Smart Cement Integrated with Real-Time Monitoring for Construction and Repairing of Various New and In-service Infrastructures

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Abstract

Smart cement is a highly sensing binder that can be used in multiple infrastructure applications in new constructions and also integrated into in-service infrastructures for real-time monitoring. In new construction the smart cement can be used as the binder in the concrete to make it highly sensing and then used in the construction of onshore and offshore infrastructures. The piezoresisitive axial strain at peak stress for the concrete with smart cement was over hundred percent which is 336 times (33,600%) higher compared to the concrete failure strain of 0.3%. Also smart cements can be used as cement grouts for construction, maintenance and repairs of infrastructures and also deep oil wells both onshore and offshore. Performance of smart cement grout with water to cement ratio of 0.8 are discussed and the piezoresistive failure strain was over 150%. In order to ensure safety and also to extend the service life of the infrastructures, it is important to monitor the changes in the construction and repair materials with the varying loadings and environments. Hence it is also important to integrate the real time monitoring tools into these applications for monitoring. It is important to monitor the real material property changes in the field and not just the temperature which is not a material property.

A new material characterization method has been developed and was used to identify the critical electrical property of the smart cement and the electrical resistivity was identified as the critical property to monitor. Hence a two probe method was developed to monitor the resistivity changes in the cement. Also a new approach has been developed to wirelessly transfer the two probes monitoring of the changes in resistivity of smart cement, smart concrete and smart grout to the phone. This monitoring method can be used to evaluate the quality of mixing and also curing of the materials with time and the stress changes. Also another new method has been developed using the band pass filters (BPF) to monitor the installation and performance of deep oil and gas wells. This method of monitoring can be used to monitor also deep foundations and also pipelines during construction and maintenance.

For monitoring infrastructures in-service including earth dams, the smart cement blocks of various shapes and sizes with and without aggregates and integrated with the two probe wireless system can be used. The shape and size of the smart cement blocks will depend on the application and the way to integrate it with the in-service infrastructures at the critical locations to be monitor.

Introduction

During the past 200 years cement and concrete have been widely used in many applications and has been well documented. Cement slurries and grouts, based on the water-to-cement ratio, have been used in the construction of shallow and deep oil, gas and water wells both onshore and offshore. Also cement slurries are used to bond the pipes to the formation in horizontal directional drilling. Cement slurries are used to bond the steel casings and pipes to the varying geological formations in the wellbore and also to isolate the formations. In the well application cement has to bond very well with the highly varying natural geological formations with depth and to the human made steel casing and pipes and also has to perform for many decades under varying loading conditions, temperatures, pressures and seismic activities. Hence it is important to monitor the performance of the cement from the time of mixing to the entire service life in-situ (Vipulanandan 2021).

There have been many concrete bridges, highways, dams, buildings, storage facilities, foundations and pipes that have failed over the past hundred years due to loadings, earthquakes, fires and aging. Also dam failures and maintenance are becoming problem around the world and recent failures in Brazil. Failures can result in many types of losses and impact the economy and hence there is a need for real-time monitoring of the changing conditions in the infrastructures.

As the production of oil and gas expands on land and offshore around the world, there are many challenges in well construction beginning at the ground surface and seafloor respectively. Recent case studies on cementing failures have clearly identified several issues that resulted in various types of delays in the cementing operations. Also preventing the loss of fluids to the formations and proper well cementing have become critical issues in well construction to ensure wellbore integrity because of varying down hole conditions (Labibzadeh et al., 2010; Eoff et al., 2009). Hence there is a need for monitoring the cementing operation in real time. At present there is no technology available to monitor the cementing operation real time from the time of placement through the entire service life of the borehole. Also there is no reliable method to determine the length of the competent cement supporting the casing.

Two separate studies have been performed on oil well blowouts offshore in the U.S., one done between the years of 1971 to 1991 and the other study was done during the period of 1992 to 2006, before the deep-water horizon blowout in the Gulf of Mexico in 2010. The two studies clearly identified cementing failures as the major cause for blowouts [Izod et al. 2007]. Cementing failures increased significantly during the second period of study when 18 of the 39 blowouts were due to cementing problems [Izod et al. 2007]. Also the deep-water horizon blowout in the Gulf of Mexico in 2010, where there was eleven fatalities, was due to cementing issues [Carter et al. 2014]. With some of the reported failures and growing interest in environmental safety and economical concerns in the oil and gas industry, integrity of the cement sheath is of major importance. In the past there was no technology available to monitor the cementing operation real time from the time of placement through the entire service life of the wells. Also there is no reliable method to determine the length of the competent cement supporting the casing. With the fluctuating oil prices it is even more important to develop technologies for safe operations and efficient oil and gas production.

It is important to eliminate the failures of the highway bridges, pipelines, dams, oil wells and other infrastructures and highly sensing chemo-thermo-piezoresistive smart cement was recently developed to address these issues. 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, tunnels 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 of 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 (U.S. Patent 10,481,143 (2019) Inventor Vipulanandan) 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. 2014-2021).

Objective

The overall objective was to highlight the potential use of the highly sensing smart cement integrated with real-time monitoring in new and also in-service infrastructures. The specific objectives are as follows:

1) Develop applications in new constructions including concrete based constructions, deep oil wells, deep foundations and other infrastructures.
2) Developing methods to integrate the smart cement blocks and smart cement grouts into in-service infrastructures.

Materials and Methods

In this study chemo-thermo-piezoresistive smart cement (Vipulanandan et al. 2014-2021; Vipulanandan 2021) 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.

(i).Sample Preparation

In this study table top blenders were used to prepare the cement and concrete specimens.

Smart cement (sensing cement): Cement was mixed with 0.1% carbon fibers to make it piezoresistive material (Vipulanandan et al., 2014a, b; 2015a, b).

Smart Cement Grout

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. Carbon 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.

Smart Cement Concrete

Smart cement concrete specimens were prepared using smart cement (less than 0.1% carbon fibers) 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.

(ii). 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 resistivity 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 parameters K and G based on the Eqn.1.

$$\rho = \frac{R}{K+GR} \tag{1}$$

In this study, electrical resistance (R) and electrical resistivity (ρ) were measured independently during the initial curing period and the effective calibration factors (K and

G) for the materials used in this study (insulators) were determined experimentally. For the smart cement and concrete Parameter G = 0 and Parameter K became stable (constant) in two to three hours. The Parameter K was more than double than the nominal Parameter K_n equal L/A where L is the spacing between the measuring wires and A is the cross section for the specimens tested.

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

$$\frac{\Delta\rho}{\rho} = \frac{\Delta R}{R} \tag{2}$$

The smart 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).

(iii). Compression Test (ASTM C39)

The cylindrical specimens (concrete, cement and grout) were capped and tested at a predetermined controlled displacement rate. Tests were performed using 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

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:

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

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.

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:

$$\sigma = \frac{\sigma_{max} \times \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right)}{q_2 + (1 - p_2 - q_2) \times \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right) + p_2 \times \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right)^{\left(\frac{p_2 + q_2}{p_2}\right)}} \tag{4}$$

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.

Material Characterization

It is important to first characterize the materials based on the electrical properties, which can be easily adopted in the field.

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:

$$Z_1(\sigma) = \frac{R_b(\sigma)}{1 + \omega^2 R_b^2 C_b^2} + \frac{2R_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2} - j\left\{ \frac{2\omega R_c^2 C_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2} + \frac{\omega R_b^2 C_b(\sigma)}{1 + \omega^2 R_b^2 C_b^2} \right\}, \tag{5}$$

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

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

$$Z_2(\sigma) = R_b(\sigma) + \frac{2R_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2} - j\frac{2\omega R_c^2 C_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2}. \tag{6}$$

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 1 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.

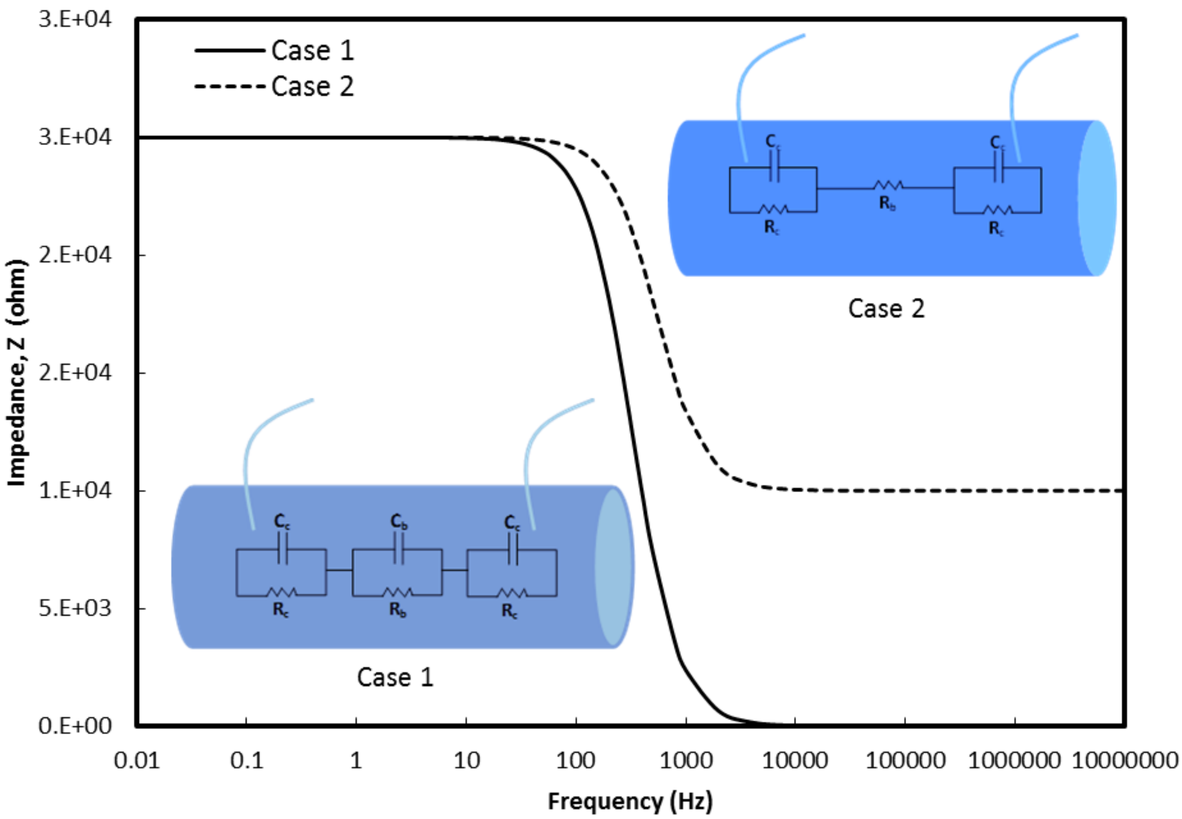

Figure 1. Vipulanandan impedance-frequency models for composite materials

Results and Analyses

Material Characterization

Impedance Vs Frequency Relations

Investigation of the impedance versus frequency relationship tested immediately after mixing and also after 28 days of curing for the smart cement grout and smart cement concrete 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. This has been verified for over 5 years.

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 Concrete:

75% Gravel*:* The average initial electrical resistivity of the smart cement concrete with 75% gravel increased by 267% to 3.74 Ω.m. This increment was due to gravel content in the concrete.

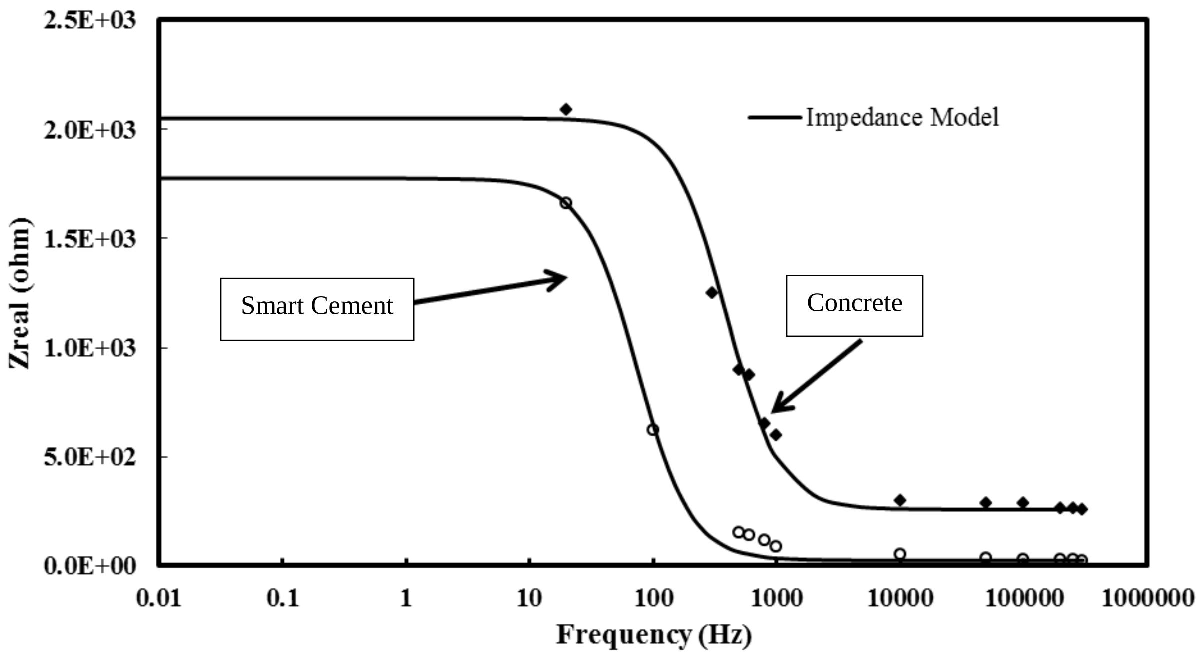

Figure 2. Impedance Characterization of the Smart Cement and Concrete Immediately after Mixing

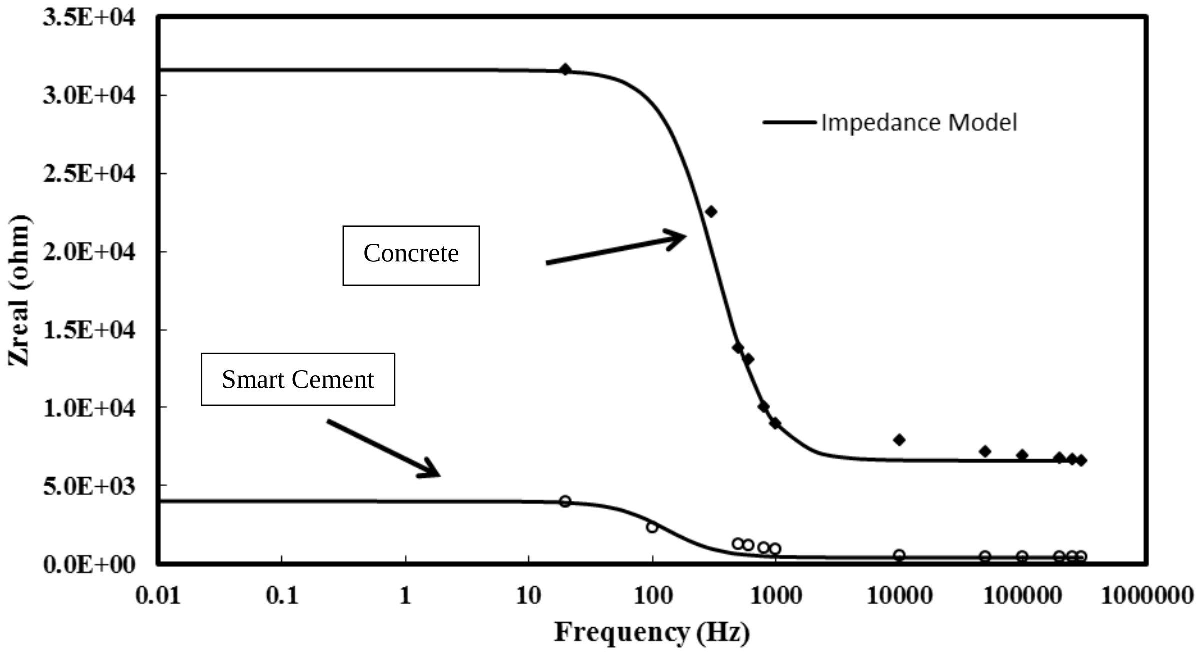

Figure 3. Impedance Characterization of the Smart Cement and Concrete after 28 Days of Curing

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 Concrete:

75% Gravel: The minimum electrical resistivity of the 75% gravel smart cement concrete increased by 339% to 3.46 Ω.m. The time corresponds to the minimum resistivity of 75% gravel smart cement concrete reduced by 30 minutes to 60 minutes compare to the smart cement.

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

Smart Cement Concrete (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%

28 Days

(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 Concrete:

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

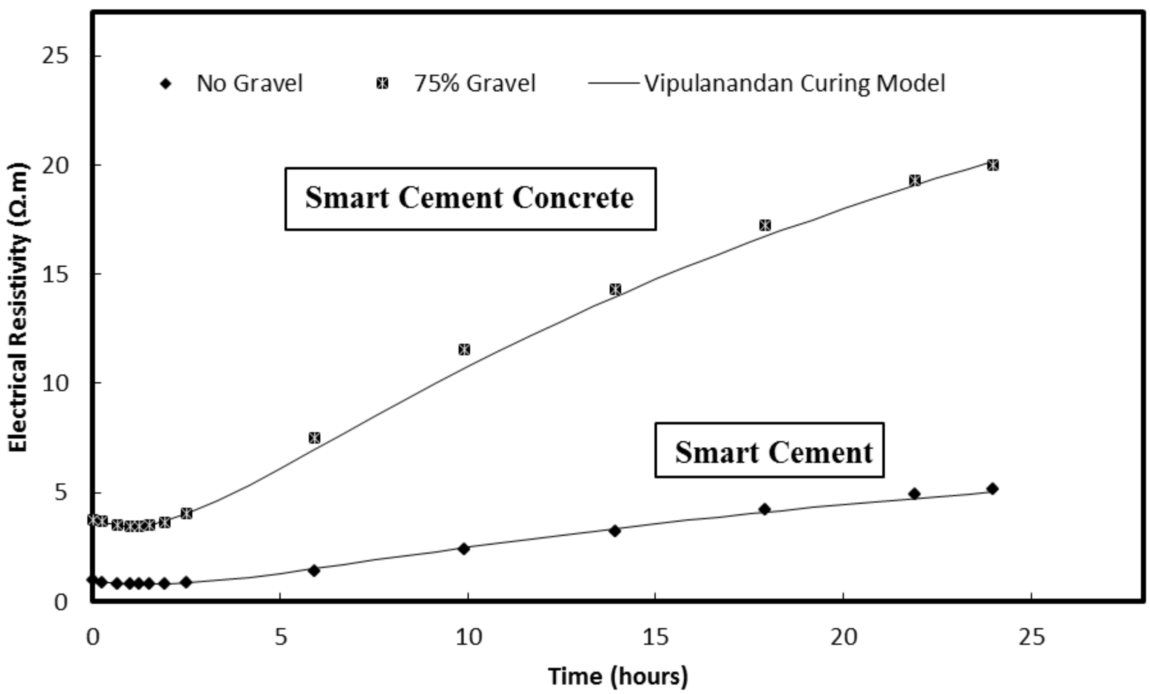

Figure 4. Development of electrical resistivity of smart cement composites during the initial 24 hours of curing

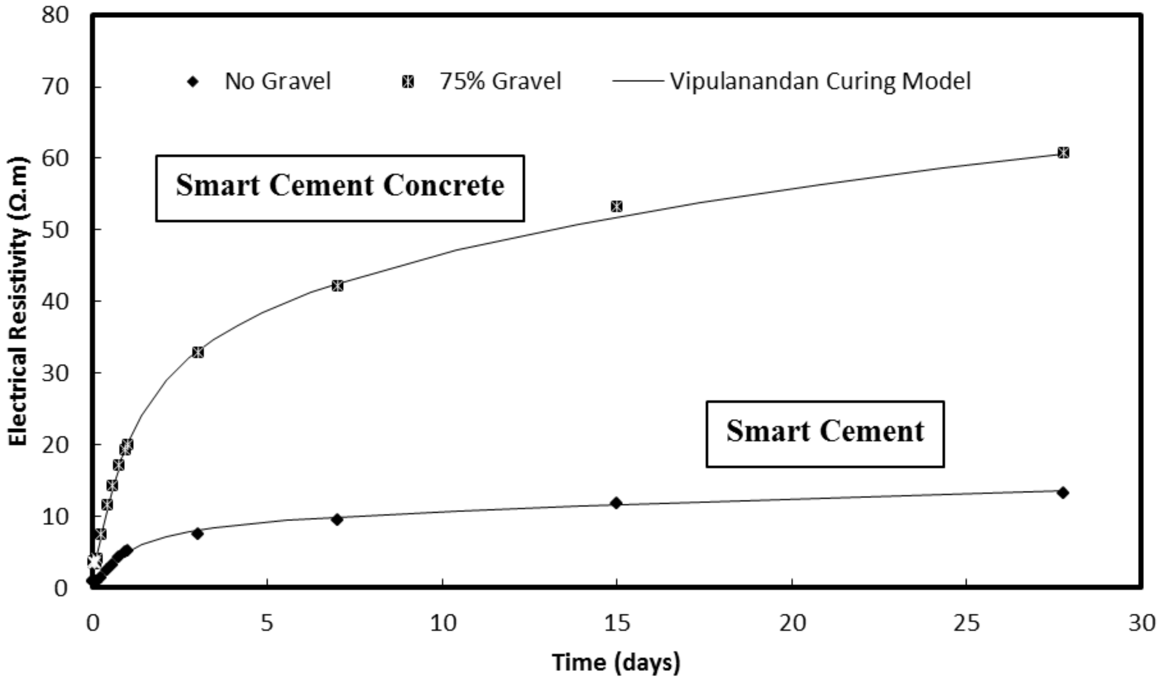

Figure 5. Development of electrical resistivity of smart cement composites during 28 days of curing

Compressive Behavior

Compressive Strength

Compressive strength of smart cement and smart concrete were 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) Smart Cement 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) Smart Cement 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 and smart cement concrete was evaluated after 1 day and 28 days of curing as shown in Figure 6.

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 2). Parameters p_2 and q_2 for the model were 0.61 and 0.57 respectively.

(b) Smart Cement Concrete*:*

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 28 days 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) Smart Cement 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 Concrete	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

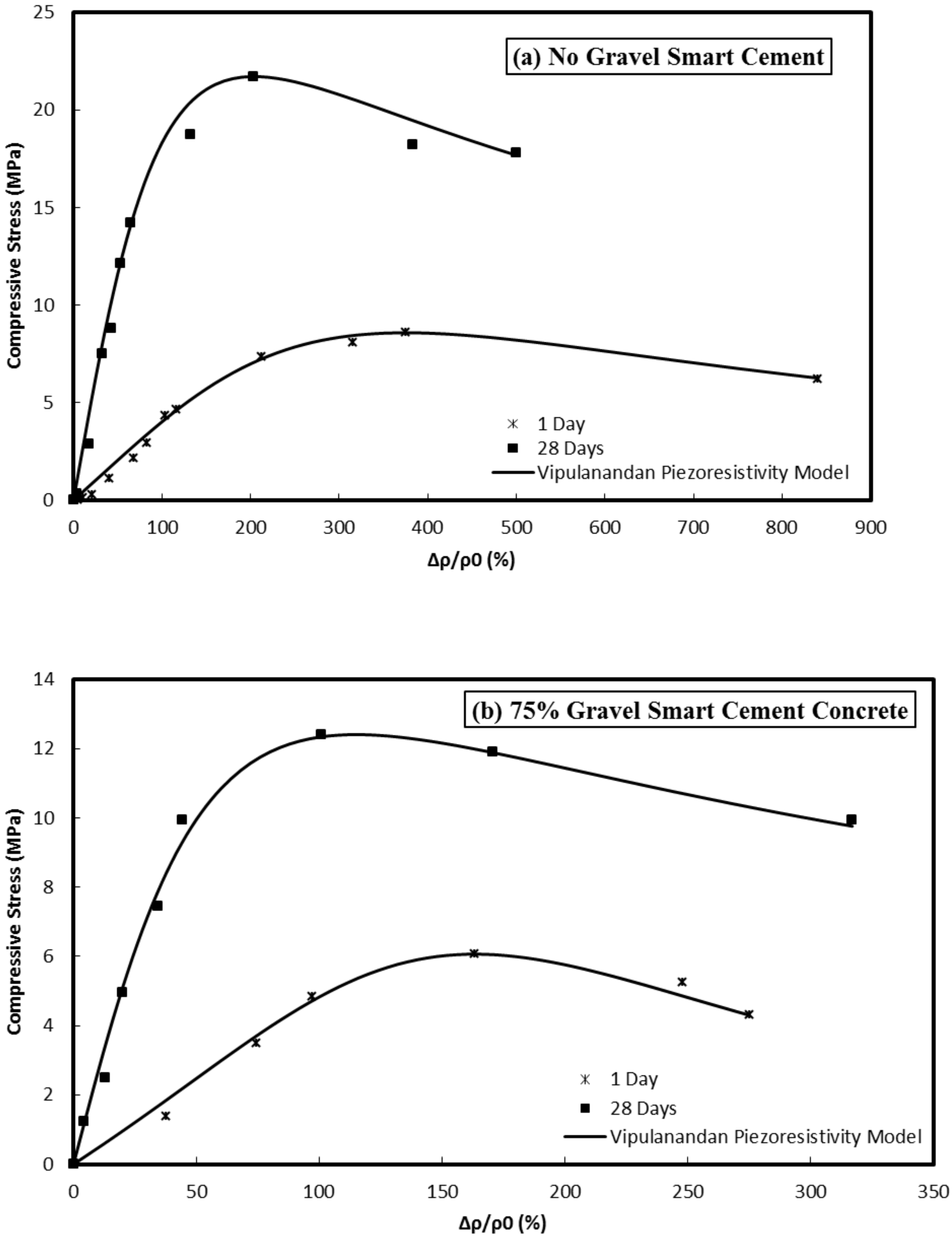

Figure 6. Piezoresistivity of smart cement composites after 1 and 28 days of curing: (a) No gravel and (b) 75% Gravel

Smart Cement Grout

Curing

The observed trend for the resistivity change with time was similar to what was observed for the concrete as shown in Figure 7. The minimum resistivity and time to reach the minimum resistivity are summarized in Table 3. The resistivity after 28 days of curing was 9.37 Ωm.

Table 3. Model parameters for the curing model of the resistivity of smart cement grout cured under room condition 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)	28 days	1.04	180	0.710	0.295	110	0.45	0.97

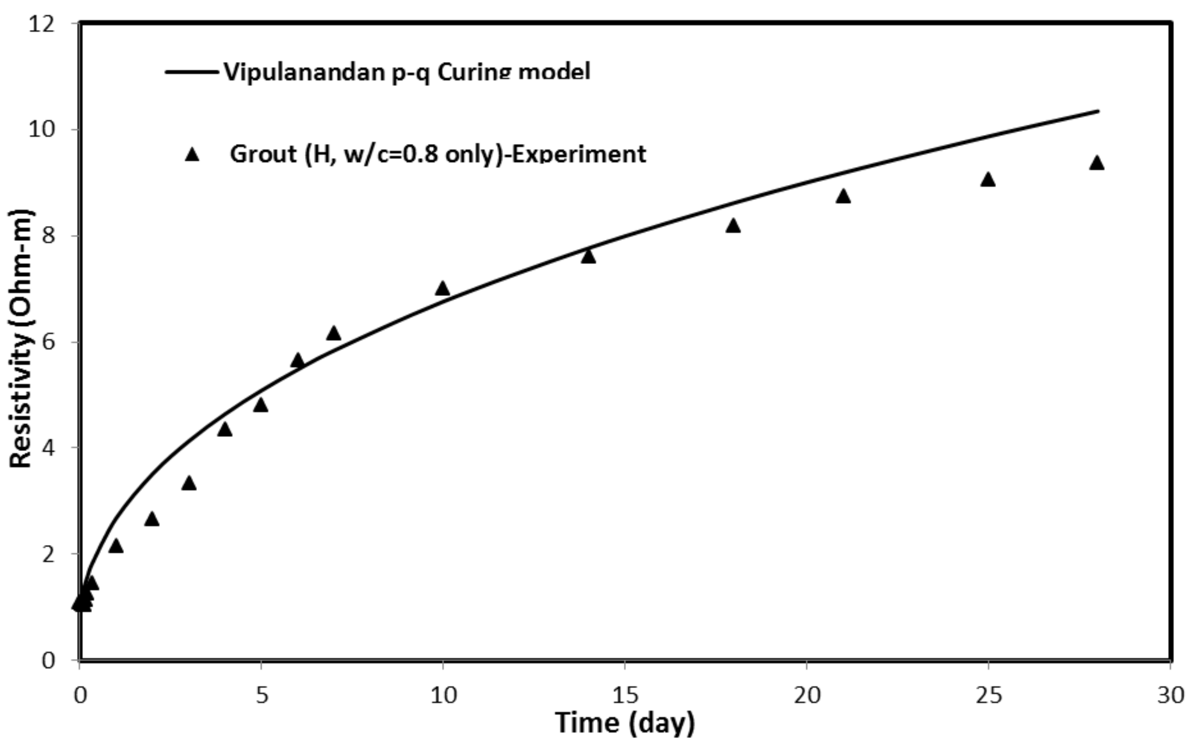

Figure 7. Variation of the resistivity with time for smart cement grouts up to 28 days of curing and modeled using the Vipulanandan p-q curing model.

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 as shown in Figure 8. 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

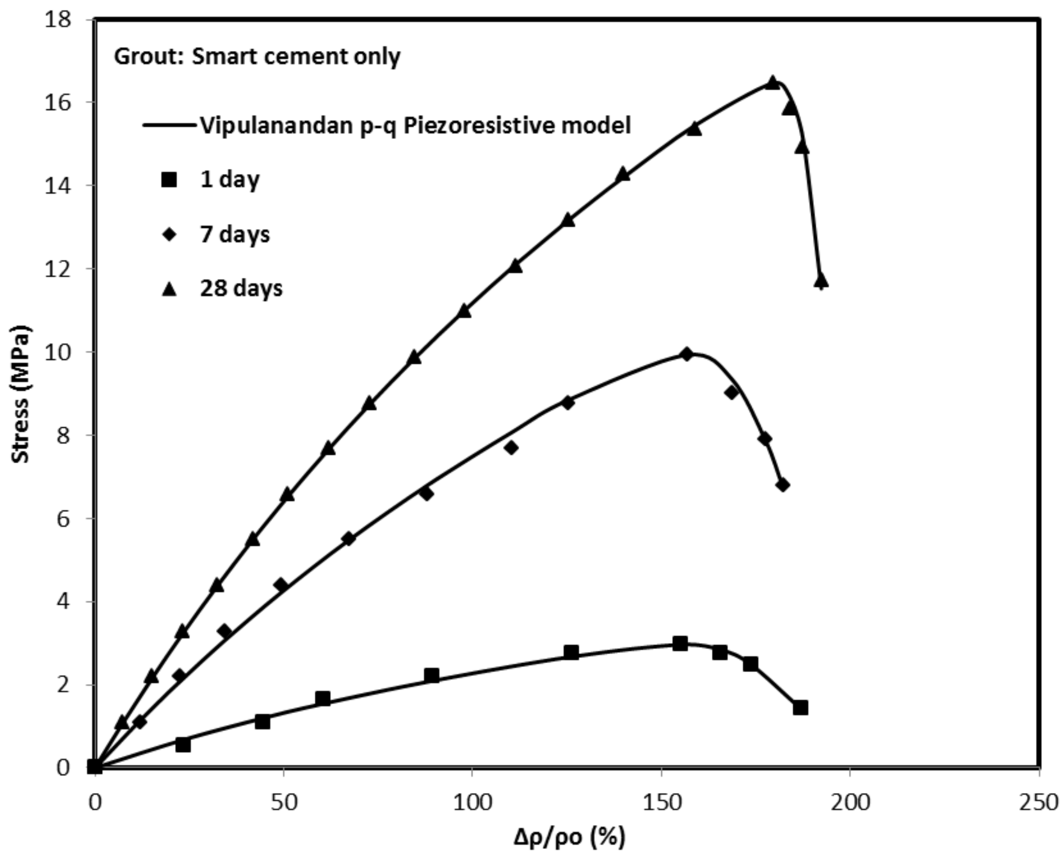

Figure 8. Piezoresistive responses of the smart cement grout after one day, seven days and twenty eight days of curing and modelled with Vipulanandan p-q piezoresistive model.

New Construction

Highly sensing smart cement (w/c ratio of 0.38), smart cement concrete and smart cement grout (w/c ratio of 0.8) can be used in many applications. But it is important to monitor the curing and performance of the smart materials.

Two Probe Wireless Transmissions

It is important to monitor the changes in the resistivity (material property) with time to ensure the quality of the mixed material and also curing under various environmental conditions. It has been proven that two probe method with alternative current (AC) supply can be used for monitoring the changes in resistivity and the schematic of the configuration is shown in Figure 9(a). A company named Sensytec has developed the wireless transmission monitoring probe including a thermocouple to monitor the temperature as shown in Figure 9(b). The measurements can be wirelessly transmitted to the phone. The probes can be place in concrete beams, column, slabs and other configuration to monitor the curing and also the stress developments in the elements.

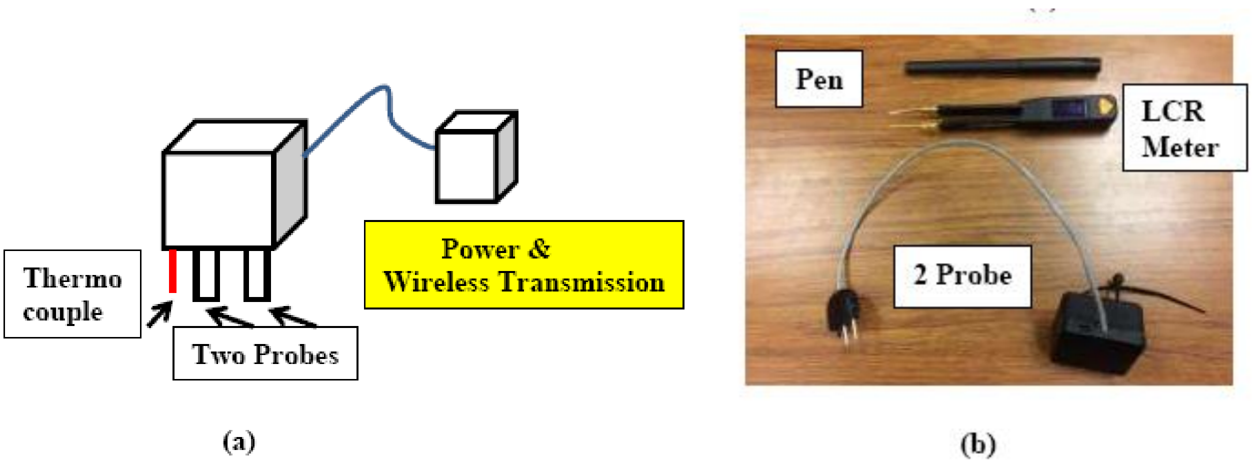

Figure 9. Two Probe Monitoring with Wireless Transmission (a) Schematic and (b) Actual Device (SensyRoc), two probe pocket LCR and a Pen.

New Wells (Oil, Gas and Water)

One of the main focuses is to develop real-time monitoring systems for the field wells which could be several thousand feet in the ground to collect data from the field wells during the installation and the entire service life of the wells. Also ways to integrate the LCR meter monitoring system into the current field monitoring systems to collect the data from the smart cement. This can eliminate the failures and also minimize the losses.

Field Instrumentation

The main focus will be to integrate the two probe method to monitor the performance of the smart drilling fluids, smart spacer fluids, smart cement and smart packer fluids during various stages operations. During the drilling the two probes will be part of the drilling tool where the smart drilling fluid conditions could be monitored with depth using the AC current at relatively high frequency of about 300 kHz. When casing is lowered into the well, it can be used as a probe with a floating ring on the surface on the fluid as the second probe. The casing couplings will have selected frequency **"Band-Pass Filter"** attached to represent various depths (Fig. 10). The **Band-Pass filters** (BPF) are simple device designed using resistances and capacitors to be effective in a selected range of frequency (Kureve et al. 2014; Zhang et al. 2015). When AC current is passed through the casing in the selected frequency range (Fig. 10), it will get to the depth of the compatible filter and the filter will allow that range of frequency to pass through to the cement to measure the vertical resistance between the selected casing ring with the filter and the floating ring on the top of the liquid. Studies have clearly indicated that the current will only pass through the cement since the resistance is the lowest compared to the resistance of the steel-cement interface and cement-geological formation interface. Also when the current is passed through the casing from the top, it will only get to the cement through the compatible frequency "Band-Pass Filter" since the interface resistance between the cement and steel are very large. For example, if 50 to 100 kHz AC current is applied at the top of the casing current will travel through to Level 4 and will be allowed to get to the cement at that level. It will then travel to the floating probe ring at the top and the Impedance – Frequency data collected in this region can be used to determine the resistance (CASE 2) and using the parameter K, the resistivity can be determined.

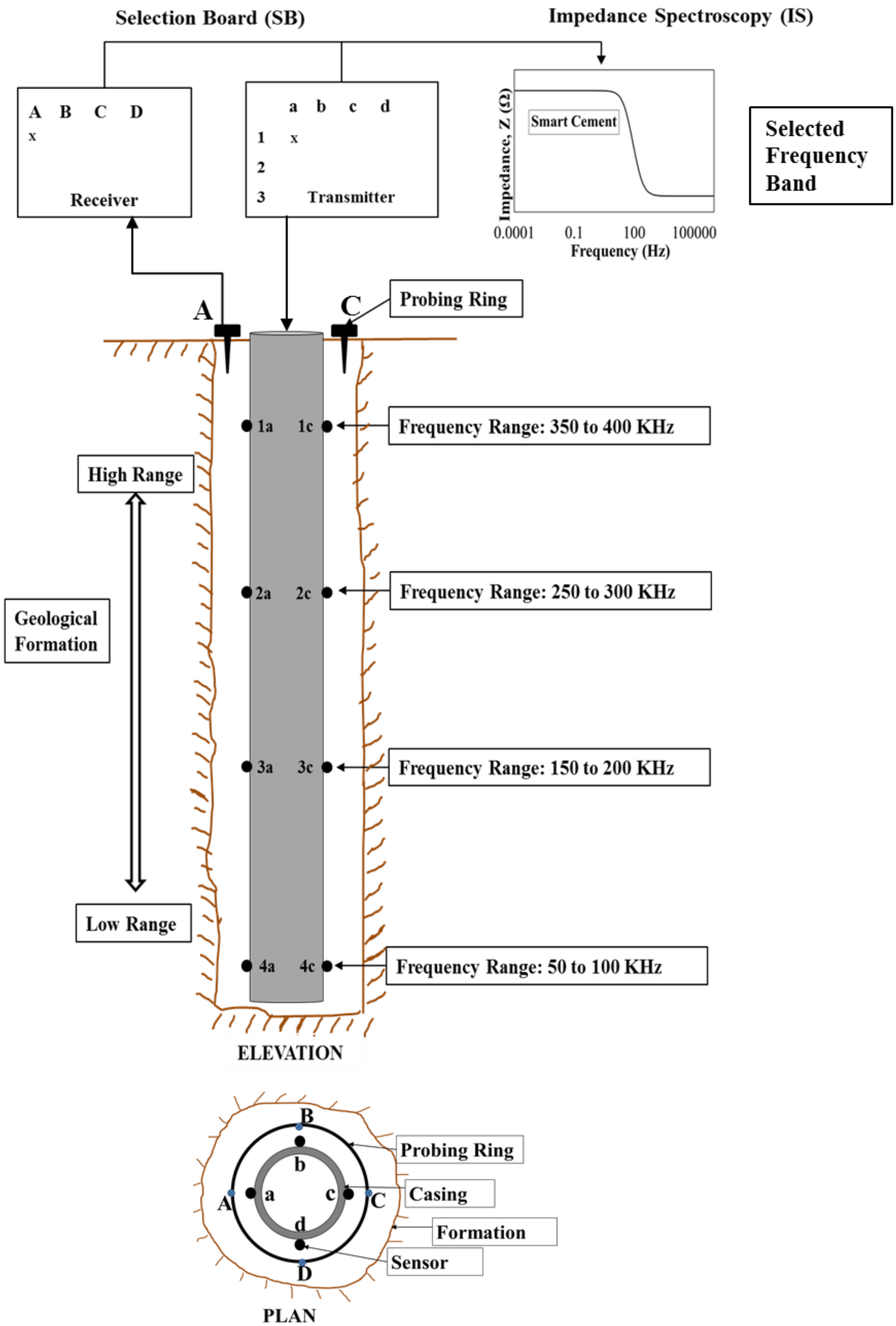

Figure 10. Schmatic Configration of the Field Wells to be Installed

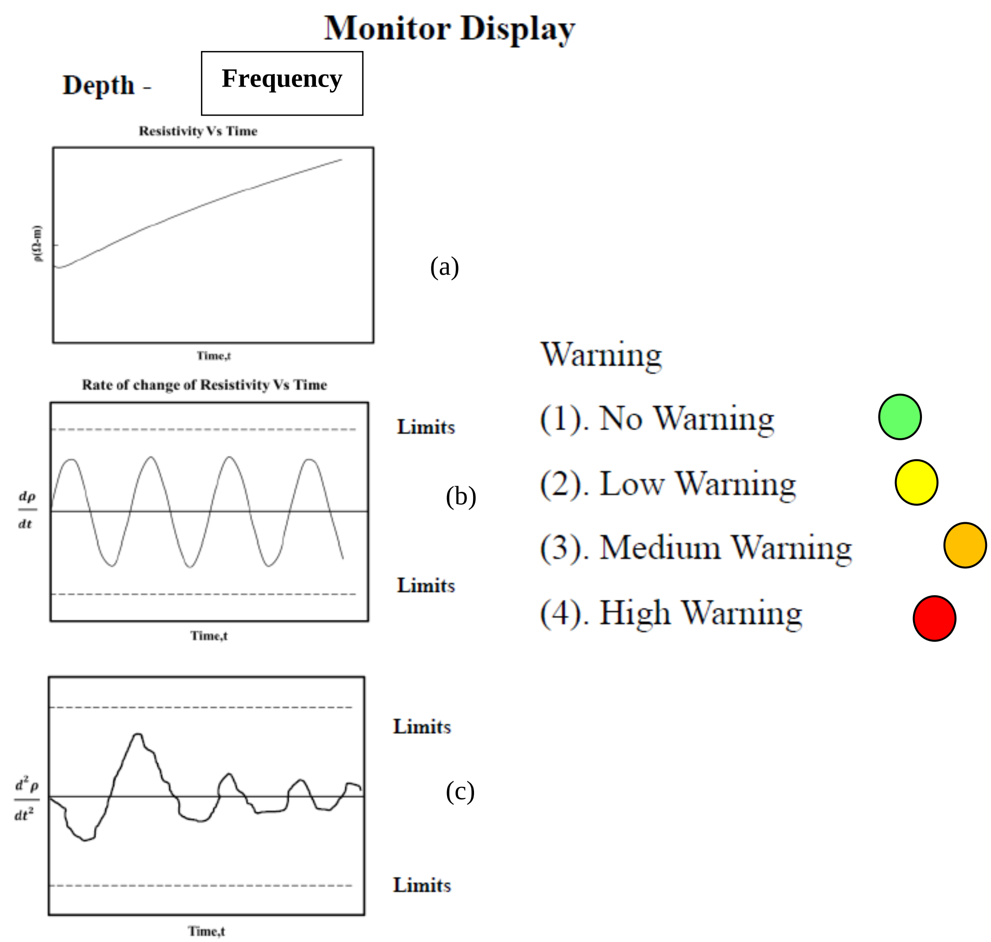

Figure 11. Variation of Total and Rates of Electrical Reisistivity with Tme at Various Depths

Processing and Analyses of Data:

Computer software will be developed to rapidly process the collected data to display it on the monitoring screen real-time. Models used to characterize the material properties including resistivity will be used. The display will focus on displaying the resistivity with time, rate of change of resistivity with time (d□/dt) and the second derivative of resistivity change ($d^2\rho/dt^2$) with time (three parameters) as shown in Fig 11. Based on the quantification, limits on the rate of changes in resistivity and second derivative of resistivity **change** will be established and used as guidance to evaluate the conditions in the well. When no limits are exceeded (three parameters) the operation is fine that there will be **No Warning** (green light will be on). When all three parameters are beyond the limit then there will be **High Warning** (Red Light). Also based on the understanding of the changes in the three parameters the causes of the problems will be listed, so the operator can do the needed modification. When one parameter is exceeded there will be **Low Warning** (Yellow Light) and the causes will be identified based on the parameter violated. When two parameters are exceeded there will be **Medium Warning**

(Orange Light) and the causes will be identified based on the two parameters violated the operators can the find t methods to fix the problem.

In-service Infrastructures

With the advancement of the new smart cement technology it is important to develop methods to integrate it with infrastructures that are in-service. This can substantial improve the current maintenance operations and also minimize failures. Also the developed methods should be relatively easy to adopt with various infrastructures.

In Figure 12, smart cement and smart concrete integrated with the two-probe monitoring system can be made into different shapes of blocks and attached at the critical locations of the the infrastructures that are in service. The resistivity and temperature can be measured in these blocks and transmitted wirelessly.

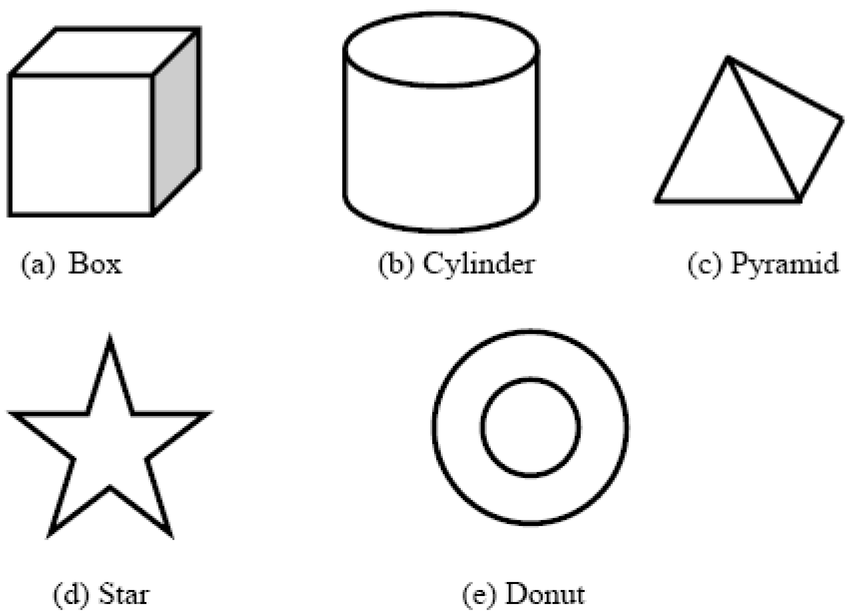

Figure 12. Diffenent Smart Cement and Smart Concrete Block Configuration

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. It is also important to develop real-time monitoring systems that can be easily adopted in the field. Based on experimental and analytical study on the behavior of smart concrete and smart grout with the real-time monitoring in the field 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 concrete 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. Real-time 2- Probe monitoring system with wireless transmission of the data to the phone has been developed and can be easily used in the field.

6. In deep wells, band pass filters (BPF) can be integrated with the casing coupling to do the real-time monitoring. This approach can be adopted for deep foundations and pipelines.

7. Smart cement and smart cement concrete blocks integrated with wireless real-time monitoring can be adopted in the in-service infrastructures for real- time monitoring for improved maintenance and minimize failure.

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