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Temperature and moisture effects on electrical resistance and strain sensitivity of smart concrete

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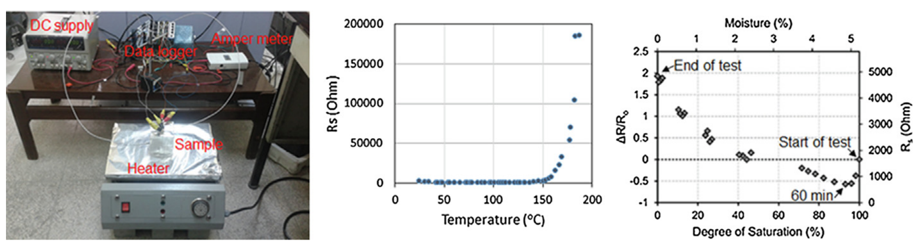
HIGHLIGHTS

- Strain sensing smart concrete was developed using brass fibers, 15 mm aggregates.
- Smart concrete sensitivity to temperature and moisture was explored.
- Smart concrete can be used as strain, temperature and moisture sensor.
- Multifunctional smart concrete can be used in structural health monitoring.

GRAPHICAL ABSTRACT



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ABSTRACT

Cement composites, with enhanced electrical properties, have been investigated as multifunctional composites, with application as strain sensors, heating elements or anode in different electrochemical technique. In this work, several aspects regarding the practical application of smart concrete with the addition of brass fibers have been addressed. In general, electrical conductivity of cement composites is dependent on their moisture content and temperature. Therefore, for a real use of this type of sensors the influence of these parameters should be determined. The electrical resistance of the smart concrete decreased linearly with temperature up to 50 °C, therefore this effect can be compensated in strain sensing applications. On the other hand, at higher temperatures, especially after 150 °C, the mismatch strain between brass fibers, cement paste and aggregates resulted in damage, which was detected as an increase of the electrical resistance on the order of 613%. Thus, smart concrete can be used as fire alarm sensor. Also, the relationship between moisture and electrical resistance change was determined. After curing, the samples with moisture content of 5.2% were put in an electric furnace at 90 °C. After 60 min of 90 °C exposure the minimum resistance was measured as 702 Ohm for an average moisture content of 4.8%. At this optimal moisture content, water between fibers was lost and direct contact between fibers was achieved, maximizing the electrical conductivity of the composite. After this point, when the smart concrete was heated for a longer time, the electrical resistance increased almost 300% because water acting as electrolyte was lost. Thus, smart concrete is sensitive to moisture change and can be used as moisture sensor, especially at constructions exposed to harmful water. The effect of moisture content on the strain sensitivity of smart concrete was tested. The mechanism relating piezoresistive properties and moisture content were enlightened. Multifunctional smart concrete can be used as strain, fire and moisture sensor while acting as a load bearing element.

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1. Introduction

Material degradations, earthquake and fire, threat the structural integrity of civil engineering structures. In USA, concrete infrastructures present material deterioration, where 30% of bridges were found to be deficient [1]. In order to control the structural reliability, structural health monitoring systems are designed to monitor different environmental and structural parameters [2]. Commercial metal foil strain gages are usually used for strain monitoring, but they have shorter lifetime, and lower durability and sensitivity than cement based smart composites [3].

The electrical resistance of these cement composites can be decreased with different conductive additions, like carbon fiber, and show an electrical response when a mechanical load is applied [4–6]. Besides, cement composites' strain and crack length have a strong linear relationship with their electrical resistance [7–10]. Therefore, piezoresistive and piezoelectric cement composites were developed and tested for strain and damage sensing by several researchers, using different conductive materials. For example, Han et al. [11] developed a nickel particle reinforced cement composite for vehicle detection, or as a wireless monitoring system in elements under compression [12,13]. There are multiple reports on the use of cement based composites as sensors even in real scale structural elements [14–16].

Research interests have been focused on the type of conductive additions, its optimal dosage and the effect on the strain sensitivity of the composite. The specific type of conductive material can affect the percolation threshold, i.e. the minimum amount of fibers for a minimum resistivity. In cement composites the water/cement ratio can affect the electrolytic conduction, hence the overall resistivity of the material, as observed for multi walled carbon nanotube (MWCNT) cement composites [17]. Other nanoparticles like carbon black [18,19], iron oxide nanoparticles [20], nickel powders [21] or graphite [22] have been used to improve the piezoresistive response of these composites, and even their mechanical performance. Strain sensing of cement composites has been applied to detect vehicles pressure in traffic monitoring [23], crack sensing and healing of concrete beams [24], or as sensor in testing of civil engineering structures [25].

Moreover, the use of conductive aggregates has been used to improve the conductivity or strain sensing response of concretes and mortars [26]. Concrete with smart aggregates was used as communication channel using lead zirconate titanate (PZT) piezoceramic [27–28]. Cracks and leakage in concrete water pipes and bond slip between steel plates and concrete in beams were detected by piezoceramic included smart aggregates [29]. Other example of damage detection thanks to smart aggregates can be found in concrete piles, in which different defects could be detected (e.g. crack, partial mud intrusion, secondary pouring, and full mud intrusion) [30].

For a successful application of smart concrete in real structures, the influence of temperature [31] and moisture changes [32] in their response should be addressed. For example, an increase of temperature or humidity decreased the specific resistance of carbon fiber reinforced concrete [33]. The piezoresistive response is usually evaluated in terms of gage factor, which can be defined as the ratio between the electrical resistivity change and the strains to be measured. Strain amplitude and history increased variability of gage factor. Carbon fiber reinforced cement based composite which was at percolation threshold had a gage factor of 12% lower when dried at room temperature [34]. It was found that resistivity and temperature had inverse exponential relationship which follows the Arrhenius relationship for carbon fiber reinforced normal and self consolidating concrete [35].

In this study, the effects of temperature and moisture on the electrical resistance and strain sensitivity of smart concrete including brass fibers were determined. For this general purpose, three different experimental setups were developed. First, open table heating tests were conducted to determine temperature – electrical resistance relationship of the smart concrete. Afterwards, the effect of moisture content was studied, monitoring the electrical resistance as samples heated in an electric furnace. Finally, moisture content effect on strain sensing response was addressed in compression tests. The results showed that smart concrete could be used as strain, fire alarm and moisture sensor. The results presented for smart concrete, which has maximum aggregate size of 15 mm, are contributions of this work to the smart materials science and technology.

2. Materials and method

In order to design the smart concrete, cement type CEM II 42.5R was used together with silica fume (silica fume/binder ratio was 10%). Cement dosage was 499 kg/m^3; water /binder ratio was 0.37; super-plasticizer/binder ratio was 1%, superplasticizer (modified polycarboxylates based polymer) water reduction was 10%. Two types of crushed limestone aggregate were used; 60% of the aggregate with size of 0–5 mm, and the other 40% having size of 5–15 mm. Total aggregate/cement mass ratio by mass was 2.7. Commercially available brass fibers (average length of 1.5 mm and average diameter of 0.5 mm) were used as conductive material at 0.8% volumetric ratio.

The electrical resistance of cement composites can be measured using two or four electrode methods. In two probe method, current supply and voltage measurement use the same electrodes while in four probe, outer contacts are used to current input while inner probes are for voltage measurement. Sample cross section and distance between electrodes did not affect measurements of four electrode method [36,37]. Four electrode method was used in this study. Besides, electrodes are usually made as an embedded plate or mesh, or as a perimetral contact (copper wire and silver paint) [38–41]. In this study, copper wire meshes were inserted in the material as shown in Fig. 1.

Pure copper wire mesh which has wire diameter of 0.6 mm and square hole size of 5 mm were used as electrode as seen in Fig. 1a. Cubic specimens of 7.5 cm were prepared using the molds shown in Fig. 1b, which had four 2 mm wide, 46 mm long slots on each sidewalls for passing the copper wire mesh electrodes through the mold. The electrodes were inserted in the mold and then concrete was cast, as seen in Fig. 1c. The samples were taken out of the molds 24 h after casting and cured in water at 20 °C for 28 days. Eighteen cube samples of 7.5 cm were cast and cured. The average properties of the concrete mix were assessed, an average 59 MPa compressive strength and 10 cm slump.

2.1. Effect of temperature on electrical resistance

Three samples were tested in order to determine the effect of temperature on electrical resistance of smart concrete. After the aforementioned curing process, in order to have a steady state moisture content, the samples were left at laboratory environment for 7 days. Then, the samples were coated with aluminum tape in order to prevent change of moisture content, and the electrodes were isolated with special ceramic clay to prevent short circuit. An open table heater was used to heat the sample as seen in Fig. 2. The top and bottom temperatures of the sample were measured using thermocouples. The temperature of the sample was increased by 10 °C intervals up to 187 °C, while 20 V DC power was supplied to the outer electrodes. The circuit diagram is presented in Fig. 2c, in which potential difference Vs of the inner electrodes was measured. The potential difference V_r of a reference electrode (R_r = 1000 Ohm) and the current on the circuit were also measured. The temperature, voltage and current measurements were conducted at a rate of 10 Hz. Data were collected at intervals less than 10 °C for 25 s. National Instruments CDAQ 9178 data logger and NI 4065 digital multi-meter were used.

Ohm's law was used to determine the current on the circuit I_c and the resistance of the sample R_s as in Eqs. (1) and (2), respectively.

$$I_c = \frac{V_r}{R_r} \tag{1}$$

$$R_s = \frac{V_s}{I_c} \tag{2}$$

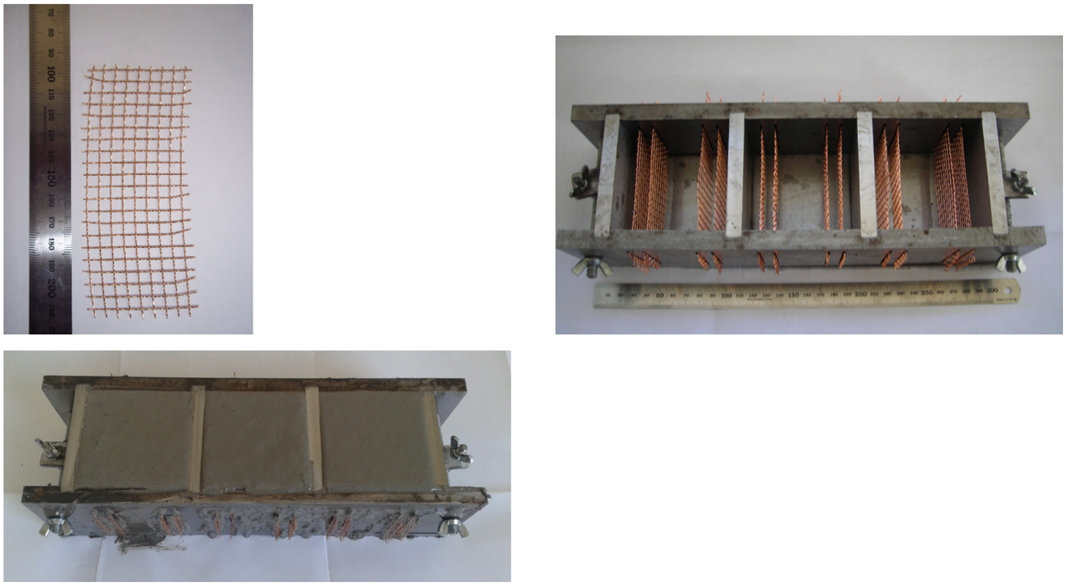

Fig. 1. (a) Copper wire mesh electrode. (b) The cube mold with electrodes. (c) After casting concrete.

2.2. Effect of moisture on electrical resistance

Three cube samples were cast and cured for 28 days. After curing, the samples were wiped with towel, weighted and their electrical resistance was measured using the circuit in Fig. 2c as explained in previous section. The samples were put in furnace which was 90 °C and heated for 10, 30, 60, 120, 180, 240, 300, 360 min, 18.5, 20.5, 22.5, 24.5, 41, 43, 44.5, 47, 63.5, 65.5, 67.5, 69.5, 86.5, 88.5, 90.5, 92.5 h. At every furnace time, the samples were weighted, electrical resistance was measured and put in the furnace again until the next time exposure. The moisture content of the samples was determined using Eq. (3).

$$Moisture\% = \frac{(W - W_{dry})}{W_{dry}} \times 100 \tag{3}$$

W_{dry} was obtained at 92.5 h of 90 °C furnace time, in which constant mass between consecutive measurements had been achieved, as shown in Fig. 3. W is the weight at a given furnace time. Degree of saturation was determined as 100% just after removing from the cure tank.

2.3. Tests of moisture effect on strain sensitivity

In order to investigate the moisture effect on strain sensitivity for compression test, 12 cube samples of 7.5 cm were cast and cured for 28 days as explained before. After curing, the samples were put in furnace at 90 °C. Three samples were removed from the furnace at each of 30, 60, 120, 180 min of furnace time, weighted and wrapped with aluminum foil to prevent moisture changes while cooling, as seen in Fig. 4a. The loss of moisture was determined for each furnace time. Compression tests were made to each sample having different moisture contents.

Shimadzu mechanical testing machine was used for the compression test with a loading rate of 0.5 mm/min. 20 V DC was supplied to outer two electrodes while potential difference between inner electrodes (Vs) was measured, as seen in Fig. 4b-c during the mechanical test. In series with the sample, a reference resistance of Rr = 1000 Ohms was used. The potential difference of the reference resistance (Vr), and the current in the circuit (Ic) were measured simultaneously. The circuit diagram used at the test is presented in Fig. 4c. Strain gages were used to measure the longitudinal strain of each sample. Voltages Vs and Vr, current Ic, strain, load were recorded at a rate of 10 Hz during the test. To isolate the sample from steel plates during the test, glass fiber epoxy composite plates were used as seen in Fig. 4b.

At any time of the test, percent change of the electrical resistance of the sample (%R) was determined by Eq. (4).

$$\%R = \left(\frac{R_s}{R_{so}} - 1\right) \times 100 \tag{4}$$

Performance measures of a strain gage are gage factor (K) and linearity (LE). The change in electrical resistance per unit strain is gage factor (K) as given in Eq. (5). The sensitivity of the strain gage increases with gage factor. The gage factor of metal foil strain gages is 2.

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}) is called linearity as presented in Eq. (6).

$$K = \frac{(R_s - R_{so})/R_{so}}{\Delta\varepsilon} \tag{5}$$

$$\%LE = \left(\frac{\Delta_{max}}{\%R_{fs}}\right) \times 100 \tag{6}$$

3. Results and discussions

Smart concrete cube samples, with 15 mm aggregates and brass fibers were prepared and conditioned at different temperature and moisture conditions. The electrical resistance of each sample was monitored unloaded and in compression tests. The results obtained are presented and discussed in this section.

3.1. Effect of temperature on electrical resistance of smart concrete

In order to determine the effect of temperature on electrical resistance, samples were coated with aluminum tape and heated. The change of electrical resistance with temperature is presented in Fig. 5. Three different stages could be detected, temperatures below 50 °C, between 50 and 115 °C, and temperatures higher than 115 °C. In the first one, from ambient temperature to 50 °C, the temperature increase evaporated the excess pore water which decreased the contact between the fibers and matrix. This loss of some excess pore water increased the contact of brass fibers and matrix, enhanced the electron transport and decreased the electrical resistance, as seen in Fig. 5b. However, the sample was insulated by aluminum tape so the water vapor had an equilibrium after 50 °C. The initial dependence on temperature between 25 °C and 50 °C is linear which allows subtraction of R_s change if there is temperature difference during strain measurement, thus temperature compensation can be applied to smart concrete.

The second stage, between 50 °C and 115 °C, showed a stable 700 Ohm resistance regardless the sample's temperature. After, the electrical resistance of the smart concrete increased with temperature. Especially at 150 °C there is an abrupt increase in electrical resistance. The electrical resistance increased from 2893 Ohms (resistivity of 46,494 Ohm cm) at 25 °C, to

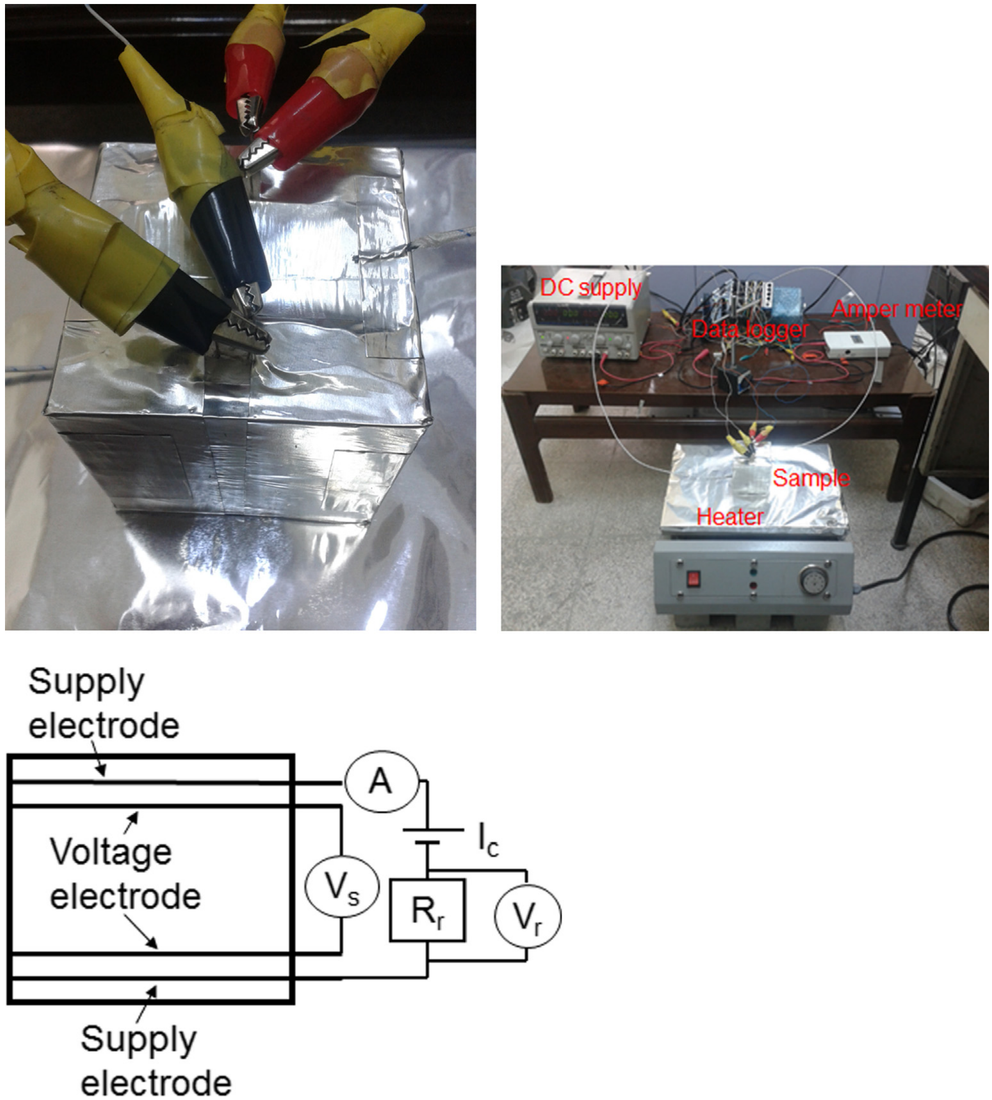

Fig. 2. (a) Aluminum tape coated sample at heating test. (b) Heating test equipment, on the front the heater, on the back from left to right, DC power supply, data logger, digital multi-meter. (c) Circuit diagram.

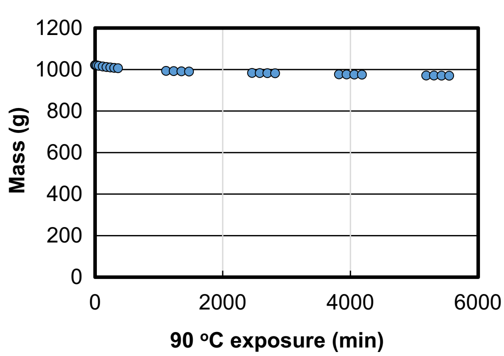

Fig. 3. Mass loss of cubic samples vs 90 °C exposure time.

186,333 Ohms (resistivity of 2,994,637 Ohm cm) at 187 °C. This increase of electrical resistance with temperature may be explained as follows: The coefficient of thermal expansion of aggregate increases with the temperature as stated by Neville [42] and Mindess et al. [43]. Aggregate and brass fibers elongate with increasing temperature. Cement paste's coefficient of thermal expansion decreases above 150 °C and gets negative values above 200 °C. Contraction occurs in the cement paste above 200 °C. The loss of water from hydrated cement and internal collapse results in decrease of coefficient of thermal expansion of cement paste. Mindess et al. [43] described it as a 'structural break down of the hydration products'. Thus, the abrupt increase of electrical resistance of smart concrete at 150 °C was due to the different elongation of aggregate and brass fibers with respect to cement paste, which resulted in tensile strain at cement paste, cement–aggregate, and cement–brass fiber interfaces. The tensile strain generated damage, resulting in an abrupt increase in electrical resistance. The loss of water in micro pores decreased ionic conduction which contributed the increase in electrical resistance. Nonetheless, this electrical behavior at elevated temperatures may serve as a fire alarm, hence the smart concrete can be used as fire alarm sensor for fire protection.

3.2. Effect of moisture on electrical resistance of smart concrete

Fig. 6 includes the evolution of smart concrete's electrical resistance with different moisture contents and saturation degrees. The electrical resistance has been also presented as the relative increase with respect to the initial value (in water-saturated

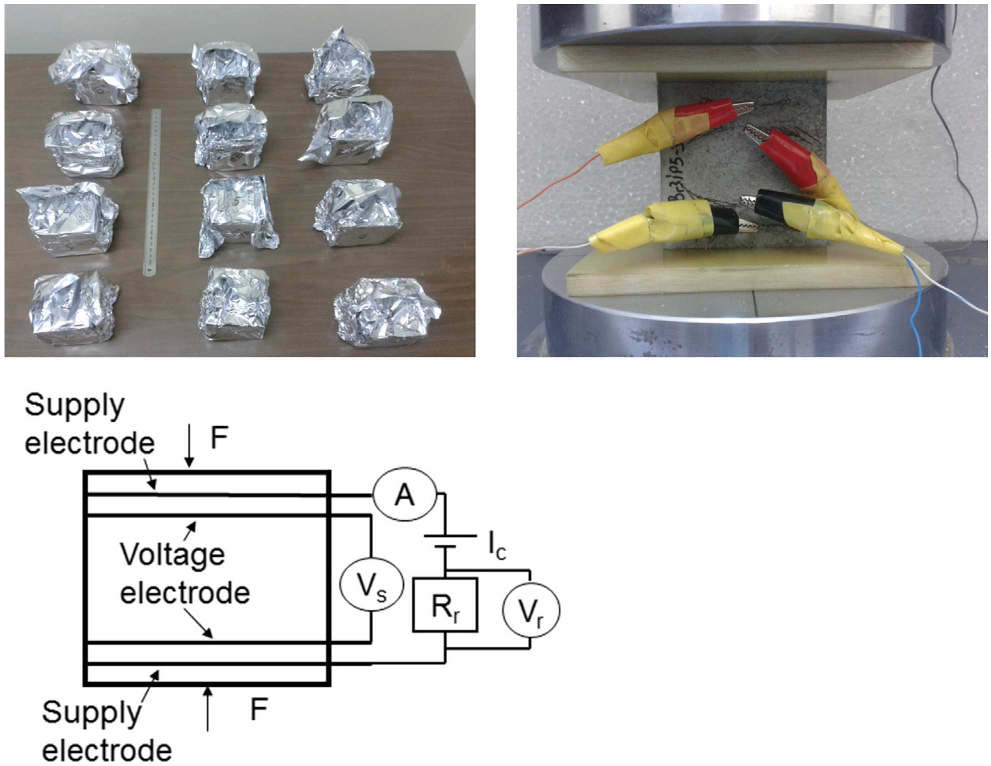

Fig. 4. (a) The samples were cooled in an aluminum folio. (b) Compression test. (c) Circuit at the compression test.

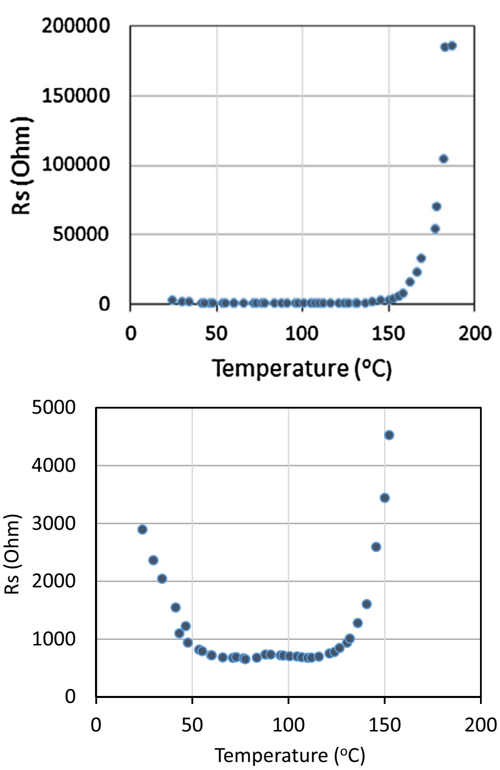

Fig. 5. The variation of electrical resistance with temperature, (a) Whole Rs range. (b) Magnified Rs upto 5000 Ohms.

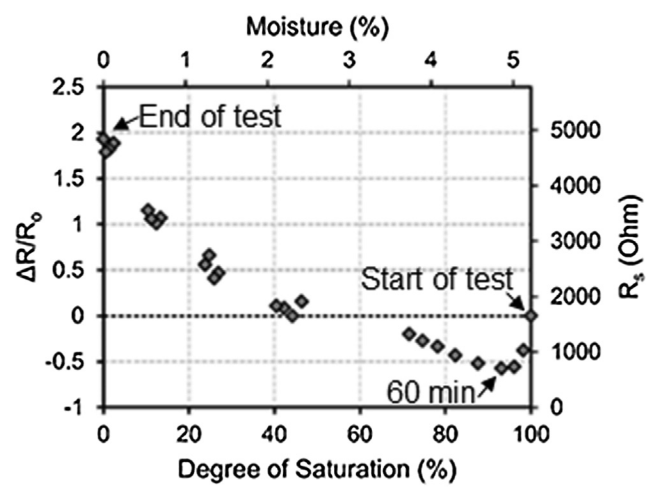

Fig. 6. Influence of the water content (saturation degree or moisture) on the electrical resistance.

conditions). The initial moisture content of the sample removed from cure tank was 5.2% (start of test at Fig. 6). As the moisture decreased to 4.8% (after 60 min exposure to 90 °C), the electrical resistance decreased due to loss of water film between brass fibers, hence enhancing the contact between the fibers. Also, the contact between fiber-matrix was enhanced due to loss of excess water between fiber and matrix, decreasing the electrical resistance as seen in Fig. 6. After 60 min of 90 °C furnace time, the electrical resistance reached a minimum of 702 Ohm. In this point, direct fiber-fiber and fiber-matrix contacts were achieved by loss of water while the micro voids were filled with water, which was acting as electrolyte and conducting electrons. The optimal moisture content was 4.8% at which the minimum electrical resistance was obtained after 60 min of 90 °C exposure.

As the moisture content decreased below this optimal value, i.e. for time exposures higher than 1 h, the water acting as electrolyte in the micro voids was lost and electrical resistance increased as seen in Fig. 6. Therefore, the smart concrete may be used as moisture sensor, especially in foundations prone to underground water.

3.3. Moisture effect on strain sensitivity of smart concrete

Twelve cube samples were cast and cured. After curing the samples were kept in 90 °C furnace and three cube samples were removed from the furnace at 30–60–120–180 min. Compression test was applied to cube samples having different moisture contents. The moisture loss increased with furnace time linearly as seen in Fig. 7a. A typical electrical resistance change (%R) – strain graph is presented in Fig. 7b, in which a strong linear correlation between the strain and electrical resistance change was observed. The gage factor decreased with decreasing moisture content (increasing furnace time) as seen in Fig. 7c. The linearity is maximum (Fig. 7d) and correlation coefficient between strain – %R graph is minimum (Fig. 7e) for 60 min of furnace time at which the minimum electrical resistance was obtained at optimum moisture content. At optimal moisture content, the electrical resistance was found to be minimum. Application of compressive strain decreased the minimum electrical resistance further, thus resulting in higher linearity and correlation coefficients.

The reported results are important for development and use of smart concrete. Smart concrete can be used in critical elements of the structures (i.e. 1st story columns etc.) and in precast concrete structures, where manufacturing is more controlled. Data collection can be continuous by wireless technology or intermittent

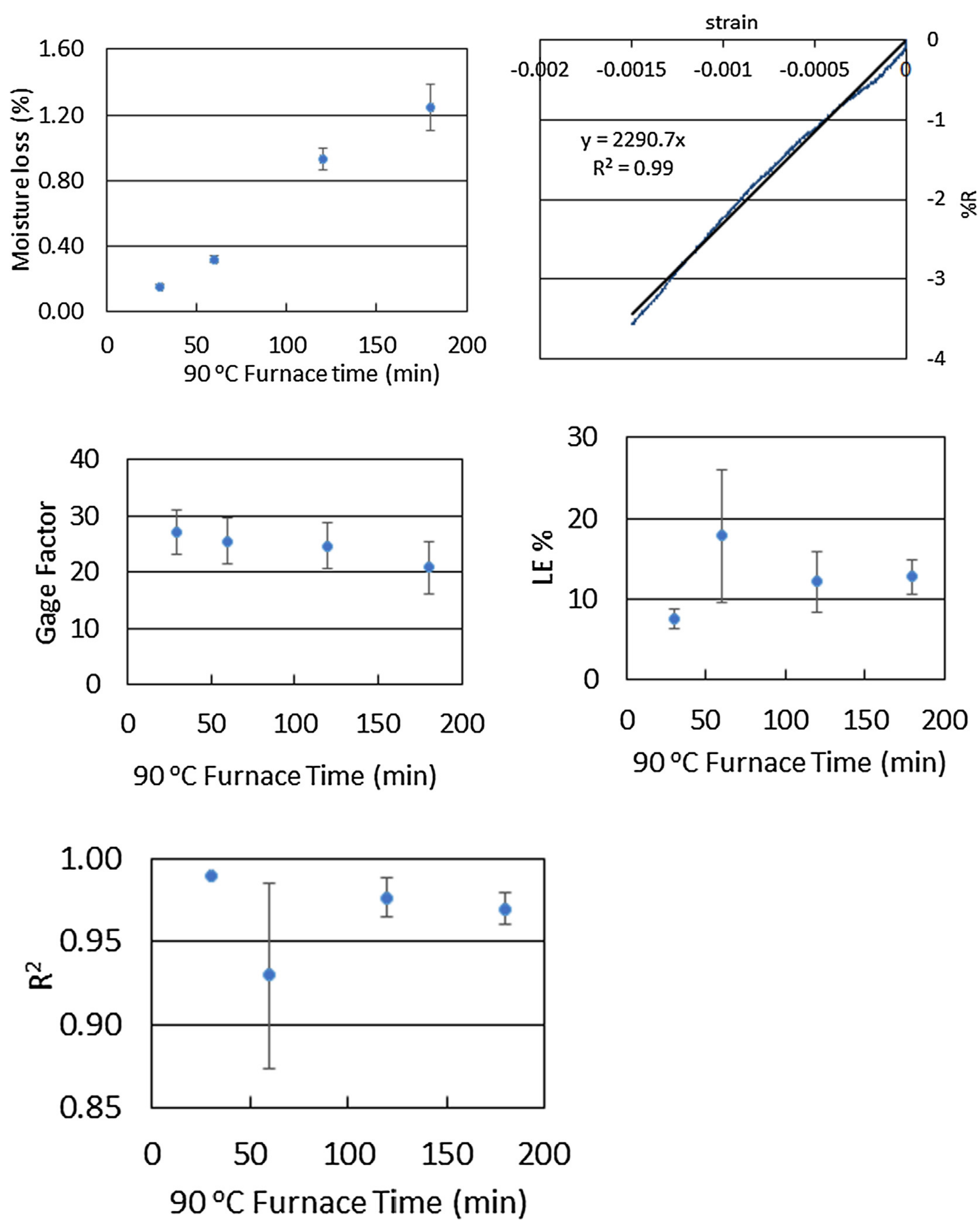

Fig. 7. (a) Moisture loss with 90 °C furnace time. (b) Compressive strain – %R relationship (c) Gage factor – 90 °C furnace time. (d) Linearity error – 90 °C furnace time. (e) R^2 – 90 °C furnace time.

where a technician can acquire data after a major event (i.e. earthquake, impact load etc.) or periodically for maintenance planning. In continuous systems, the system can alert the residents, technicians, etc. to evacuate the structure (building, bridge, tunnel…) in case of danger.

4. Conclusions

The effects of temperature and moisture on electrical resistance and strain sensitivity of smart concrete with brass fiber addition were determined, and the following conclusions were obtained:

1. There is a linear relationship between temperature and electrical resistance of the material at temperatures between 25 °C and 50 °C. Therefore, temperature compensation may be possible for strain sensing applications.
2. At higher temperatures, the mismatch strain between brass fibers, cement paste and aggregate developed damage, which resulted in an increase of the electrical resistance, especially after 150 °C. Therefore, the smart concrete can be used as a fire alarm sensor due to its sensitivity to temperature change.
3. There is an optimal moisture content from a resistivity point of view. Electrical resistance decreased initially as samples dried. When the optimal moisture was reached, the water loss led to a direct fiber-fiber contact, while the water in micro voids acted as electrolyte.
4. However, for lower moisture contents, the electrolyte was lost and the electrical resistance was increased. This sensitivity of electrical resistance to moisture enables the use of smart concrete as moisture sensor in structures exposed to harmful water.
5. A good strain sensing capacity was observed, as shown by the strong linear relationship between strain and electrical resistance changes. Moisture effects the strain sensitivity.

As a summary, fire, harmful water and moisture effects challenge concrete structures. In this work, the relations between strain sensitivity and electrical resistance with temperature and moisture were determined. Smart concrete can be used as strain, fire alarm and moisture sensor while in service as a load bearing element in critical elements of a structure.

Declaration of Competing Interest

None.

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