivity, followed by an increase due to pressure compaction which brought MWCNT closer in the matrix enhancing network connectivity leading to higher conductivity (Yoo et al., 2018) and a balance state with no change in conductivity. This cycle of decrease-balance-increase in $\Delta\rho/\rho\%$ continued during the loading history till the sample failed.

The initial stage of showing gradual increase in $\Delta\rho/\rho\%$ was generally associated with pressure compaction leading to improvement in MWCNT connectivity, as discussed earlier. The sudden rise and drop in $\Delta\rho/\rho\%$ was associated with how quickly the MWCNT connectivity restored and decreased, respectively, which might also depend on the rate of loading. The initiation of fresh cracks led to the disruption and subsequent reconstruction of the conductivity network. Finally, the propagation of cracks resulted in the breakdown of the conductivity network and produced drop in electrical conductivity. This phenomenon has been observed in various experimental studies on self-sensing concrete with different fillers under monotonic uniaxial compression, although the relationship curves between electrical resistivity and compressive loading (or stress and strain) might exhibit some variations (Hanjitsuwan 2011).

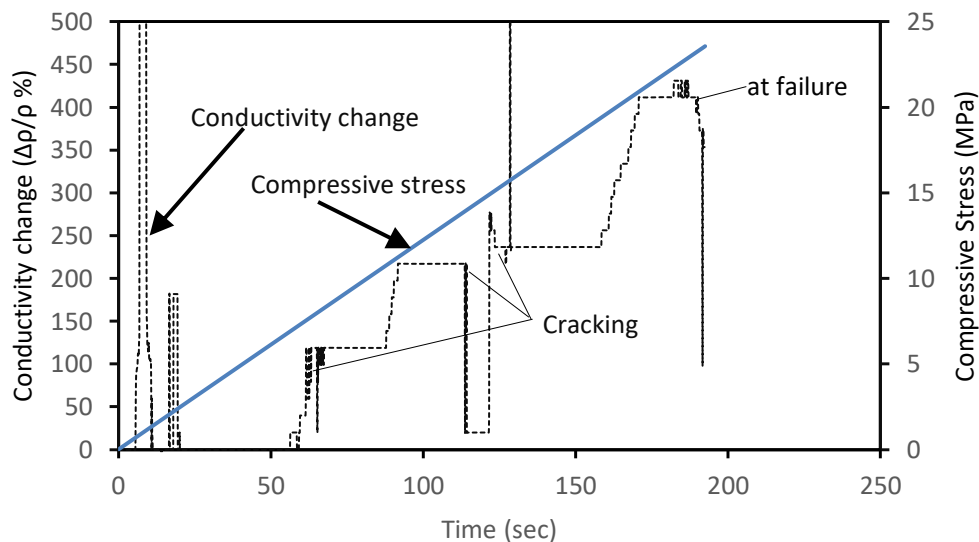


Figure 2(a). The conductivity change ($\Delta\rho/\rho\%$) with compressive stress during loading of MWCNT-AAEC cube specimen

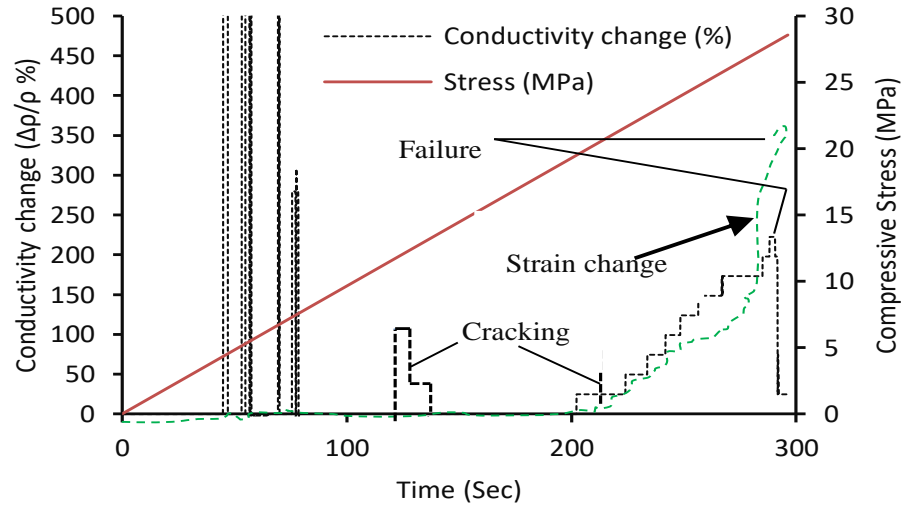


Figure 2(b). Typical conductivity change ($\Delta\rho/\rho$ %) and axial strain change with compressive stress during loading of MWCNT-ECC cube specimen

Therefore, conductivity evolution was able to detect or self-sense the changes in the specimens during loading differentiating the behaviour (for example, indication of cracking load through conductivity evolution) of each of the mixes to some extent.

Figure 2(b) also explains the typical piezoresistive effect (electrical conductivity change, $\Delta\rho/\rho$) observed in response to flexural stress, displaying compressive strain change (%) of cube specimen made of MWCNT-ECC. As the load on specimen increased, the compressive strains gradually increased. Notably, the electrical conductivity exhibited sudden fluctuations (drop) when crack formed, coinciding with an increase in strain change (%). At failure, large drop in conductivity change was associated to the large increase in strain change (%), signifying simultaneous failure detection capability through sensing apart from crack or damage detection during loading.

CONCLUSIONS

Based on the tests results the following conclusions are drawn:

- MWCNT incorporating enhanced the electrical conductivity of AAEC and ECC materials with both showing similar electrical conductivity.
- Electrical conductivity is related to matrix connectivity due to MWCNT incorporation in AAECs.
- MWCNT incorporated AAEC/ECCs exhibited promising self-sensing abilities by showing electrical conductivity changes at the onset of various events such as cracking, crack propagation and failure during compression loading of specimens.
- Research shows potential of MWCNT-AAEC/ECC s as smart self-sensing multi-functional composites. However, further research is needed to fine tune their self-sensing properties and explore their potential for application in various civil infrastructures especially for construction and health monitoring of critical infrastructures such as NPP and small modular reactors.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by NSERC, Canada. Supports provided by the technical staff of Concrete and Advanced Concrete Material laboratories of Toronto Metropolitan University are also acknowledged.

REFERENCES

- Al-Dahawi, A., Yıldırım, G., Öztürk, O., and Şahmaran, M. (2017). Assessment of Self-Sensing Capability of Engineered Cementitious Composites within the Elastic and Plastic Ranges of Cyclic Flexural Loading. *Construction Building Mater.* 145, 1–10. doi:10.1016/j.conbuildmat.2017.03.236
- Chen, B., Wu, K., & Yao, W. (2004). Conductivity of carbon fiber reinforced cement-based composites. *Cement and Concrete Composites*, 26(4), 291–297.
- Gao, D., Sturm, M., & Mo, Y. L. (2009). Electrical resistance of carbon-nanofiber concrete. *Smart Materials and Structures*, 18(9). <https://doi.org/10.1088/0964-1726/18/9/095039>
- Han, B., Ding, S., & Yu, X. (2015). Intrinsic self-sensing concrete and structures: A review. *Measurement*, 59, 110–128. <https://doi.org/10.1016/J.MEASUREMENT.2014.09.048>
- Hanjitsuwan, S., Chindaprasirt, P., & Pimraksa, K. (2011). *Electrical conductivity and dielectric property of fly ash geopolymer pastes. International Journal of Minerals, Metallurgy, and Materials*, 18(1), 94–99.
- Hossain, M.A, and Hossain K.M.A. (2025), Physical, Compressive Strength, and Microstructural Characteristics of Alkali-Activated Engineered Composites Incorporating MgO, MWCNTs, and rGO, *Appl. Sci.* 2025, 15(4), 1712; <https://doi.org/10.3390/app15041712>
- Jittabut, P., & Horpibulsuk, S. (2019). Physical and Microstructure Properties of Geopolymer Nanocomposite Reinforced with Carbon Nanotubes. *Materials Today: Proceedings*, 17, 1682–1692. www.sciencedirect.com/www.materialstoday.com/proceedings2214-7853
- Lee, H., Yu, W., Loh, K. J., and Chung, W. (2020). Self-heating and Electrical Performance of Carbon Nanotube-Enhanced Cement Composites. *Construction Building Mater.* 250, 118838. doi:10.1016/j.conbuildmat.2020.118838
- Siad, H., Lachemi, M., Sahmaran, M., Mesbah, H. A., & Hossain, K. A. (2018). Advanced engineered cementitious composites with combined self-sensing and self-healing functionalities. *Construction and Building Materials*, 176, 313–322. <https://doi.org/10.1016/j.conbuildmat.2018.05.026>
- Yıldırım, G., Öztürk, O., Al-Dahawi, A., Afşın Ulu, A., and Şahmaran, M. (2020). Self-sensing Capability of Engineered Cementitious Composites: Effects of Aging and Loading Conditions. *Construction Building Mater.* 231, 117132. doi:10.1016/j.conbuildmat.2019.117132
- Yoo, D. Y., You, I., & Lee, S. J. (2018). Electrical and piezoresistive sensing capacities of cement paste with multi-walled carbon nanotubes. *Archives of Civil and Mechanical Engineering*, 18(2), 371–384. <https://doi.org/10.1016/j.acme.2017.09.007>
- Zhu, S., & Chung, D. D. L. (2007). Numerical assessment of the methods of measurement of the electrical resistance in carbon fiber reinforced cement. *Smart Materials and Structures*, 16(4), 1164–1170. <https://doi.org/10.1088/0964-1726/16/4/026>