Self-Sensing Ability of High Performance Concrete by Using Carbon Fibre and Graphene Fillers

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ABSTRACT

Sensing concrete has the capability to sense its condition and environmental changes, including stress (or force), strain (or deformation), crack, damage, temperature, and humidity, by incorporating functional fillers. Self sensing behavior has been observed in high performance concrete with the addition of small amount of fillers (0.05% and 0.1% by volume of cement) of Graphene and 6mm short length (1% and 1.25% by volume of cement) of Carbon fibers. It is seen that there is an increase/decrease in electrical resistance on loading up to crack propagation or fracture. On reaching the inelastic stage, the resistance change is not reversible. A method is developed which can be used in place of, often used strain gage technique or fiber optic technique for health monitoring of structures. There is change in resistance during filler pull out in the elastic range. The change in elastic resistance was measured by a two probe method and was seen to be reversible for elastic deformation. Also, the crack propagation and fiber breakage of the specimen can be identified by irreversible resistance change. The Load vs. Resistivity graphs plotted for monitoring of health of structure. This phenomenon can be used to find the real time weight of vehicles in traffic and finding stress values of a loaded structure including bridges etc.

Keywords: Self sensing, health monitoring, Carbon Fiber, Grapheme, Silica fumes, Metakeolin, Resistivity, stress.

INTRODUCTION

Concrete, the most commonly used structural material for the construction of infrastructure, from buildings to highways, dams, tunnels, bridges, high-rise towers, and sewage systems. Concrete is a durable, affordable, aesthetic, and readily available composite material. However, physical effects, including surface abrasion/erosion, cracking, aging, temperature variation and crystallization of salts in pores, and penetration of water and fire or frost actions, associated with deleterious chemical effects such as alkali-aggregate reaction, carbonation, sulfate attack, and corrosion of reinforcing steels, would cause the deterioration of concrete. The absence of advanced design and condition assessment tools and timely maintenance also plays a considerable role in the failure of concrete structures. Therefore, surveillance, evaluation, and assessment of the "health" of concrete structures at an early stage to alleviate deterioration or avoid sudden accidents are of great importance to the extension of the service life and the security of lives and property. The process of monitoring changes that occur within concrete structures and providing real-time information of structural conditions for safety assessment and afterward maintenance planning is known as structural health monitoring (SHM). To achieve this, an entire SHM system should include a sensory system; a data acquisition, transmission, and management system; and an evaluation system. Up to now, for the purpose of diagnostics and evaluation of structural conditions, a great number of sensing techniques have been developed and implemented with specific functions and mechanisms. For monitoring changes in structural health conditions, expensive, large, and heterogeneous sensors or transducers have to be installed externally or internally in large quantities in the structures. Hence, there is a constant drive for the development of advanced and high-level SHM sensing technologies.

With the rapid growth in modern science and engineering, it is unsurprising to imagine that if a concrete structure is so "smart/intelligent" or has its own sensing functionality, then it can assess the health conditions without the integration of any extrinsic sensing element. As an emerging sensing technology, sensing concrete with the capability to sense its condition and environmental changes has attracted significant interest and been envisioned to become the future of SHM.

Sensing concrete, also known as intrinsic self-sensing, self-monitoring, or self-diagnosing Concrete. It is fabricated through incorporating some functional fillers such as carbon fibers (CFs), carbon annotates (CNTs), Grapheme and nickel powder into conventional concrete. The functional fillers with intrinsic sensing properties usually are electrically conductive in nature. Well distributed functional fillers at a critical concentration will form an extensive conductive network inside the concrete composite, making the composite conductive. Changes in the composite caused by external forces or environmental actions disturb the conductive network, leading to changes in the composite's electrical properties (usually electrical resistance). With this principle, stress (or force), strain (or deformation), crack, damage, temperature, and humidity under static and dynamic conditions can be detected.

LITERATURE REVIEW

Limited research has been carried out in this field. Various authors have studied effect of Carbon fiber in concrete matrix for self sensing. Few have studied Grapheme as substitute material and strength of concrete and mechanical properties needs further investigations.

Significance of Work

Though the earlier authors studied carbon fiber and Grapheme concrete as a smart material, the relative performances of Metakeolin and Silica Fume in high performance concrete with variation in the % of filler materials were not studied in detail. Hence the present work aims at their relative performances.

Self-Sensing Concrete

Self-sensing or monitoring concrete refers to a structural material that can monitor its own condition and identify if there is any damage without any external intervention in the form of embedded, attached or remote sensors. The benefit of using such a material is twofold; firstly, structural performance is maintained or even enhanced and secondly, the sensing performance is superior to external sensors due to the intrinsic property, the higher sensitivity, natural compatibility and extended durability of the sensing component. It is also important to highlight that self-sensing materials are themselves structural materials hence they would not compromise the overall structural performance.

Functional Fillers (Carbon Fiber and Grapheme)

A conventional concrete matrix has no or poor sensing capability and it acts as an electrical insulator. Hence, conductive, functional fillers need to be incorporated in order to reduce the electrical resistance of the cement composite and aid the monitoring of piezoresistive effects and damage. There are different types of functional fillers along with hybrid combinations that have been explored for self-sensing properties, including carbon fibers and annotates, carbon black, grapheme, and natural graphite. The choice of the functional filler is important as it will dictate the resulting mechanical, durability and electrical properties of the material. The concentration of the functional filler is of utmost importance as it affects the other parameters of concrete. The minimum dosage required to create conductive networks within the cement matrix is known as the percolation threshold. This percolation threshold will vary between functional fillers and their concentration will also affect the mechanical and durability properties. Therefore, finding the right balance between structural performance and electrical conductivity is necessary for the success of functional fillers.

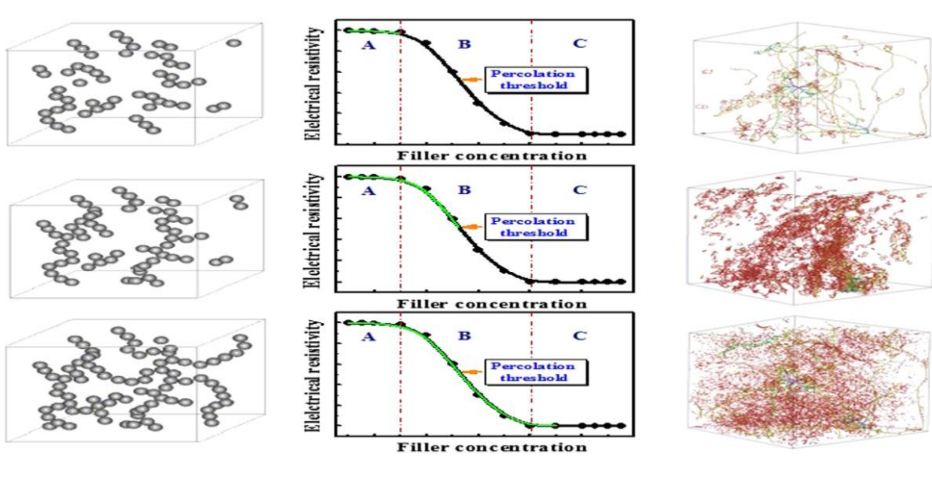


Figure1: Variation of the electrical resistivity with change of functional filler concentration

Experiments were conducted to assess the smart behavior of carbon fibers and Grapheme. Unlike other sensors like strain gauges, fiber optic gauges etc. Grapheme and Carbon fiber due to its smart property namely to conduct electricity, acts as a self sensing material and senses resistance changes. Hence it senses elastic resistance change and inelastic failures. Also both fillers possess high flexural strength which is an added advantage.

Experimental Programme

Concrete cubes and beams were cast to characterize the effect of fillers (Carbon fiber and Grapheme) and its combinations (Silica fumes and Metakeolin) with mortar. The technical specifications of the filler material given in table 1 and 2.

Table 1: Technical Specification of Chopped Carbon Fiber

Length mm	6mm
Diameter (µm)	5-7
Tensile Strength (MPa)	3600-3800
Tensile Modulus (GPa)	220-240
Elongation (%)	1.5
Density (g/cm3)	1.76
Color	Black
Carbon Content (%)	95

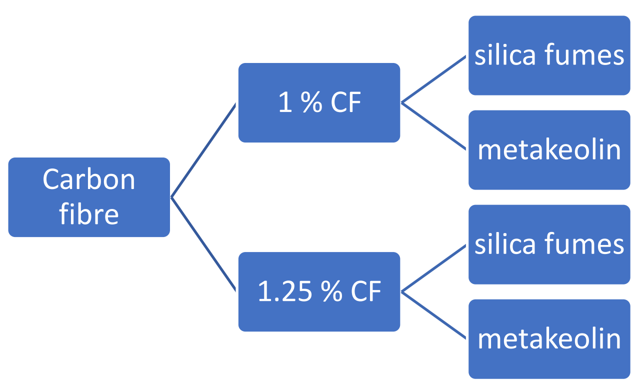
Table 2: Technical Specification of Grapheme

Purity	~99%
Thickness	~ 5 - 1 0 nm
Number of layers	5 - 10
Average lateral dimension(x&y)	5 - 10 µm
Surface area	80 - 2 2 0* m^2/g
Bulk density	0. 1 4 g/cm^3
Physical form	Liquid
Odour	Odour less
Color	Black

Mix Preparation and Design

The mix preparation design for self-sensing of high performance concrete follows a similar protocol as in the case of conventional concrete design except for the addition of filler in self-sensing concrete. Due to high surface area of the filler, the workability of the concrete mix could be affected, and the chemicals that are used as dispersant materials could influence the mechanical properties of concrete at the same time.

The addition of a specific percentage of filler in the mix should be carefully selected to achieve the desired results. For these experiments total 8 variants of three samples of Cubes and Beams each was casted as shown in Table 3. Each specimen was embedded with brass electrode as shown in Fig 2.



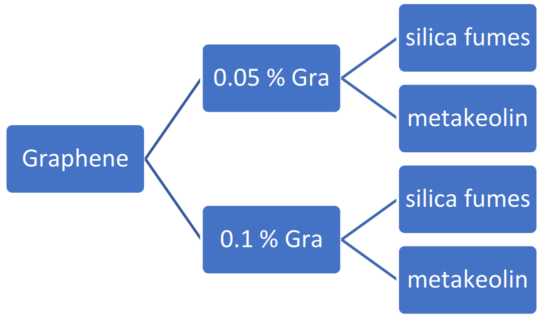


Table 3: Variation in the Specimen Based on Functional Fillers.

Figure 2: Casting of Cube and Beam specimens with embedded brass electrodes.

Curing Procedure

The specimen cubes and beams were demoded after one day and allowed to cure at room temperature for 28 days.

Testing Procedure

For Compression testing, 24 cubes of 8 specimens (150mm x 150mm x 150mm) and for Flexural strength testing total 24 beams of 8 specimens (150mm x 150mm x 700mm) were prepared. During flexural and compressive testing up to failure the load was measured in a Servo displacement controlled UTM 3000KN capacity (Figure 3 &4). Voltage input from a DC Power Supply (15 V) was given to the cube using two probe methods (Figure 3) and the current output and voltage output were measured using a voltmeter and an ammeter and the fractional change in resistance computed at each loading stage. The two brass electrodes of cube were connected to the two probes of the voltmeter. The positive end of ammeter was connected to positive end of DC Power supply and negative end of DC Power supply was connected to one brass electrode of cube. The negative end of ammeter was connected to another brass electrode of Cube. In this study two probe method of measuring resistance is adopted. From the voltage and current values obtained at each stage of loading, the resistance is calculated. The current value in ammeter and the voltmeter give the voltage. Resistance was computed using

$$R=V/I \qquad (1)$$

Then the Electrical Resistivity was computed by using Electrical Resistivity $\rho = (R-Ro)/Ro\ \Omega$ where Ro initial volume electrical resistance of the self-sensing concrete subjected to no external force. Testing was performed in equal interval of loading and continued up to failure and the readings were taken at each stage.

Figure 3: Compressive testing of cube

International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 12 Issue 4, April-2023, Impact Factor: 7.957

Figure 4: Flexural Testing of Beam.

RESULTS AND DISCUSSION

The results plotted are shown in Figures, below for compression and flexural test for the cases of different functional filler materials with varying percentage. It essentially means that it is quite possible to predict the resistance values in the field using the carbon fiber and Grapheme. It is also seen that once the Resistance vs Load graphs are drawn using a cube compression test and beam flexural test, Field experiments can be conducted to get actual stress values. Thus health monitoring of structures can be carried out using this simple procedure.

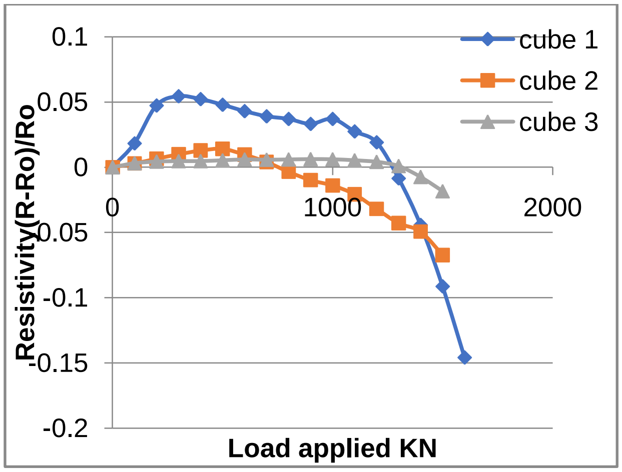


Figure 5: Cubes made of Flyash+ Silica fume+ 1% Carbon fiber (150x150x150 mm).

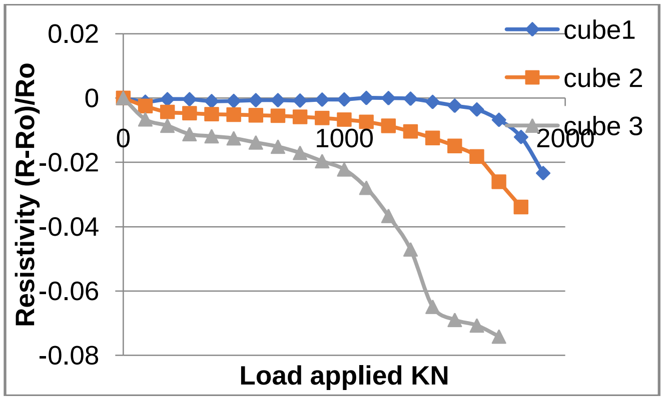


Figure 6: Cubes made of Flyash+ Silica fume+ 1.25% Carbon fiber (150x150x150 mm).

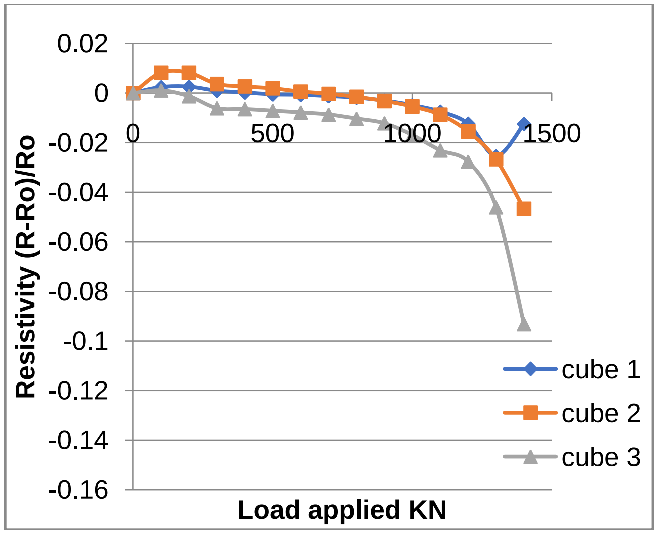


Figure 7: Cubes made of Flyash+ Silica fume+ 0.05% Grapheme (150x150x150 mm).

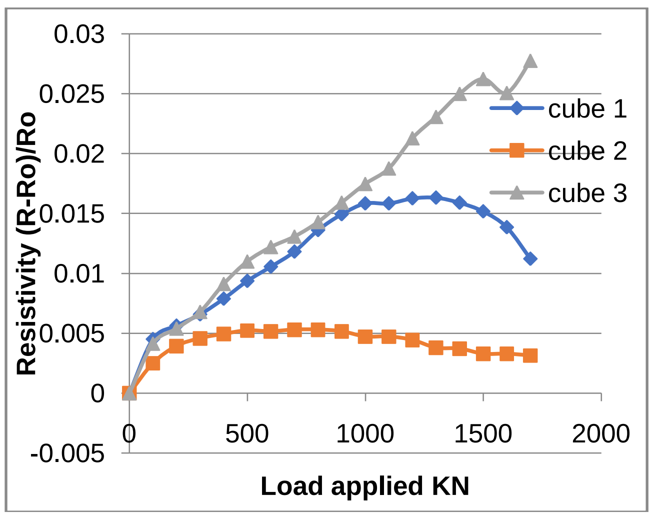


Figure 8: Cubes made of Flyash+ Silica fume+ 0.1% Grapheme (150x150x150 mm).

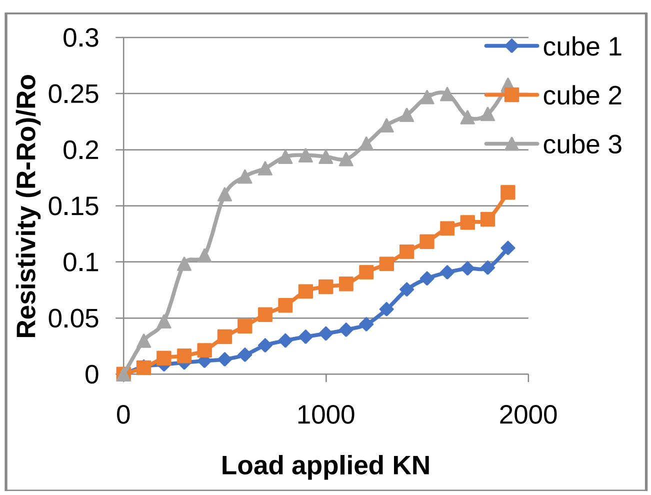


Figure 9: Cubes made of Flyash+ Metakeolin+ 1%carbon fiber (150x150x150 mm).

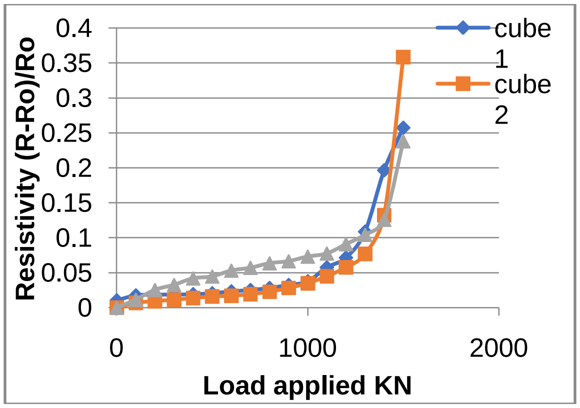


Figure 10: Cubes made of Flyash+ Metakeolin+ 1.25 % carbon fiber (150x150x150 mm).

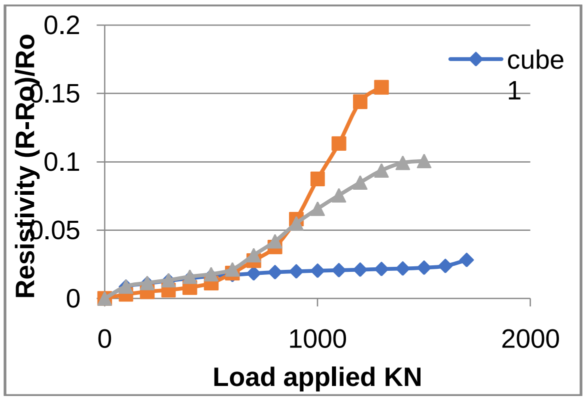


Figure11: Cubes made of Flyash+ Metakeolin+ .05% Grapheme (150x150x150 mm).

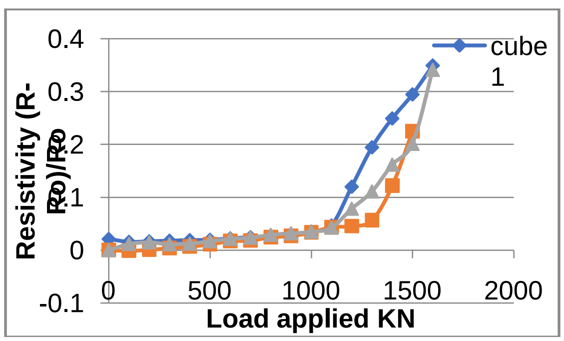


Figure 12: Cubes made of Flyash+ Metakeolin+ .1% Grapheme (150x150x150 mm).

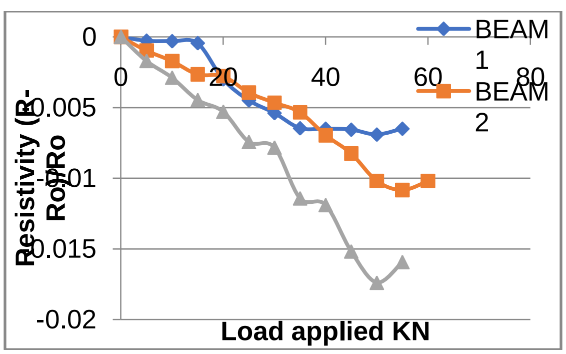


Figure 13: Beams made of Flyash+ Silica fume+ 1% Carbon fiber (150x150x700 mm).

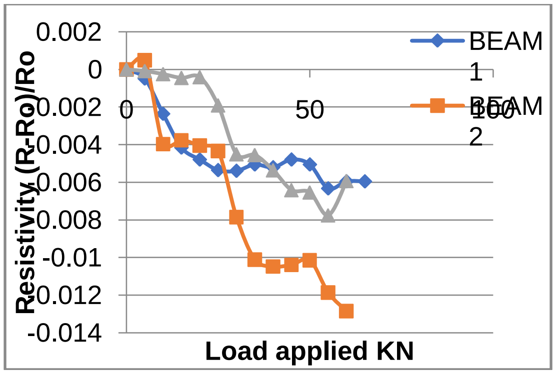


Figure 14: Beams made of Flyash+ Silica fume+ 1.25% Carbon fiber (150x150x700 mm).

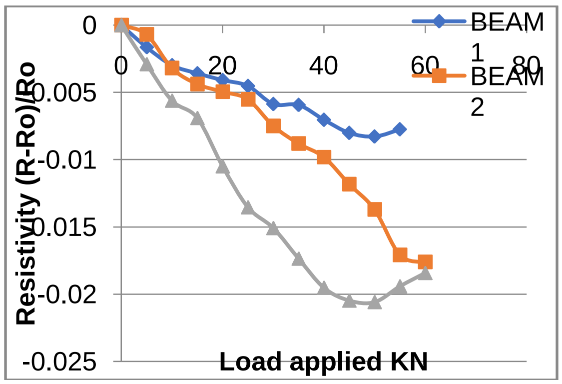


Figure 15: Beams made of Flyash+ Silica fume+ 0.05% Grapheme (150x150x700 mm).

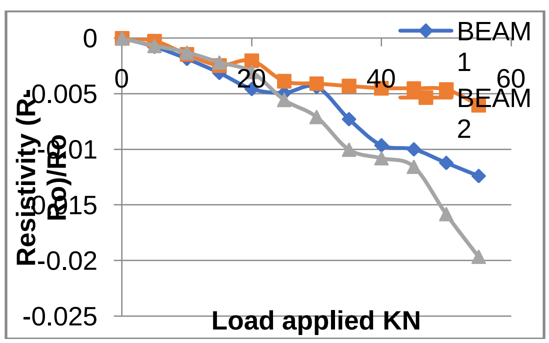


Figure 16: Beams made of Flyash+ Silica fume+ 0.1% Grapheme (150x150x700 mm).

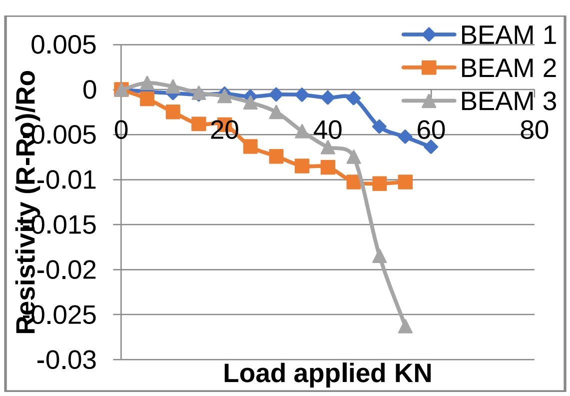


Figure 17: Beams made of Flyash+ Metakeolin+ 1%carbon fiber (150x150x700 mm).

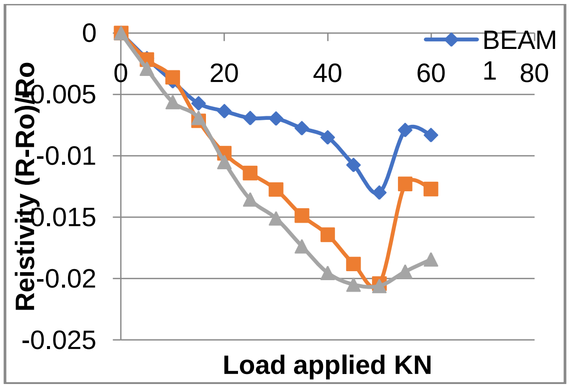


Figure 18: Beams made of Flyash+ Metakeolin+ 1.25 % carbon fiber (150x150x700 mm).

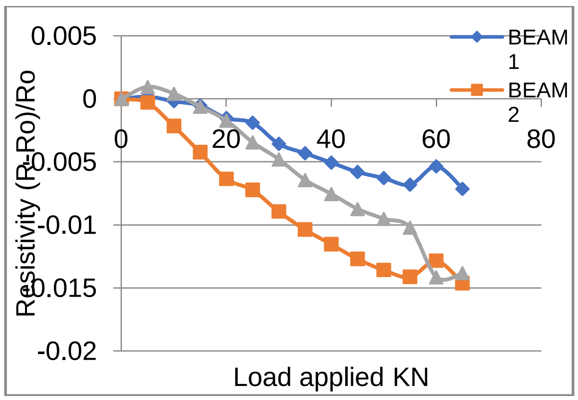


Figure19: Beams made of Flyash+ Metakeolin+ .05% Grapheme (150x150x700 mm).

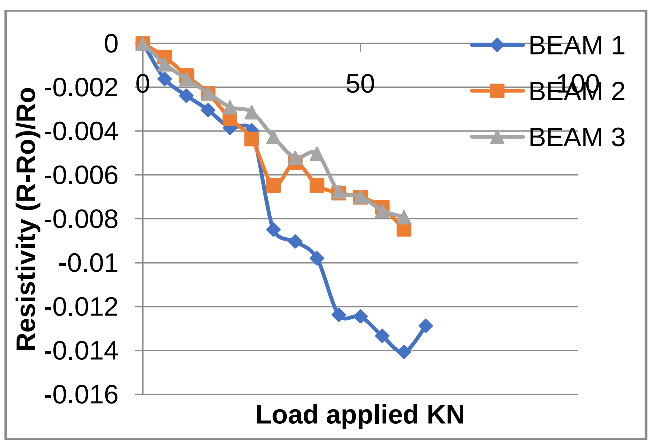


Figure 20: Beams made of Flyash+ Metakeolin+ .1% Grapheme (150x150x700 mm).

CONCLUSION

The outcome of the experimental study is a self-sensing material that can detect the stress responses under loading by electric resistance measurements. Electric-based testing of concrete containing different functional fillers with variation in percentage of fillers under loading test indicates corresponding responses in stress/strain, which is not detected in concrete specimen without any filler. Full scale specimens can be developed according to the process described herein to determine the electro-elastic properties associated with other mechanical behaviors and to derive the calibration factors for different concrete mixtures.

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