Smart Cement for Concrete and Repairing Grout Applications with Real-Time Monitoring and Characterized Using Vipulanandan Models

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Abstract

Cement based concrete and grouts are used in the construction, maintenance and repairing of onshore and offshore infrastructures such as building, highways, bridges, foundations, pipelines, tunnels, storage facilities, oil and wind platforms and all types of wells (oil, gas, water). In order to ensure safety and also to extend the service life of these infrastructures, it is important to monitor the changes in the construction and repair materials with the varying environments. Recently, chemo-thermo-piezoresistive smart cement, which is a highly sensing cement was developed and its potential applications in concrete and cement grouts to make these materials highly sensing must be investigated.

In this study the behavior of concrete and grout made using the piezoresisitive smart cement was investigated to test and model the bulk sensing properties. The coarse aggregate content in the concrete was 75% (by volume). The grout was prepared using water-to-cement (w/c) ratio of 0.8. The concrete and grout property changes during curing were monitored using electrical resistivity, since it can be easily adopted for real-time monitoring. The initial electrical resistivity of smart cement with w/c ratio of 0.38 was 1.02 Ω.m which increased to 3.74 Ω.m. with the addition of 75% aggregate, a 267% increase in the initial electrical resistivity with the addition of aggregates. After 28 days of curing, the electrical resistivity of smart cement was 14.14 Ω.m and with 75% aggregate it increased to 61.24 Ω.m, a 333% increase in the electrical resistivity with the addition of aggregates. Smart grout with piezoresistive behavior was developed using the smart cement with water-to-cement ratio of 0.8. The initial grout resistivity was 1.08 Ω.m and it increased to 9.37 Ω.m in 28 days of curing, a 768% increase in the electrical resistivity. Vipulanandan p-q curing model was used to predict the resistivity changes in the concrete and grout with the curing time. The piezoresistivity of the smart cement without and with 75% aggregate after 28 days of curing were 204% and 101% at the peak compressive stresses of 21.7 MPa and 12.4 MPa respectively. The reduction in the piezoresistivity at peak compressive stress was due to not only the reduction of smart cement content in the composite but also the strength. Compared to the compressive failure strain of 0.3%, the resistivity change for the concrete with 75% gravel after 28 days of curing was over 336 times (33,600%) higher making the concrete with the smart cement binder a highly sensing bulk material. The

piezoresistivity at peak stresses of the smart cement grout after one, seven and twenty eight days of curing were 155%, 156% and 179%. The piezoresisitive behavior of the concrete and grout with smart cement were modeled using the Vipulanandan p-q curing and piezoresistivity model. Based on the coefficient of determination (R^2) and root mean square error (RMSE), Vipulanandan models predicted the experimental results very well.

Introduction

Cement can be used in multiple applications because of some of its unique properties, easy to mix with aggregates/additives and also there are several economical benefits. Concrete is a very popular construction material and has been used for over two thousand years. Concrete with high aggregate content in with a binding agent can be used in the construction of very small to very large structures such as bricks, roads, houses, bridges, pipes, dams, canals, storage, missile silos and nuclear waste containment. To attain the required levels of safety and durability of such structures, mixing proportions and especially aggregate content must be adjusted according to application in order to achieve mechanical requirements which will significantly affect the performance during its life time (Hou et al., 2017). In preparing the concrete and cement slurries, the water-to-cement ratios have been varied from 0.38 to 0.6 based on the mixing method, constituents of the concrete mix and applications (Vipulanandan et al. 2008, 2015a, 2016a, 2018). There are many different testing techniques such as ultrasound, fiber optic, electronic microscopy, X-ray diffraction, thermography and vibro-thermography have been used to study the aging of cement composites and for damage detection (Parvasi et al., 2016). However, many of these methods are difficult to adopt under field conditions where accessibility becomes an issue in deep foundations, buried storage facilities, wells, dams, canals and pipes.

Grouts are used in both construction and also repairing and maintenance of all types of infrastructures, dams and stabilization of soils. The repaired materials are generally evaluated using ultrasonic waves or impact hammer response in the field.

Concrete

Concrete is composed of cement, aggregates, water and additives based on the applications. Cement is the most essential constituent in the concrete, which helps in the binding of the aggregates. The additives and water are part of the cement mix to enhance its performance. Immediately after mixing, the concrete quality is determined using the flow cone method for over nine decades. There is a need for better characterization concrete using material properties which must be easy to adopt in the field.

Grouts

Grout is composed of water with cement and/or polymers that can be easily injected into various types of openings and cracks to achieve the strength and also sealing against liquids and gas leaks. Grouts are used in many applications to not only strength pre-stressed concrete beams, pipes and piles but also repairing and maintaining various types of facilities. Grouts are evaluated using the flow cone method. There is a need for better characterization of grouts using material properties which must be easy to adopt in the field.

Smart Cement

Cement is the largest quantity of material manufactured in the world, 4.2 trillion tons in 2017, and is used in many applications. Chemo-thermo-piezoresisitive smart cement has been recently developed (Vipulanandan et al. 2014-2017) which can sense and real-time monitor the many changes happening inside the cement during cementing of wells to concreting of various infrastructure to the entire service life of the structures. In concrete smart cement is the binder which can sense the changes within the concrete. The smart cement can sense the changes in the water-to-cement ratios, different additives, contamination and pressure applied to the cement sheath or concrete in terms of chemo-thermo-piezoresistivity. The failure compressive strain for the smart cement was 0.2% at peak compressive stress and the resistivity change is of the order of several hundred percentage making it over 500 times (50,000%) more sensitive (Vipulanandan et al. 2014-2017).

Objective

The overall objective of this study was to compare the changes in the electrical resistivity with curing time and the piezoresistive behavior of concrete with up to 75% aggregate (by volume) and smart cement binder. Also develop smart cement grout with highly sensing characteristics. The specific objectives are as follows:

1) Investigate the effect of using smart cement as the binder in concrete with 75% gravel (based on the total volume of concrete) in concrete and evaluate the curing and piezoresistive behavior.
2) Develop smart cement grout and characterize its behavior.
3) Modeling the curing and piezoresisitive behavior of concrete and repairing grout made with smart cement.

Materials and Methods

In this study chemo-thermo-piezoresistive smart cement (Vipulanandan et al. 2014-2018) was used to develop the concrete and grout. For the curing and compressive behavior studies cement slurry was cast in plastic cylindrical molds with diameter of 50 mm and a height of 100 mm. Two conductive wires were placed in all of the molds to measure the changing in electrical resistivity. At least three specimens were tested under each condition investigated in this study.

Sample Preparation

In this study table top blenders were used to prepare the cement and concrete specimens. Concrete specimens were prepared using smart cement with water-cement ratio of 0.38 (Vipulanandan et al. 2015a). Concrete specimens were prepared using 75% coarse aggregates based on the total volume of concrete. Sieve analysis (ASTM C136) was performed to determine the gradation of aggregate and the gradation. The median diameter (Katzer, 2012), which also represents d_{50} (ASTM) the size of 50% of the particles less than 4.2 mm. After mixing, the concrete were placed in 100 mm height and 50 mm diameter cylindrical molds with two conductive flexible wires 1 mm in diameter (representing the probes) were placed 50 mm apart vertically to measure the electrical resistance. The specimens were cured up to 28 days under relative humidity of 90%. At least three specimens were test under each condition and the average values are presented in the figures, tables and discussion.

Smart cement (sensing cement): Class H oil well cement was mixed with conductive filler (metallic fibers, carbon fibers or a mixture with diameter in the micrometer range) to make it piezoresistive material (Vipulanandan et al., 2014a, b; 2015a, b).

Cement Grout Mixture

Sensing cement grout was prepared by adding water (w/c ration of 0.8) in this study. Commercially available table top mixture was used at a speed of 1000 rpm for five minutes. Conductive fillers were added during the mixing process. The test specimens were prepared in plastic cylindrical molds. All specimens were capped to minimize moisture loss and were cured under room condition (23^{o}C and relative humidity of 50%) up to the day of testing for the changes in resistivity with applied stress (piezoresistivity) under compressive loading.

Repairing damaged sensing cement

After testing the one day old cylindrical sensing cement specimens to failure the samples with micro cracks along the length of the specimens were submerged in the grout solutions for three hours. The damaged sensing cement specimens had the wires in place inside the cement at 50.8 mm apart. The specimens were cured under room temperature after repairing for one day before testing. The weight and resistance of the specimens were monitored to determine moisture loss and change in the electrical resistivity before the compressive changes in resistivity with applied stress test performed on the repaired specimens.

Electrical Resistivity

Two different devices were used to measure the changes in the electrical resistivity of concrete and grout immediately after mixing up to the time they solidify. Both of the electrical resistivity devices were calibrated using the standard solutions of sodium chloride (NaCl).

Conductivity Probe

A commercially available conductivity meter was used to measure the conductivity (inverse of electrical resistivity). The conductivity measuring range was from 0.1μS/cm to 1000 mS/cm, representing a resistivity of 100,000 Ω.m. to 0.01 Ω.m. respectively.

Digital Resistivity Meter

The digital resistivity meter measured the resistivities in the range of 0.01Ω-m to 400 Ω-m.

Electrical Resistance

LCR meter (inductance (L), capacitance (C), and resistance (R)) was used to monitor the electrical resistance of the specimens during the curing time. Two wire method with AC at 300 kHz frequency was used in order to minimize the contact resistances (Vipulanandan et al. 2013). During the initial stage of curing both the electrical resistivity (ρ) electrical resistance (R) were measured to determine the parameter K based on the Eqn.1.

$$R = \rho * \left(\frac{L}{A}\right) = \rho K \quad (1)$$

Where L is the distance between two points where resistance is measured, A is the cross-sectional area through which the current is flowing. The ratio L/A is called the geometry factor (nominal K_n) and used for conductive materials. In this study, electrical resistance (R) and electrical resistivity (ρ) were measured independently during the initial curing period and the effective calibration factor (K_e) for the materials used in this study (insulators) were determined experimentally. For the smart cement and concrete Parameter K_e became stable (constant) in two to three hours. The Parameter K_e was more than double than the Parameter K_n for the specimens tested.

Normalized change in resistivity $\Delta\rho$ with the changing conditions can be represented as follows:

$$\frac{\Delta\rho}{\rho} = \frac{\Delta R}{R} \quad (2)$$

The modified cement material is represented in terms of resistivity (ρ) and the changes due to stress will be quantified to evaluate the sensitivity of the material.

Two Wire Method

The change in resistance was measured using the two probe method with the LCR meter. To minimize the contact resistances, the resistance was measured at 300 kHz using two-wire method. This configuration was first calibrated using the same liquid (cement slurry) to determine the parameter K in Eqn. (1).

Compression Test (ASTM C39)

The cylindrical specimens 9concrete, cement and grout) were capped and tested at a predetermined controlled displacement rate. Tests were performed in the Tinious Olsun machine at a controlling the displacement rate to 0.125 mm per minute. In order to measure the strain, a commercially available extensometer (accuracy of 0.001% strain) was used. During the compression test, the change in resistance was measured continuously using the LCR meter. Two probe method with alternative current (AC) at 300 kHz frequency was used in order to minimize the contact resistances (Vipulanandan and Amani, 2015). The change in resistance was monitored using the two-probe method, and the parameter in Eqn. (2) was used relate the changes in resistivity to the applied stress.

Modeling

I. Vipulanandan Curing Model

In order to represent the electrical resistivity development of the cement, Vipulanandan Curing model was used (Vipulanandan and Mohammed, 2015) and the relationship is as follows:

$$\frac{1}{\rho} = \frac{1}{\rho_{min}}\left[\frac{\left(\frac{t+t_0}{t_{min}+t_0}\right)}{q_1+(1-p_1-q_1)\left(\frac{t+t_0}{t_{min}+t_0}\right)+p_1\left(\frac{t+t_0}{t_{min}+t_0}\right)^{\left(\frac{p_1+q_1}{p_1}\right)}}\right] \quad (3)$$

Where ρ is the electrical resistivity in Ω.m, ρ_{min} is the minimum electrical resistivity in Ω.m, t_{min} is the time corresponding to the minimum electrical resistivity (ρ_{min}), t represents the curing time, t_0 is the model parameter influenced by the initial resistivity and p_1 and q_1 are time-dependent model parameters as follows:

$$p_1 = p_{1_0} + \frac{t}{A+B.t} \quad (4)$$

$$q_1 = q_{1_0} + \frac{t}{A\prime+B\prime.t} \quad (5)$$

In which p_{1_0}, A, $B(min)^{-1}$, q_{1_0}, $A'$and $B'(min)^{-1}$ are model parameters.

II. Vipulanandan Piezoresistivity Model

In order to represent the piezoresistive behavior of the hardened cement, Vipulanandan Piezoresistivity Model (Vipulanandan et al., 2015, 2016) was used and the relationship is as follows:

$$\sigma = \frac{\sigma_{max}\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)}{q_2+(1-p_2-q_2)\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)+p_2\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)^{\left(\frac{p_2+q_2}{p_2}\right)}} \quad (6)$$

Where σ_{max} is the maximum stress, $(\Delta\rho/\rho)_0$ is the piezoresistivity of the hardened cement under the maximum stress and p_2 and q_2 are model parameters influenced by the material properties.

III. Vipulanandan Impedance Model

Vipulanandan et al. (2013) studied different possible equivalent circuits for composite materials with two probes measurement and found appropriate equivalent circuits to represent materials.

Case 1: General Bulk Material – Capacitance and Resistance

In the equivalent circuit for Case1, the contacts were connected in series, and both the contacts and the bulk material were represented using a capacitor and a resistor connected in parallel. In the equivalent circuit for Case 1, R_b and C_b are resistance and capacitance of the bulk material, respectively; and R_c and C_c are resistance and capacitance of the contacts, respectively. Both contacts are represented with the same resistance (R_c) and capacitance (C_c), as they are identical. Total impedance of the equivalent circuit for Case 1 (Z_1) can be represented as:

$$Z_1(\sigma) = \frac{R_b(\sigma)}{1+\omega^2 R_b^2 C_b^2} + \frac{2R_c(\sigma)}{1+\omega^2 R_c^2 C_c^2} - j\left\{\frac{2\omega R_c^2 C_c(\sigma)}{1+\omega^2 R_c^2 C_c^2} + \frac{\omega R_b^2 C_b(\sigma)}{1+\omega^2 R_b^2 C_b^2}\right\}, \quad (7)$$

where ω is the angular frequency of the applied signal. When the frequency of the applied signal is very low, $\omega \rightarrow 0$, $Z_1 = R_b + 2R_c$, and when it is very high, $\omega \rightarrow \infty$, $Z_1 = 0$.

Case 2: Special Bulk Material - Resistance Only

Case 2 is a special case of Case 1 in which the capacitance of the bulk material (C_b) is assumed to be negligible. The total impedance of the equivalent circuit for Case 2 (Z_2) is

$$Z_2(\sigma) = R_b(\sigma) + \frac{2R_c(\sigma)}{1+\omega^2 R_c^2 C_c^2} - j\,\frac{2\omega R_c^2 C_c(\sigma)}{1+\omega^2 R_c^2 C_c^2}\,. \quad (8)$$

When the frequency of the applied signal is very low, $\omega \rightarrow 0$, $Z_2 = R_b + 2R_c$, and when it is very high, $\omega \rightarrow \infty$, $Z_2 = R_b$ (Fig. 1).

The shape of the curves shown in Figure 2 is very much influenced by material response and the two probes used for monitoring. Testing of smart cement and concrete indicated that Case 2 represented their behaviors and hence the bulk material properties can be represented by resistivity and characterized at a frequency of 300 kHz using the two probes.

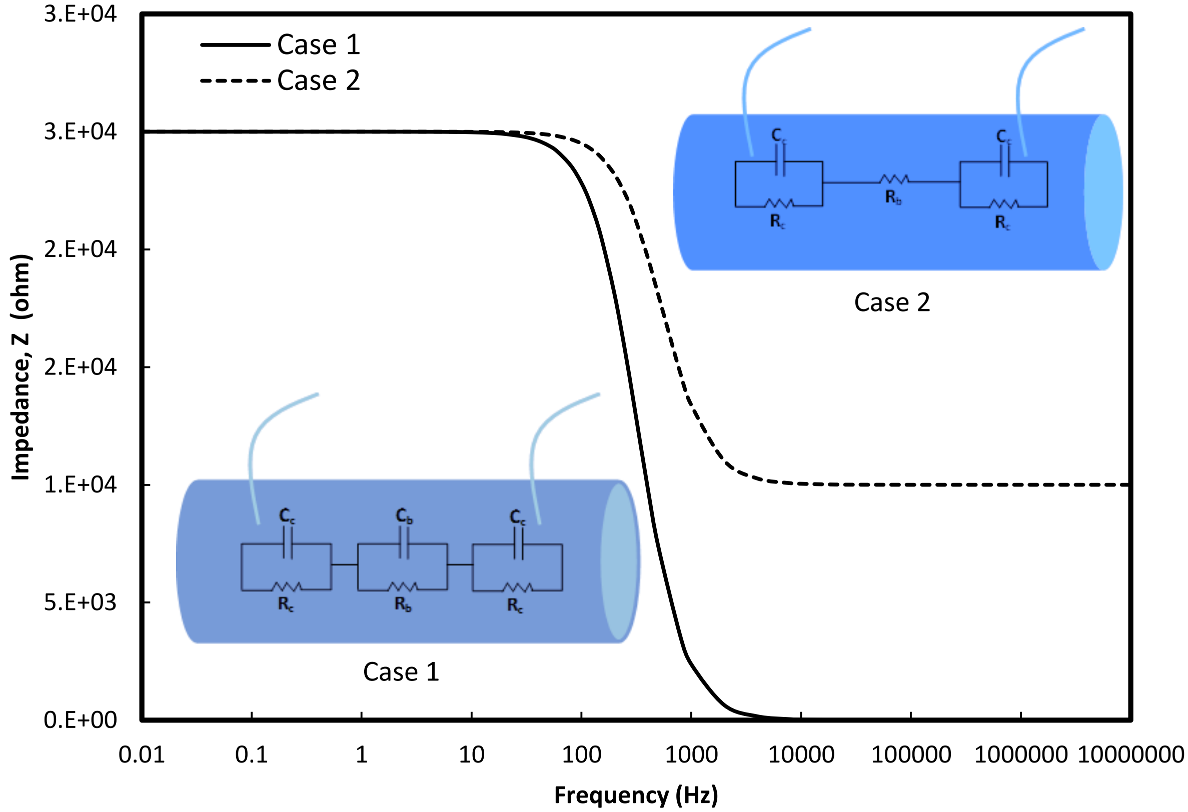


Figure 1. Vipulanandan impedance-frequency models for composite materials

Results and Analyses

Electrical Resistivity

Impedance Vs Frequency Relations

Investigation of the impedance versus frequency relationship tested immediately after mixing and also after 28 days of curing for smart cement composites is shown in Figures 2 and 3. The observed shape of the curve represents the Case 2, indicating that the bulk material can be represented by resistance.

Initial resistivity

Initial electrical resistivity increased with the addition of aggregates.

(a) Smart Cement:

The average initial electrical resistivity of the smart cement was 1.02 Ω.m.

(b) Smart Cement Composite:

75% Gravel: The average initial electrical resistivity of the 75% gravel smart composite increased by 267% to 3.74 Ω.m. this extraordinary increment is due to gravel content in the concrete.

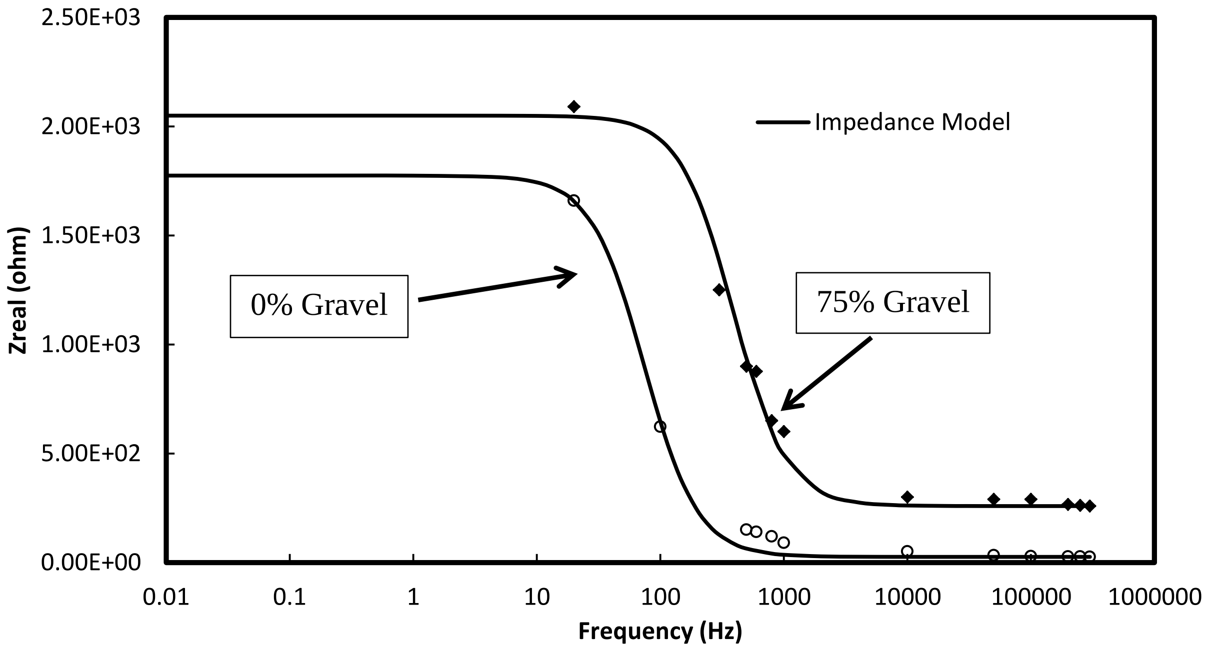


Figure 2. Impedance Characterization of the Smart Cement Composites Immediately after Mixing

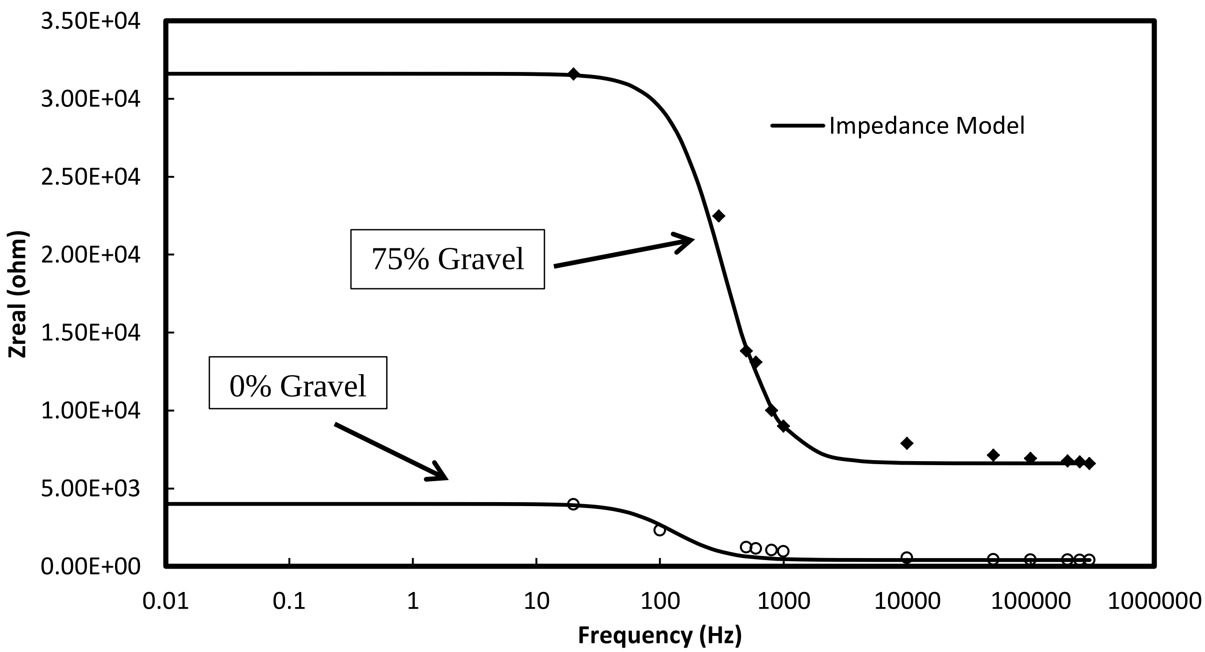


Figure 3. Impedance Characterization of the Smart Cement Composites after 28 Days of Curing

Resistivity during curing

Electrical resistivity of a concrete is determined mainly by the porosity and conductive ion concentration in the pore solution. From the standpoint of conductivity, concrete can be regarded as a two-component composite material, pore solution and solid phase (aggregate + hydration products + unhydrated binders) (Xiao and Li, 2008). During the setting of the cement, the capillary porosity is constant and changes in the pore solution resistivity leads to determine the evolution of the slurry resistivity (Zhiyong Liu et al., 2014). As shown in Figure 10, the pore solution resistivity decreased initially and reached a minimum resistivity of ρ_{min} at specific time of t_{min} which is due to increment of ionic concentration in pore solution. By preceding the hydration, production of C-S-H network caused later increment in bulk paste resistivity (Jie Zhang et al., 2009).

(a) Smart Cement:

The minimum electrical resistivity of the smart cement after 90 minutes of mixing was 0.79 Ω.m (Table 1, Figure 4).

(b) Smart Cement Composite:

75% Gravel: The minimum electrical resistivity of the 75% gravel smart composite increased by 339% to 3.46 Ω.m. The time corresponds to the minimum resistivity of 75% gravel smart composite reduced by 30 minutes to 60 minutes compare to no gravel smart cement composite.

Table 1. Electrical resistivity parameters of the smart cement composites slurries

Smart Cement Composite (by volume)	ρ_0 $(\Omega.m)$	ρ_{min} $(\Omega.m)$	t_{min} $(minute)$	ρ_{24} $(\Omega.m)$	$\frac{\rho_{24}-\rho_{min}}{\rho_{min}}$ %
No Gravel	1.02	0.79	90	5.14	550%
75% Gravel	3.74	3.46	60	20.01	478%

Long term resistivity

After the setting time, hardened cement composite has a complete connected network which leads to form percolated path of C-S-H causing high resistivity due to its continuous gel micropores. Later, volume fraction of C-S-H will play the main role in changes of the resistivity of the cement composites. (Liu et al., 2014).

(a) Smart Cement:

*A*fter 28 days of curing, the electrical resistivity of smart cement was 14.14 Ω.m. (Fig. 5).

***(b) Smart Cement Composites**:*

75% Gravel: After 28 days of curing the electrical resistivity of 75% gravel smart cement composite increased by 333% to 61.24 Ω.m.

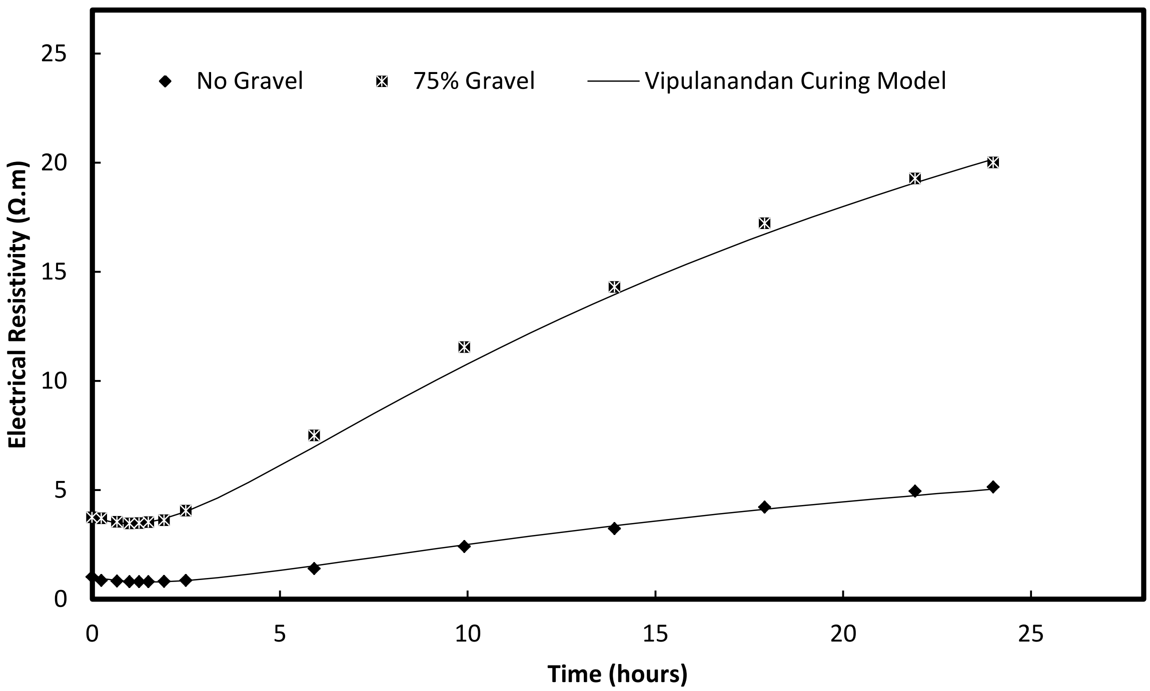


Figure 4. Development of electrical resistivity of smart cement composites during the initial 24 hours of curing

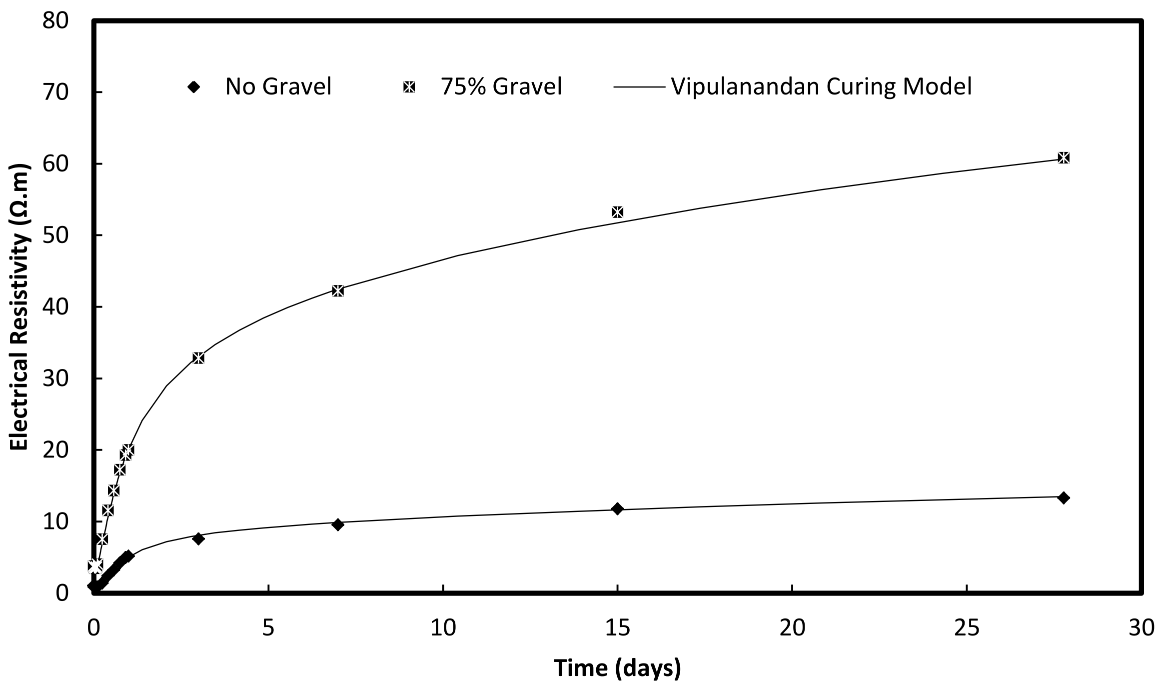


Figure 5. Development of electrical resistivity of smart cement composites during 28 days of curing

Table 2. Curing Model parameters of p-q model for evaluating the electrical resistivity of the smart cement composites during 28 days of curing

Smart Cement Composite	q_{1_0}	A'	B'	p_{1_0}	A	B	t_0	t_{min}	ρ_{min}	R^2	$RMSE$
No Gravel	0.75	130	1.65	1.21	2000	0.24	100	90	0.79	0.99	0.18
75% Gravel	0.91	100	1.09	2.59	1000	0.15	130	60	3.46	0.99	0.44

Both Parameters **B** and **B′** are $(min)^{-1}$

Compressive Strength

Compressive strength of smart concrete was tested after 1 and 28 days of curing.

1 day curing

(a) Smart Cement:

After 1 day of curing, the compressive strength of the smart cement was 8.6 MPa.

(b) Concrete:

75% Gravel: The compressive strength of the 75% gravel smart composite decreased by 29% to 6.1 MPa compare to the smart cement with no gravel.

28 days curing

(a) Smart Cement:

After 28 days of curing, the compressive strength of the smart cement was 21.7 MPa.

(b) Concrete:

75% Gravel: The compressive strength of the 75% gravel concrete decreased by 43% to 12.4 MPa compare to the smart cement with no gravel.

Changes in compressive strength of the concrete can be justified with the percentage of cement in the concrete.

Piezoresistivity

Piezoresistive behavior of smart cement composites was evaluated after 1and 28 days of curing.

1 day curing

(a) Smart Cement:

After 1 day of curing, the piezoresistivity of the smart cement at the peak compressive stress was 375% (Fig. 6. Table 3). Parameters p_2 and q_2 for the model were 0.61 and 0.57 respectively.

(b) Smart Cement Composites:

75% Gravel: The piezoresistivity of the 75% gravel smart composite reduced by 57% to 163% compare to the smart cement. Parameters p_2 and q_2 for the model were 0.40 and 0.80 respectively.

28 days curing

(a) ***Smart Cement:***

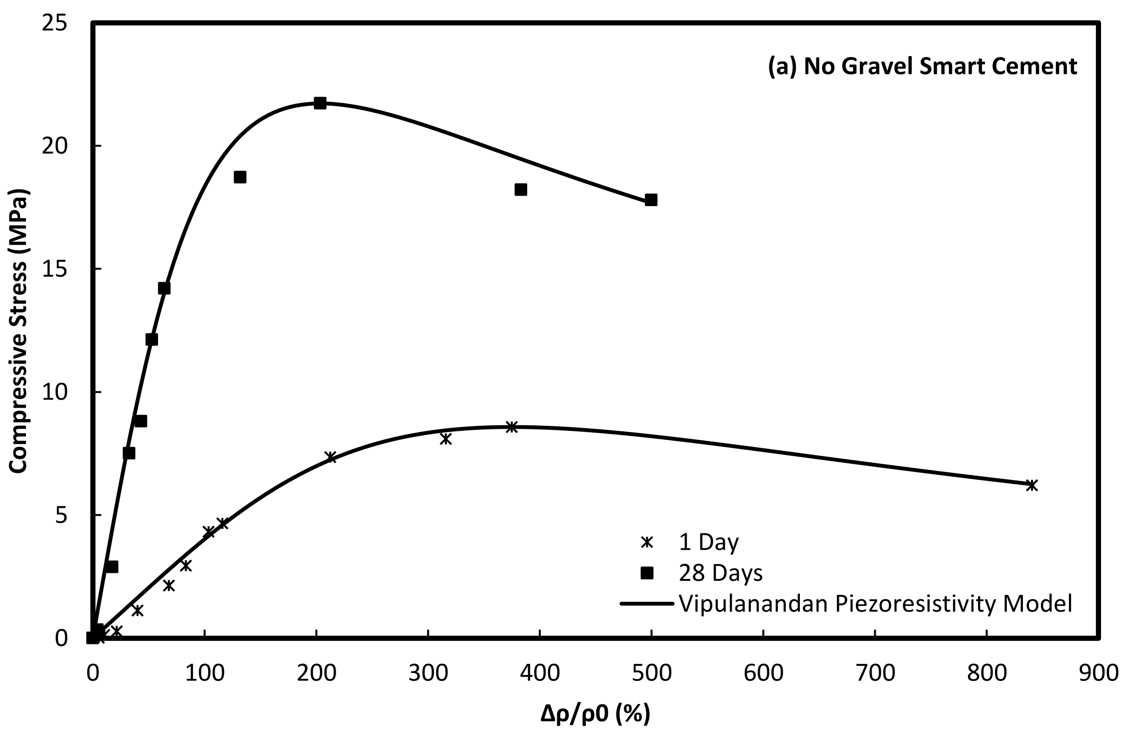
After 1 day of curing, the piezoresistivity of the smart cement was 204%. Parameters p_2 and q_2 for the model were 0.83 and 0.42 respectively.

(b) ***Concrete:***

75% Gravel: The piezoresistivity of the 75% gravel smart composite reduced by 51% to 101% compare to the smart cement. Parameters p_2 and q_2 for the model were 0.81 and 0.40 respectively.

Table 3. Model parameters of p-q model for evaluating the piezoresistivity behavior of the concrete

Smart Cement Composite	p_2	q_2	R^2	*Compressive Strength (MPa)*	*Ultimate Piezoresistivity (%)*	*RMSE (MPa)*
1 Day Curing						
No Gravel	0.61	0.57	0.99	8.6	375	0.3
75% Gravel	0.40	0.80	0.99	6.1	163	0.3
28 Days Curing						
No Gravel	0.83	0.42	0.98	21.7	204	1.0
75% Gravel	0.81	0.40	0.99	12.4	101	0.4



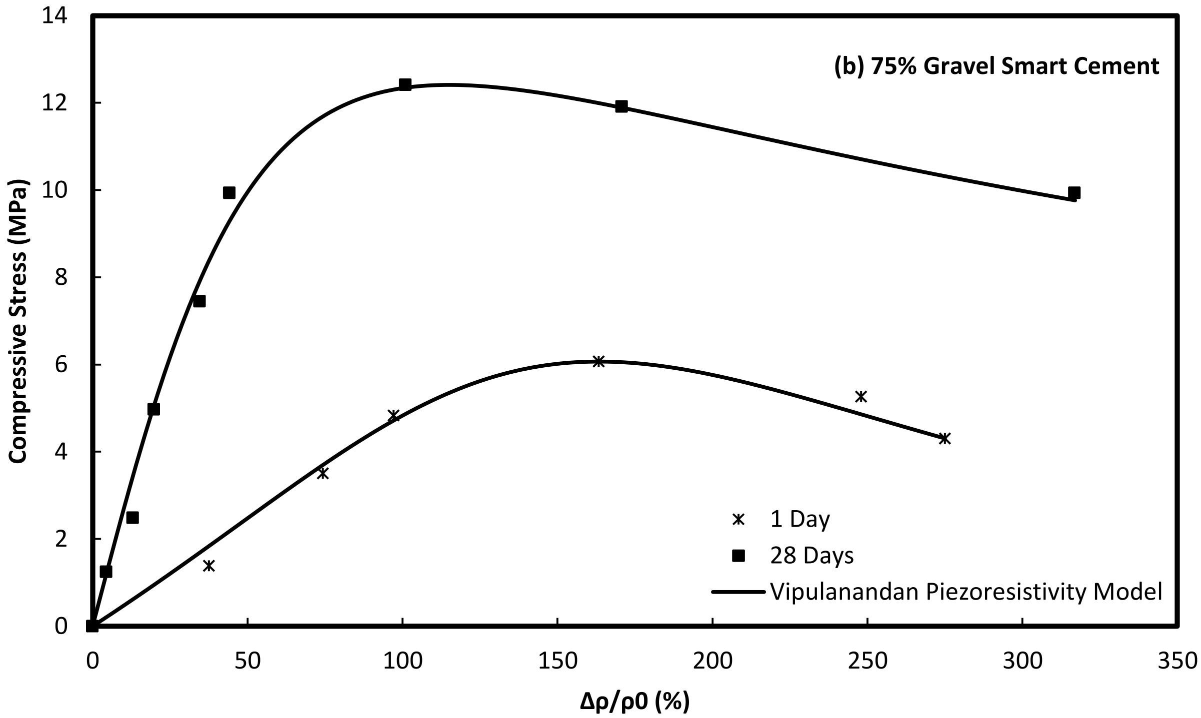


Figure 6. Piezoresistivity of smart cement composites after 1 and 28 days of curing: (a) No gravel and (b) 75% Gravel

Grout

Curing

The observed trend for the resistivity change with time was similar to what was observed for the concrete. The minimum resistivity and time to reach the minimum resistivity are summarized in Table 4. The resistivity after 28 days of curing wa 9.37 Ωm.

Table 4. Model parameters for the curing model of the resistivity of smart cement grout with and without SS cured at room temperature up to 28 days

Mix Type	Curing Time (day)	ρ_{min} (Ω.m)	t_{min} (min)	p_1	q_1	t_o (min)	RMSE (Ω.m)	R^2
Grout (H, w/c=0.8 only)	1 day	1.04	180	0.286	0.188	63	0.04	0.98
Grout (H, w/c=0.8 only)	28 days	1.04	180	0.710	0.295	110	0.45	0.97

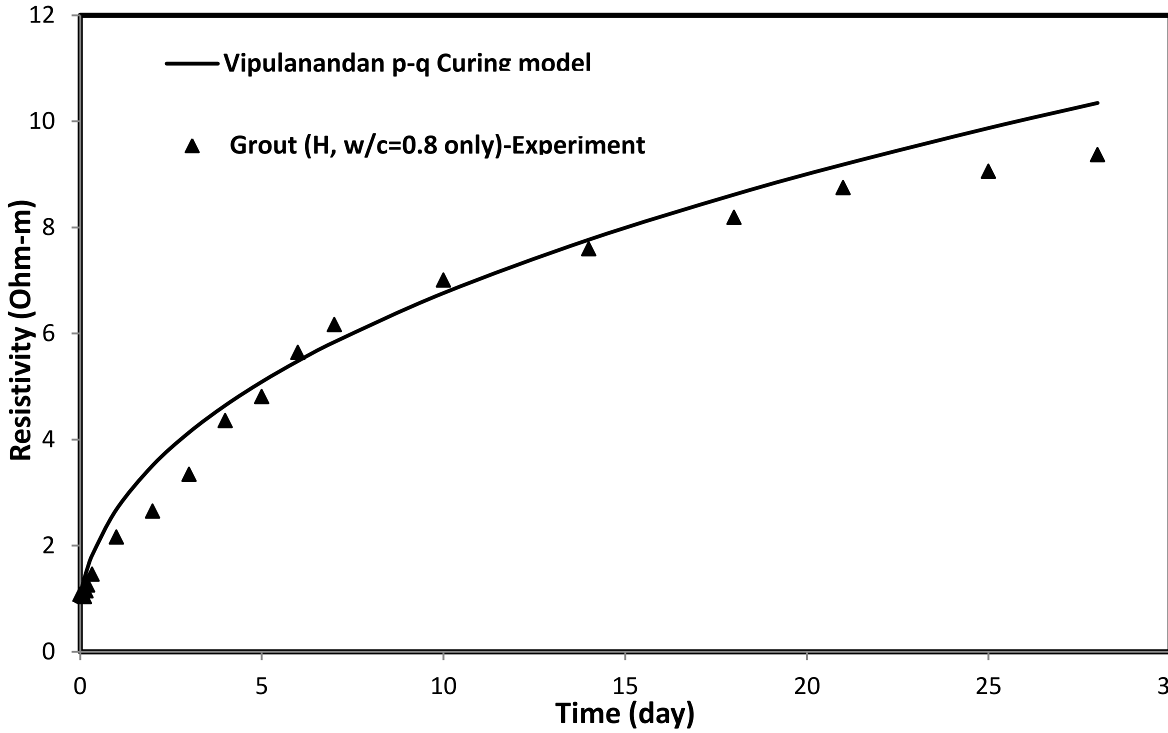


Figure 7. Variation of the resistivity with time for smart cement grouts up to 28 days of curing and modeled using the Vipulanandan p-q curing model.

Piezoresistive Behavior

The change in sensing property at failure $\left(\frac{\Delta\rho}{\rho_o}\right)_f$ for the sensing cement grout only after one, seven and twenty eight days of curing were 155%, 156% and 179%. Using the Vipulanandan p-q piezoresistive model (Eqn. (8)), the relationships between compressive stress and the change in sensing property $\left(\frac{\Delta\rho}{\rho_o}\right)$ of the sensing cement grout with and without SS for one, seven and twenty eight days of curing were modeled. The piezoresistive model (Eqn. (8)) predicted the measured stress-change in resistivity relationship very well (Fig. 3, Fig. 4, Fig. 5). The model parameters q_2 and p_2 are summarized in Table 3. The R^2 were 0.95 to 0.99. The root mean square of error (RMSE) varied between 0.04 MPa and 0.64 MPa as summarized in Table 3.

Table 3. Peak stress, piezoresistivity, model parameters p_2, and q_2 for the piezoresistivity model for the smart cement grout cured after 1 day, 7 days and 28 days.

Mix Type	Curing Time (day)	Strength σ_f (MPa)	Piezoresistivity at peak stress, $(\Delta\rho/\rho_o)_f$ (%)	p_2	q_2	R^2	RMSE (MPa)
Grout (H, w/c=0.8 only)	1 day	2.96	155	0.031	0.607	0.99	0.08
Grout (H, w/c=0.8 only)	7 days	9.94	156	0.035	0.642	0.99	0.18
Grout (H, w/c=0.8 only)	28 days	16.47	179	0.012	0.613	0.99	0.10

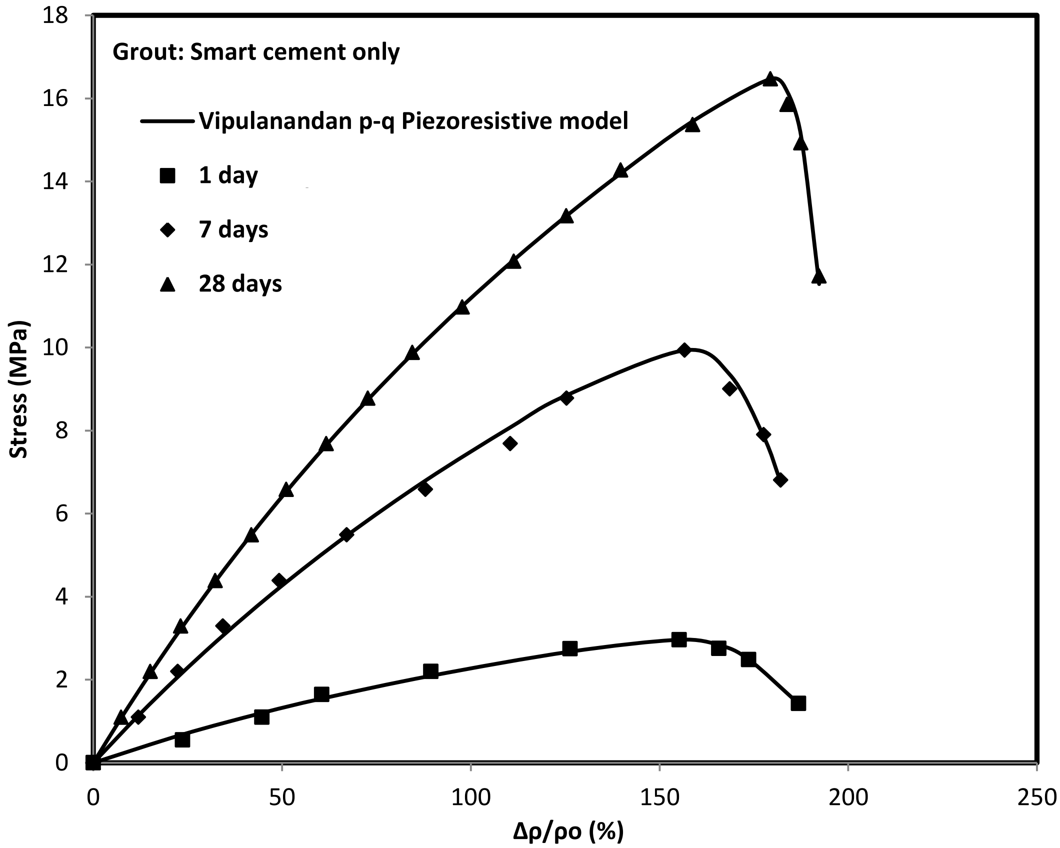


Figure 8. Piezoresistive responses of the smart cement grout after one day, seven days and twenty eight days of curing and modeled with Vipulanandan p-q piezoresistive model.

Repaired sensing cement

Several one day cured sensing cement specimens (0.38 w/c ratio) were used for the repair study after failing the specimen under compression loading (Vipulanandan et al. 2014a, b; 2015a, b). The compressive strength of the one day cured sensing cement varied from 10.81 MPa to 12.00 MPa (Table 4). The resistivity change of the one day cured sensing cement at peak stress varied from 268% to 300% and the data on the repaired specimens are summarized in Table 4.

Strength

Sensing cement grout was used to repair the sensing cement specimen with a strength of 12.00 MPa and 300% changes in resistivity with applied stress at failure. After submerging the damaged specimen for 3 hours in the grout, it was cured for one day and tested under compression load. The percentage weight change in the repaired specimen was 0.24%. The compressive strength of the repaired specimen was 10.09 MPa, a 84% strength recovery, the highest strength recovery.

Piezoresistive behavior

The changes in sensing property with applied stress (Δρ/ρ %) at 4 MPa for the repaired sample was 15% compared to the sensing cement 86%, recovery of 18%. The change in sensing property at failure (Δρ/ρ %)$_f$ for the repaired specimen was 48% at peak stress of 10.09 MPa. The sensing property change in sensing cement at 10.09 MPa was 234%. Hence smart grout repair resulted in 21% recovery of the change in sensing property with applied stress behavior (Fig. 9).

Table 4: Peak stress, piezoresistivity, model parameters p_2 and q_2 for the piezoresistivity model for the smart cement specimens repaired with grout after 1 day.

Mix Type	Curing Time (day)	Strength σ_f (MPa)	Piezoresistivity at peak stress, $(\Delta\rho/\rho_o)_f$ (%)	p_2	q_2	R^2	RMSE (MPa)	Strength Regain (%)	Piezoresistivity Regain* (%)
Initial smart cement	1 day	12.00	300	0.01	0.693	0.99	0.14	N/A	N/A
Repaired cement with grout (H, w/c=0.8 only)		10.09	48	0.039	0.601	0.99	0.19	84	21

* At the failure stress of the repaired specimen

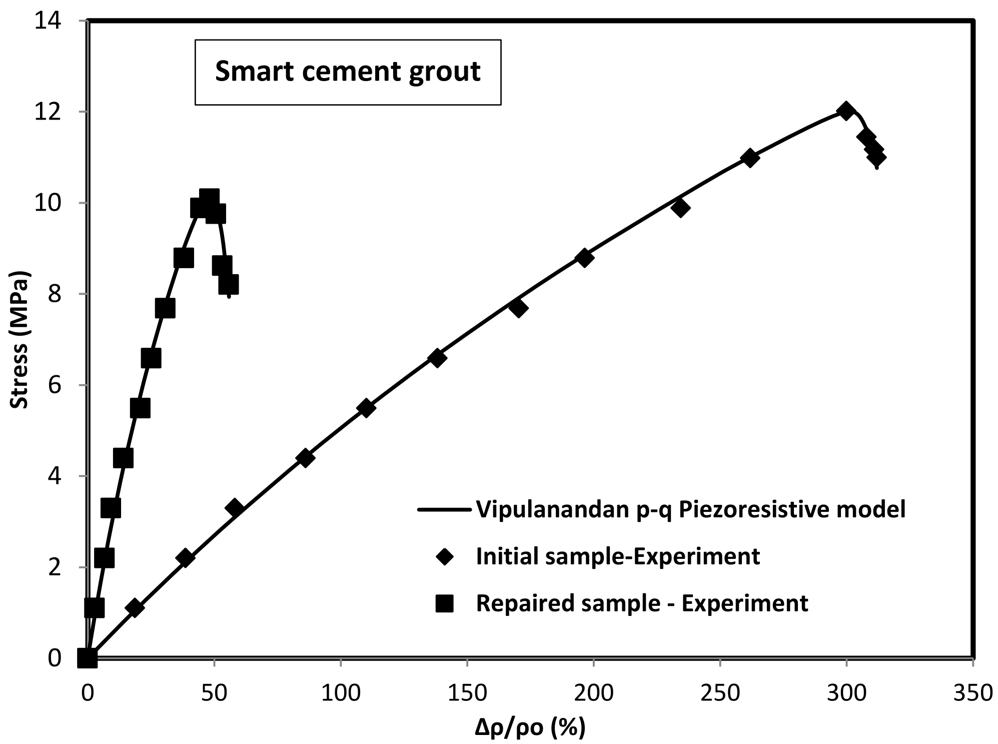


Figure 9. Comparing the predicted and measured compressive stress-resistivity change relationships for smart cement before and after repairing with smart cement grout after one day of curing.

Conclusions

The smart cement was used as the binder in the concrete to make it a highly bulk sensing concrete. Also smart grout was developed using the smart cement with water-to cement ratio of 0.6. Based on experimental and analytical study on the behavior of concrete and grout following conclusions are advanced:

1. Addition of coarse aggregate and curing time increased the initial electrical resistivity of the smart cement composite as well as long term electrical resistivity. The initial electrical resistivity of smart cement was 1.02 Ω.m which increased to 3.74 Ω.m. with 75% gravel respectively. After 28 days of curing, the electrical resistivity of smart cement was 14.14 Ω.m which increased to 61.24 Ω.m. with 75% gravel respectively. Also Vipulanandan Curing Model predicted the electrical resistivity development in th concrete very well.
2. The piezoresistivity of the smart cement with 0% and 75% gravel content after 28 days of curing were 204% and 101% at a peak compressive stress respectively. Vipulanandan Piezoresistivity Model can be used to predict the piezoresistivity behavior of the smart cement composites very well.
3. The failure strain of concrete is 0.3%, hence piezoresisitive concrete has magnified the monitoring resistivity parameter by 336 times (33,600%) or more higher based on the aggregate content and making the concrete a bulk sensor.
4. The smart cement grouts showed change in sensing property with applied stress behavior under compressive stress. The piezoresisitivity at peak stress increased from 155% to 179% with curing time.
5. The repaired smart cement showed piezo-sensing property. The strength regained was 84% and the piezo-sensing property regained was 42%.

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