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The strain sensitivity of copper powder reinforced concrete

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ABSTRACT

Earthquakes, material deteriorations and other environmental factors challenge the structural safety. In order to protect the lives, structural health monitoring is crucial. The metal foil strain gages have low durability, low sensitivity and can get point wise measurements which are disadvantages. In this study six different concrete mixtures were designed; one without any copper powder, the rest five having different copper powder volume fractions. Three cube samples from each mixture were cast and cured. Simultaneous measurement of electrical resistance and strain were conducted during the compression tests. A strong linear relationship between strain and electrical resistance change was obtained for copper powder reinforced concrete. The results are contribution to the development of "Smart Concrete" which can sense its strain and damage.

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1. Introduction

Material degradations, earthquakes and other environmental factors challenge the structures. Concrete infrastructures are deteriorated before the design life and 30% of bridges were reported to be structurally deficient (Reza et al., 2003). For this reason structural health monitoring is an important task. One of the widely used sensors in structural health monitoring is metal foil strain gages. Metal foil strain gages have low durability, low sensitivity and high cost. These properties of metal foil strain gages restrict their use for a long time and in vast numbers (Chung, 2001). Self-sensing smart concrete is an ideal engineering material for satisfying this issue.

Relation between electrical resistance change and compressive strain for copper powder reinforced concrete was investigated in this project. Copper powder was used as a conductive phase in the concrete mix due to its good electrical characteristic. Addition of carbon fibers in cement matrix decreases its electrical resistance. Under strain, electrical resistance of carbon fiber reinforced cement composites changes (Chung, 1998; Fu et al., 1997). Addition of carbon fiber in cement matrix improves tensile strength, ductility and flexural strength while decreasing shrinkage cracking (Chung, 2000). Different test setups and electrode configurations were tested in determining the strain sensitivity of carbon fiber reinforced cement composites (Chiarello and Zinno, 2005; Han et al., 2007; Reza et al., 2004; Chen and Liu, 2008). The sample cross section and the distance between the electrodes affect the resistance measurements in two electrode method while they do not have an effect on four electrode method. Four electrode method is preferred as it gives more accurate results (Chiarello and Zinno, 2005; Han et al., 2007). Under compressive load, the fibers are under compression during loading so the electrical resistance decreases. Loading will develop damage in the material which will change the electrical resistance (Chung, 2000). Strain sensing, crack detection and damage assessment of concrete structures can be achieved by the carbon fiber reinforced cement based composites (Teomete, 2015).

In this study, different volume fractions of copper powder were used in the mix design of concrete. Four electrode method was used at the tests. The strain and electrical resistance of the samples were simultaneously measured during compression test. The electrical resistance change - strain correlations were determined. Gage factor, linearity and strain limit which are performance measures of a strain gage were determined for the copper powder reinforced smart concretes.

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2. Experimental Method

In this study, six different concrete mixes were designed; one without any copper powder, the rest five having different copper powder volume fractions. Three cube samples from each mix were cast and cured. In all mixes, cement Batıçim CEM II/B-M (L-W) 42,5R was used. BASF silica fume/cement was 10%; water/binder was 0.37; super plasticizer Sika ViscoCrete High Tech 30/binder was 1%. The maximum and the minimum diameter of the aggregate was 0-15mm. Two type of aggregate was used in the mix. Fine aggregate size was between 0-5mm and coarse aggregate size was between 5-15mm. Copper powder was examined under the microscope as seen in Fig. 1. The shape of the copper powder is circular and has a maximum diameter of 300 µm. In mix M0, there was not any conductive material. The mixes Cop1, Cop2, Cop3, Cop4 and Cop5 have copper powder volume fractions of 0.2% - 0.35% - 0.5% - 0.8% and 1% respectively.

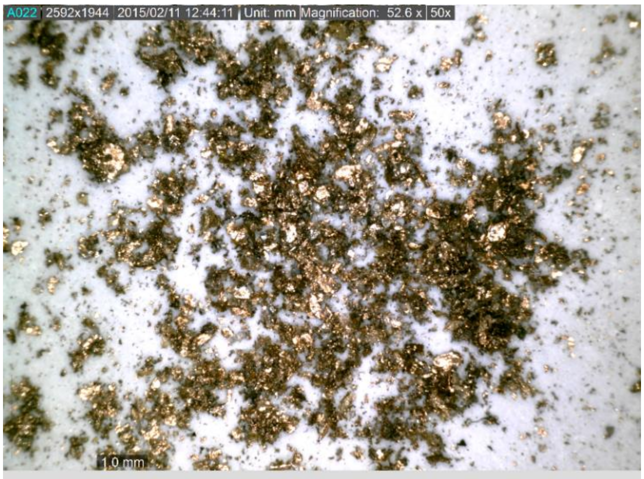

Fig. 1. Copper powder microscope image (magnification: 50x).

Three samples of 7.5 cm cubes were casted for each mix. Special 7.5 cm cube shaped molds were designed and manufactured for this study. The molds have four 2 mm wide, 55 mm long slots on each side. Pure copper wire mesh was passed through the molds as seen in Fig. 2. The mix was cast in the mold as in Fig. 3. The samples were taken out of molds 24 hours later after casting and the samples were cured in water for 28 days. The samples were taken out of water at 28th day and were kept at laboratory environment for 7 days to have steady state moisture content.

The compression test was achieved with a displacement controlled Shimadzu mechanical test machine at a load rate of 0.5mm/min. The total voltage in put to the circuit in Fig. 4 was 20V. While conducting the test, a DC current was supplied by outer electrodes of the sample as in Fig. 4. Four electrode method was used as it gives more accurate results. There was a reference resistance (R_r=1000 Ohm) and an ampere meter (A) which was in series with the sample. The potential difference between voltage electrodes of the sample (E_v) was measured as V_s and the potential difference across the reference resistance was measured as V_r. A strain gage was used to measure the strain of the sample in force direction. The load, the stroke of the loading head, strain gage data, current, potential differences V_s and V_r were recorded at a rate of 10Hz (10 data in a second) during the test. An image of the sample during compression test was given in Fig. 5.

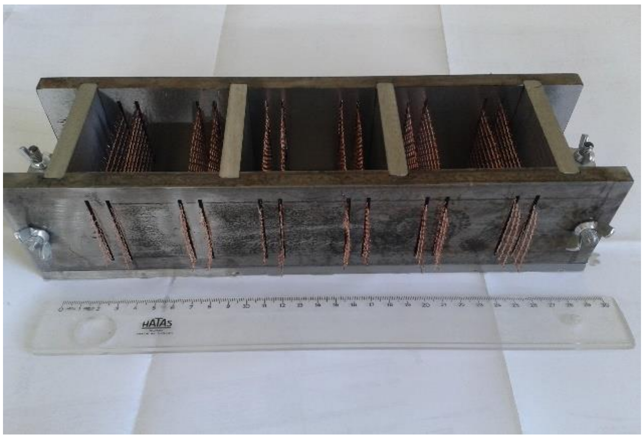

Fig. 2. Mold and copper mesh electrodes.

Fig. 3. Mix casted in mold.

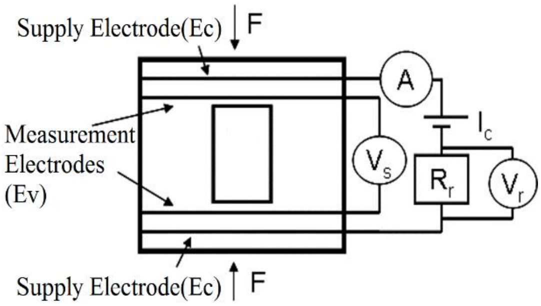

Fig. 4. Circuit diagram used during compression test.

The current on the circuit and the resistance of the sample were determined by using Ohm's law as in Equations 1 and 2. The current determined from Eq. 1 was verified with the ampere meter values. The % change in the resistance of the sample (%R) was determined by Equation 3. R_{so} is electrical resistance of sample without application of any load.

$$I_c = \frac{V_r}{R_r}, \quad (1)$$

$$R_s = \frac{V_s}{I_c}, \quad (2)$$

$$\%R = \left(\frac{R_s}{R_{so}} - 1\right) \times 100 \,. \quad (3)$$

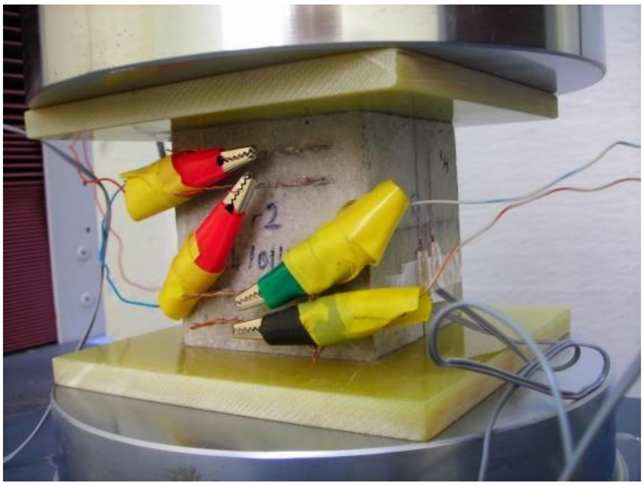

Fig. 5. Compression test.

The gage factor (K), linearity (LE) and strain limit (SL) are performance parameters of a strain gage. Gage factor (K) is the fractional change in electrical resistance per unit strain, and can be determined using Eq. (4). It is a measure of strain sensitivity for strain gages. It is the slope of percent change in resistance ($\%R$) versus strain graph divided by 100. The higher the K, the more sensitive the sensor is. The gage factor of commercial metal strain gages is around 2. Linearity (LE) is the percent of maximum difference (Δ_{max}) between input-output curve ($\%R$ versus strain curve) and fitted linear regression line, to full scale output (R_{fs}), as given in Eq. (5). The error in measurement of strain decreases by decreasing linearity. The strain limit (SL) of a strain gage is the maximum strain that can be measured with a small error. The strain limit (SL) of typical commercial metal strain gage is between 0.005-0.03.

$$K = \frac{(R_S - R_{SO})/R_{so}}{\Delta\varepsilon}, \quad (4)$$

$$\%LE = \left(\frac{\Delta_{max}}{\%R_{fs}}\right) \times 100 \,. \quad (5)$$

3. Results and Discussion

Six different concrete mixtures were designed; one without any copper powder, the rest five having different copper powder volume fractions. From each mix, three of 7.5 cm cubes were tested with compression test. The relations between compressive strain – electrical resistance change were determined. These results are presented in this section.

The $\%R$ – strain graph of mix M0 is given in Fig. 6. The gage factor of mix M0 which does not have any conductive materials is K=21. It is 10 times more sensitive to strain than metal foil strain gages. It has a linearity of 15% and its strain limit (SL) is 2%. The correlation coefficient of best fit line to the data is 0.93.

The $\%R$ – strain graph of mix Cop1 is given in Fig. 7. The volume fraction of the copper powder in the Cop1 mix is 0.2%. The gage factor is K=41 which is 20 times more sensitive to strain. The linearity is LE=5% and the strain limit is 1.5%. The correlation coefficient of best fit line to the data is 0.99.

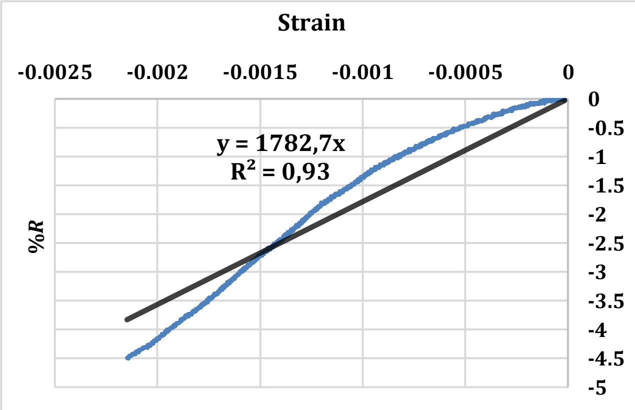

Fig. 6. M0 mixture without conductive (K=21; LE=15%; SL=2%).

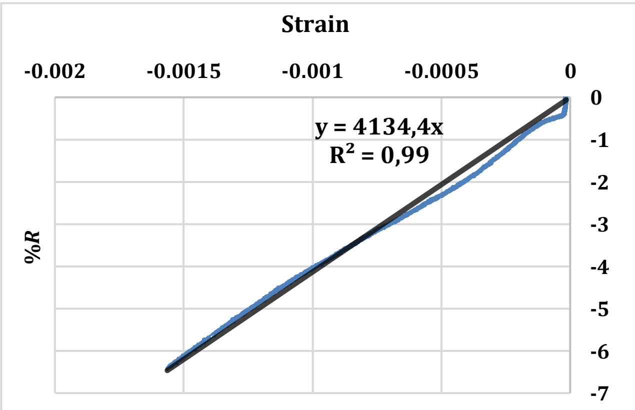

Fig. 7. Cop1 mixture with 0.2% copper powder (K=41; LE=5%; SL=1.5%).

The $\%R$ – strain graph of mix Cop2 is given in Fig. 8. The volume fraction of the copper powder in the Cop2 mix is 0.35%. The gage factor is K=53 which is 26 times more sensitive to strain. The linearity is LE=5% and the strain limit is 1.3%. The correlation coefficient of best fit line to the data is 0.98.

The $\%R$ – strain graph of mix Cop3 is given in Fig. 9. The volume fraction of the copper powder in the Cop3 mix is 0.5%. The gage factor is K=27 which is 13 times more sensitive to strain. The linearity is LE=6% and the strain limit is 2.4%. The correlation coefficient of best fit line to the data is 0.99.

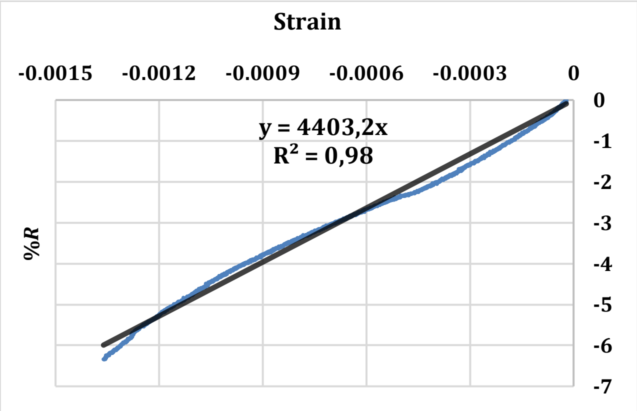

Fig. 8. Cop2 mixture with 0.35% copper powder (K=53; LE=5%; SL=1.3%).

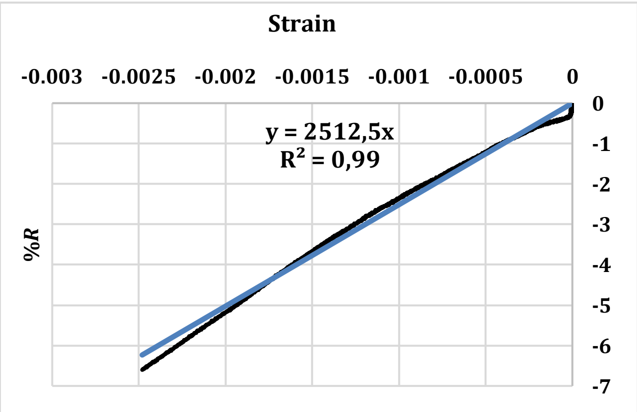

Fig. 9. Cop3 mixture with 0.5% copper powder (K=27; LE=6%; SL=2.4%).

The %R – strain graph of mix Cop4 is given in Fig. 10. The volume fraction of the copper powder in the Cop4 mix is 0.8%. The gage factor is K=33 which is 8 times more sensitive to strain. The linearity is LE=23% and the strain limit is 1.6%. The correlation coefficient of best fit line to the data is 0.94.

The %R – strain graph of mix Cop5 is given in Fig. 11. The volume fraction of the copper powder in the Cop5 mix is %1. The gage factor is K=38 which is 19 times more sensitive to strain. The linearity is LE=10% and the strain limit is 1.8%. The correlation coefficient of best fit line to the data is 0.99.

The gage factor (K), linearity (LE) and correlation coefficient (R^2) versus copper powder volume percent were given in the Figs. 12-13-14. The Figs. 12-13-14 shows average values of three samples that casted for each group. There are five copper powder reinforced mix groups which have different copper powder volume fractions and there is M0 group which does not have any copper powder.

The gage factor (K) – copper powder volume fraction graph of the tested mixes was given in Fig. 12. As seen on the graph all of mixes with copper powder has more gage factor than M0 which does not have any copper powder. Cop2 mix (0.35% copper powder volume fraction) has the highest gage factor in all of the mixes. Cop2 mix has an average of 44 gage factor. This mix was 22 times more sensitive to strain than commercial foil strain gages. The gage factor is decreasing with the increasing copper powder volume fraction. As the copper powder volume percent increased from 0.35% to 1%, strain could disrupt a smaller percent of the conductive-conductive and conductive-matrix contact; the effect of strain on the electrical resistance got smaller; %R changed less; strain sensitivity decreased and gage factor decreased.

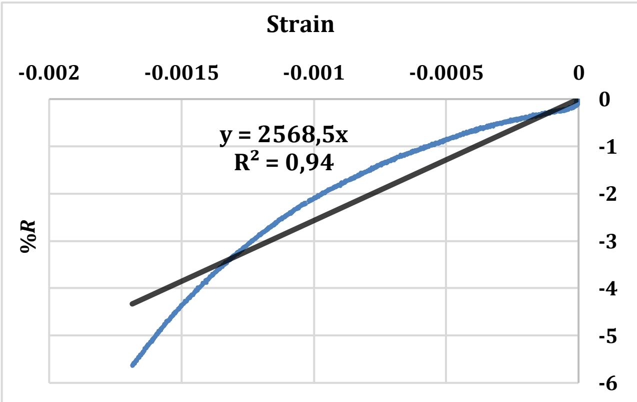

Fig. 10. Cop4 mixture with 0.8% copper powder (K=33; LE=23%; SL=1.6%).

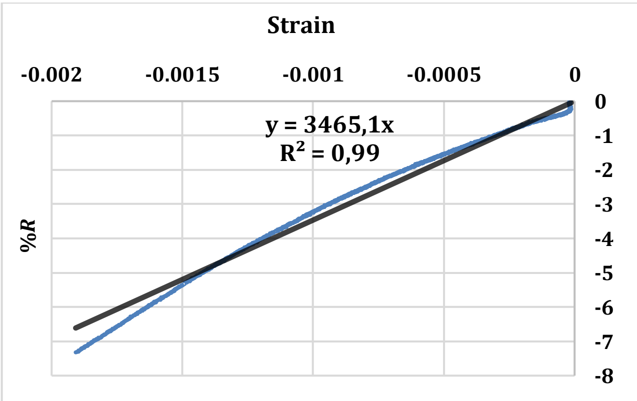

Fig. 11. Cop5 mixture with 1% copper powder (K=38; LE=10%; SL=1.8%).

The linearity (LE) – copper powder volume fraction graph of mixes was given in Fig. 13. As seen on the graph all of mixes with copper powder has LE deviation than M0 which does not have any copper powder in it. Cop1 (0.2% copper powder volume fraction) and Cop2 (0.35% copper powder volume) have the lowest LE in all of the mixes. The average linearity of Cop1 mix is LE = 6.79% and the average linearity of Cop2 mix is LE = 6.65%. The deviation is increasing with the increasing copper powder volume fraction.

The correlation coefficient (R^2) – copper powder volume fraction graph of mixes was given in Fig. 14. As seen on the graph all of mixes with copper powder had higher correlation coefficient than M0 which did not have any copper powder. The highest correlation coefficient was 0.99 which testified the strong linear relationship between compressive strain and electrical resistance change.

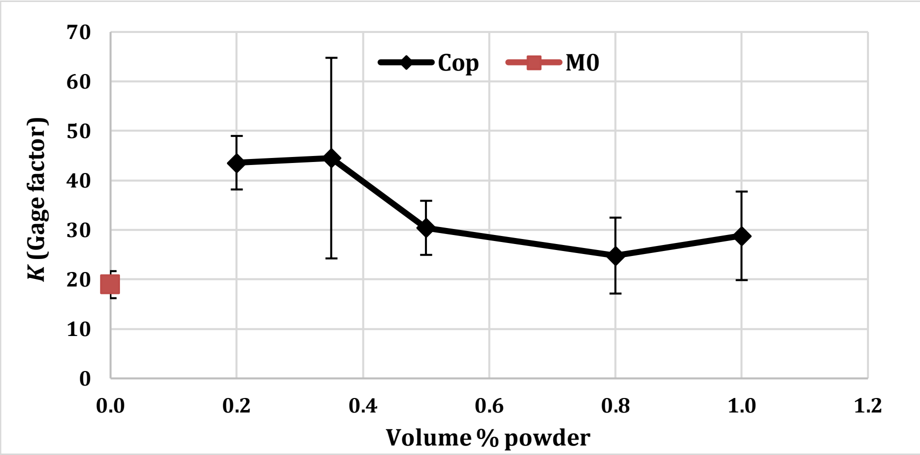

Fig. 12. The gage factor (*K*) vs. copper powder volume fraction graph of mixes.

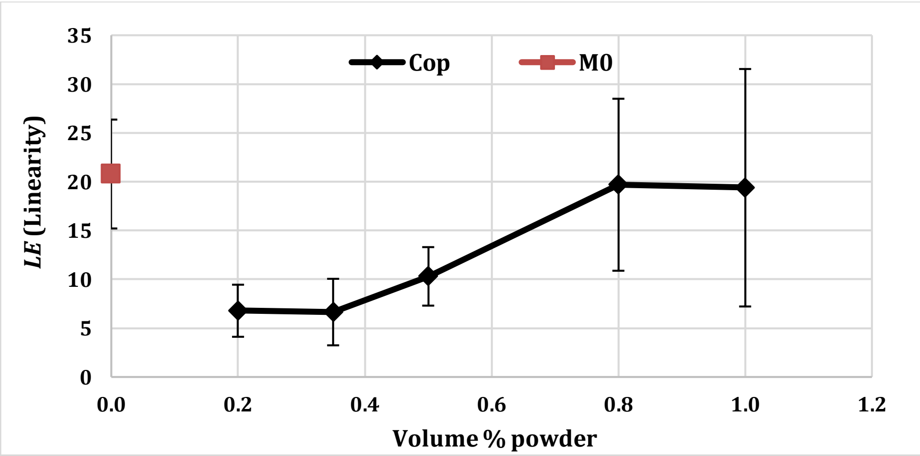

Fig. 13. The Linearity (*LE*) vs. copper powder volume fraction graph of mixes.

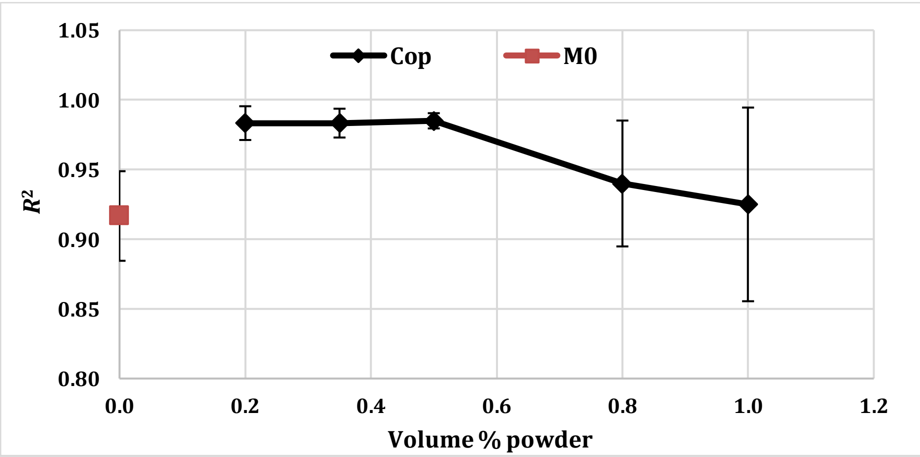

Fig. 14. The correlation coefficient (R^2) vs. copper powder volume fraction graph of mixes.

4. Conclusions

Five different samples with different copper powder volume fractions and one sample without any copper powder in it were tested in this study. Simultaneous measurement of sample resistance and strain were recorded. It was observed that:

- The compressive strain closed micro cracks and voids, increased contact between concrete matrix-copper powder, powder- powder and resulted in a decrease in the electrical resistance.
- There was a strong linear relationship between compressive strain and electrical resistance change. An average gage factor of 44 was obtained which was the

almost 20 times the gage factor of commercial metal foil strain gages.

- Copper powder reinforced concrete was more sensitive to strain and had better signal than plain concrete.
- The copper powder reinforced concrete composites were much more sensitive to strain with respect to commercial metal strain gages.
- At low volume fractions (0.2% and 0.35%), copper powder reinforced concrete had a high gage factor and a better signal quality with respect to other volume fractions.

The results are contribution to the development of "Smart Concrete" which can sense its strain and damage.

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