

Smart Cement Modified with A Polymer to Detect and Control Fluid Loss and Gas Leaks Using Vipulanandan Curing, Fluid Loss and Fluid Flow Models

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“Vipulanandan Rheological Model”

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Abstract

In this study, highly sensing chemo-thermo-piezoresistive smart cement with a water-to-cement ratio of 0.38 was investigated with the addition of a polymer on the effects of various sensing properties. Series of quality control, curing and high pressure high temperature (HPHT) experiments were performed to evaluate the smart cement behavior with and without the commercially available styrene butadiene rubber (SBR) polymer. Addition of 1% and 3% SBR polymer (by the weight of the cement) increased the initial resistivity by 4% and 12% respectively and hence this parameter can be used for quality control in the field. Vipulanandan p-q curing model was used to predict the changes in resistivity with curing time. Addition of 1% and 3% SBR polymer also increased the compressive strength of the smart cement by 18% and 32% after 1 day of curing respectively, The piezoresistivity of smart cement with the addition of SBR polymer after 1 day of curing was over 500 times (50,000%) higher than the regular cement failure strain of 0.2%. The Vipulanandan p-q piezoresistivity model also predicted the experimental results very well. Addition of SBR polymer reduced the fluid losses 30 minutes and 24 hours after curing. The fluid loss was predicted using the Vipulanandan fluid loss model and compared it to the American Petroleum Institute (API) model. The smart cement with and without SBR polymer detected the gas leak during initial slurry condition and also after solidification. Addition of SBR polymer reduced the gas leak. During the gas leak in the piezoresistive smart cement slurry the resistivity change was positive and for the solid smart cement the resistivity change was negative. During gas leak in the smart cement slurry the resistivity increase was about 45% and it reduced to 30% with the addition of 3% SBR polymer at pressure gradient of 2000 psi/ft. During gas leak in the solidified smart cement the resistivity reduced, opposite to the piezoresistive response to compressive stress, by about 30% and it reduced to 12% with the addition of 3% SBR polymer at a pressure gradient of 2000 psi/ft. Vipulanandan fluid flow model, generalized Darcy's Law, predicted the non-linear responses of gas leak velocity (discharge per unit area) to the applied pressure gradient. Also electrical resistivity changes can be used to predict the gas leak velocity in the smart cement with and without SBR polymer.

Introduction

In the construction and petroleum industries, cement is used to fill the annular space between the geological formations and the tunnels, well casings and also horizontal pipelines to enhance the

performance in-situ for decades after installation. The cement will support the casing and pipelines and protect them against corrosion and impact loading, restrict the movement of fluids between formations, and isolate the productive and the nonproductive zones. Oil well cement is used under different conditions of exposures compared to the cement used in the conventional construction industry. The strength of oil well cement usually depends on factors such as time and conditions of curing, environmental conditions, slurry design and use of additives and any additional treatments to the cement. Different additives have been used in the cement to mitigate the strength degradation (Choolaei et al. 2012). The real-time monitoring of the changes in the cement in-situ are critical to evaluate the performance of the cemented wells (Vipulanandan and Mohammed 2015). 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 downhole conditions (Labibzadeh et al., 2010 and Vipulanandan et al., 2015). The catastrophic accident in the Gulf of Mexico in April 2010 is one of the world's worst oil spills (Shadravan et al., 2012). Therefore, proper monitoring and tracking the entire process of well cementing become important to ensure cement integrity during the service life of the well (Vipulanandan et al., 2015-2018).

Gas leaks are a major problem in both in-service wells and abandoned wells. Gas leaks are also a problem in CO₂ sequestration wells too. With the advancement of nanotechnology, polymer science, and engineering, several of these materials can be used as additives for solving some of the problems encountered in oil and gas well cementing (Mangadlao et al. 2015, Vipulanandan and Mohammed 2015 & 2017; Houk 2017). Gas leakage may be described into three stages initial stage, intermediate and long term gas leakage. Main reasons for gas migration failure at initial stage gas migration occurs due to incorrect cement densities, poor mud and filter cake removal leaving route for gas migration, premature gelation leading to hydrostatic pressure control, high shrinkage of cement. Excessive fluid loss creates increases space in the cement slurry for gas to enter and high stresses around cement sheath leads to the formation micro annulus (Bonett and Pafitiss, 1996). Various method have been suggested to prevent the gas migration in oil cement such as addition of polymers to cement to control gas migration, use of thixotropic and high gel strength cement, use of right angle set cement. (Pour & Moghadasi, 2007). In case of thixotropic cement, transmitted hydrostatic pressure should revert to the interstitial water and its high gel strength offers resistance to gas bubble. Right angle set cement slurries provide short transition time where the viscosity remain relatively low and then rapidly sets to relatively high gel strength (Rogers et al., 2004). There are many types of polymers that are being used to enhance the performance of cement. To control gas migration, polymer additives are widely used. Polymer additives modify the hydration and sensing behavior of cement. In this study, smart cement has been modified commercially available polymer such as styrene butadiene polymer. Styrene butadiene rubber was first developed in Germany in 1929 as an alternative to natural rubber and was started to be manufactured in the U.S. in 1942. Styrene butadiene promotes the reaction of calcium aluminate with gypsum while restrain the formation of calcium (C) silicate (S) hydrates (H) (C-S-H) gel and calcium aluminate hydrate (C₅AH₁₃). (Bonnet et al. 1996). Styrene Butadiene polymer enhances bond strength and also prevents the annular gas flow till 350° F (Gowida et al. 2018). Different manufacturers recommend different percentages of polymer for controlling fluid loss and gas migration. Unfortunately the conditions in-situ cannot be monitored with the currently available technologies.

Electrical resistivity measurement has been applied by many researchers in concrete and cement applications (McCarter et al., 2000; Han et al. 2007; Han et al. 2016; Mohammed 2017; Houk 2017; Vipulanandan et al. 2004-2018). Electrical response characteristics measurement has appropriate

sensitivity in monitoring the characteristics of cementitious materials (Mc Carter et al., 1994; Mohammed 2017; Houk 2017). The electrical resistivity of cement is affected by a number of factors such as pore structure (continuity and tortuosity), pore solution composition, cementitious content, water-to-cement ratio, moisture content, and temperature (Polder et al., 2001). Vipulanandan et al. (2004 - 2023) developed piezoresistive materials using the new piezoresistive theory (Vipulanandan 2021) and have shown that the changes in electrical resistivity increased with the applied compressive or tensile stress in both cementitious and polymeric composites because the changes in resistivity was influenced by the deviatoric stress. These studies have also shown that the changes in resistivity in the materials at the peak stresses were 30 to 2800 times higher than the strain in the materials. Hence, instead of strain, the change in resistivity has the potential to be used to determine the integrity of the materials. In recent years, chemo-thermo-piezoresistive cement, very highly smart cement has been developed and tested (Vipulanandan et al. 2012-2021). A field well was installed and cemented using the smart cement mixture with enhanced piezoresistive properties and is being continuously monitored successfully for over seven years (Vipulanandan et al. 2016 a; Maddi et al. 2024).

Objectives

The overall objective of this study was to investigate the effects up to 3% styrene butadiene rubber (SBR) polymer on the smart cement behaviors. The specific objectives were as follows:

- i. Investigate and quantify the changes in the initial and curing electrical resistivity during the curing time of the SBR polymer modified smart cement.
- ii. Characterize the piezoresistive behavior of smart cement with and without polymer addition.
- iii. Quantify the fluid loss with and without SBR polymer addition to the smart cement and verify the Vipulanandan Fluid Loss model with API Fluid loss model.
- iv. Investigate the control and detection of gas leak with the SBR polymer addition at two different curing times (slurry and solid).
- v. Correlate the gas leak rates with changes electrical resistivity for the smart cement with and without SBR polymer.

Materials and Methods

In this study, smart well cement (Class H) with water-to-cement (w/c) ratio of 0.38 was used. Also commercially available SBR polymer was used. The samples were prepared according to the API standards. To improve the sensing properties and piezoresistive behavior of the smart cement, it was modified with 0.1% of conductive fillers (CF) by weight of cement and mixed in all of the samples. Three series of smart cement slurries were prepared with SBR polymer up to 3 % (by the weight of the cement) and tested up to one day of curing. Cement, water, and additives (0.1% CF and SBR polymer) were mixed at the speed of 4000 rpm for 3 minutes and 35 seconds at the speed of 1200 rpm. Total of four wires were placed in the mold and the vertical distances between any two wires were the same. Embedment depth of the conductive wire was 1 inch. For setting time monitoring and compressive stress tests, cylinders with the diameter of 50 mm (2 inches) and a height of 100 mm (4 inches) were prepared. For real-time monitoring, a two-probe method was selected (Vipulanandan et al. 2013 - 2023). In this study, three or more specimens were prepared and tested under every condition investigated.

Electrical resistivity

Digital resistivity meter was used to measure the resistivity of the cement slurries and semi-solids. The measurable resistivity range for the instrument was $0.01\Omega\text{-m}$ to $400\ \Omega\text{-m}$. The device was calibrated using standard solutions of sodium chloride (NaCl).

The electrical resistance was measured using an inductance, capacitance, and resistance (LCR) meter during the cement curing and compression test. To minimize the contact resistances, the resistance was measured at 300 kHz using the two-wire method. The electrical resistivity (ρ) was related to the measured electrical resistance (R) based on the Eqn.1 (Vipulanandan et al. 2013 and 2017).

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

where L is the distance between the wires, A is the cross-sectional area through which the current is flowing, and L/A is called the nominal geometry factor. In insulator material, such as cement, the actual pathway of the current is not well defined as compared to the conductive material such as metals. Hence, L/A in Eqn. (1) was replaced by an experimentally determined effective calibration factor (K), by measuring the bulk resistance (R) and the resistivity (ρ) of the material at the same time (Vipulanandan and Prashanth 2013). Also normalized change in resistivity with the changing conditions (curing, stress) can be represented as follows:

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

In this study modified cement materials are represented in terms of resistivity (ρ) to the changes (composition, curing and stress) since it has been shown to be a sensitive parameter (Vipulanandan et al. 2015-2018).

Compressive strength test (ASTM C 39)

The cylindrical specimen with the diameter of 2 inches and a height of 4 inches (50mm Dia.*100 mm height) was capped (sulfur capping) and tested at a predetermined controlled displacement rate. Compression tests were performed on cement samples after 1 day of curing using a hydraulic compression testing machine.

Piezoresistivity test

Piezoresistivity describes the change in the electrical resistivity of a material under pressure. Since oil well cement serves as the pressure-bearing part of wells in real applications, the piezoresistivity of modified and unmodified cement was investigated under compressive loading. During compression testing, electrical resistance was measured in the stress axis. To eliminate the polarization effect, alternating current resistance measurements were made using a LCR meter at a frequency of 300 kHz (Vipulanandan and Prashanth 2013).

HPHT Fluid Loss and Gas Migration Test.

High Pressure and High Temperature (HPHT) device was modified to measure the resistance real-time during the fluid loss for 30 min (API 13A and API 13 B) and gas leak study (Fig. 1). HPHT device has an area of $22.58\ \text{cm}^2$ and can withstand a pressure of around 2000 psi and for this study up to 700 psi was used with the cement height of 4 inches. Polymer modified smart cement and smart cement were placed in the device for gas migration tests. Gas migration tests were performed using nitrogen gas. During the entire test, samples cured for 30 minutes and 24 hours, vertical resistances of the samples were measured using the LCR device. The change in resistance was used to determine the resistivity (Eqn. (2))

which is a material property. Also gas flow meter was used to determine the gas leak with applied pressures,

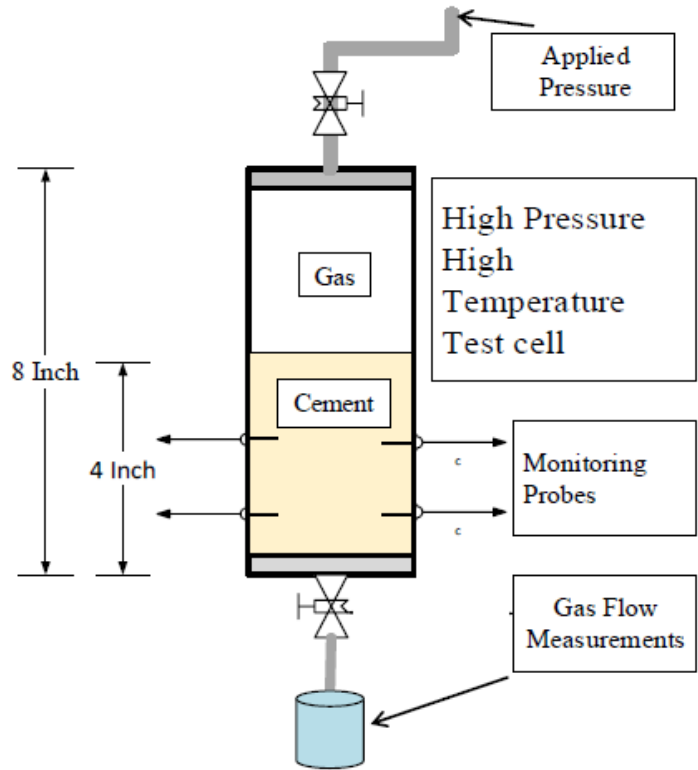


Figure 1. HPHT Gas Flow Study Device

Results and Discussion

Curing of cement slurry

Initial resistivity was measured immediately after mixing the smart cement with and without the SBR polymer. Initial resistivity of the smart cement was 0.99 Ωm (Table 1). With the addition of 1% SBR it increased to 1.03 Ωm, a 4% increase, 4 times the amount of SBR added. With 3% SBR, the initial resistivity increased to 1.11 Ωm, a 12% increase, 4 times the amount of SBR added. Hence initial resistivity could be adopted as a quality control measure in the field to determine the amount of SBR added and also the quality of mixing. During the curing process, the resistivity rapidly changed with the time as shown in Fig. 2. Hence, there are several parameters can be used in monitoring the curing (hardening process) of the cement. The parameters are initial resistivity (ρ_0), minimum resistivity (ρ_{min}), time to reach the minimum resistivity (t_{min}), resistivity after 24 hours of curing (ρ_{24}), and percentage of maximum change in resistivity as referred as Resistivity Index [$RI_{24hr} = (\frac{\rho_{24} - \rho_{min}}{\rho_{min}}) * 100$]. The test results from various smart cement compositions are summarized in Table 1. Fig. 2 illustrates the change in electrical resistivity (ρ) during curing time for modified smart cement with SBR polymer. After initial mixing, the electrical resistivity reduced to a minimum value (ρ_{min}), and then it gradually increased with time. Time to reach minimum resistivity, t_{min} , can be used as an index of speed of chemical reactions and

cement set times. With the formation of resistive solid hydration products which block the conduction path, resistivity increased sharply with curing time. The following increase in electrical resistivity was caused by the formation of large amounts of hydration products in the cement matrix. Finally, a relatively stable increase in trend was reached by the ions diffusion control of hydration process, and resistivity increased steadily for up to 24 hours, reaching a value of ρ_{24hr} . Change in the electrical resistivity with respect to minimum resistivity quantifies the formation of solid hydration products, which leads to a decrease in porosity and, hence, the cement’s strength development. Also the t_{min} was increased by 12% and 38% when SBR polymer contents were 1% and 3% respectively as summarized in Table 1. The minimum resistivity (ρ_{min}) of smart cement with 0%, 1% and 3% of polymers were 0.97 Ω -m, 1.00 Ω -m and 1.05 Ω -m, a 3% and 8% increase in the minimum electrical resistivity when the polymer concentration increased to 1% and 3% respectively as summarized in Table 1. The resistivity index (RI_{24hr}) for smart cement with 0%, 1% and 3% of SBR polymer were 259%, 307% and 341% respectively. Change in RI_{24hr} increased with increasing the polymer content. These observed trends clearly indicate the sensitivity of resistivity to the changes occurring in the curing of cement.

Table 1. Initial Resistivity and Curing Model Parameters for Smart Cement with and Without SBR

SBR Content (%)	Initial Resistivity, ρ_0 (Ω -m)	ρ_{min} (Ω -m)	t_{min} (min)	ρ_{24h} (Ω -m)	RI ₂₄ (%)	p_1	q_1	t_0 (min)
0	0.99 ± 0.03	0.97 ± 0.01	58 ± 5.0	3.48 ± 0.02	259	0.65	0.298	142.8
1	1.03 ± 0.02	1.00 ± 0.03	65 ± 4.5	4.07 ± 0.02	307	0.65	0.325	173.4
3	1.11 ± 0.04	1.05 ± 0.04	80 ± 3.5	4.63 ± 0.02	341	0.65	0.337	183.3

Vipulanandan p-q curing model

Based on experimental results, a theoretical model proposed by Vipulanandan and Paul (1990) was modified and used to predict the electrical resistivity of smart cement during hydration up to 28 days of curing a shown in Fig. 2. The Vipulanandan p-q curing model (Vipulanandan et al. 2015) is defined as follows:

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

Where ρ : electrical resistivity (Ω -m); t is the curing time (minutes); ρ_{min} : minimum electrical resistivity (Ω -m); t_{min} : time corresponding minimum electrical resistivity (ρ_{min}), p_1 , t_0 and q_1 are model parameters (Table 1). In general, model parameters are influenced by the composition of the cement and curing conditions (temperature, humidity and stress), In the range of variable investigated up to 24 hours of curing parameter q_1 and t_0 were influenced by the polymer content and parameter p_1 was not. The parameter t_0 is influenced by the initial resistivity ρ_0 .

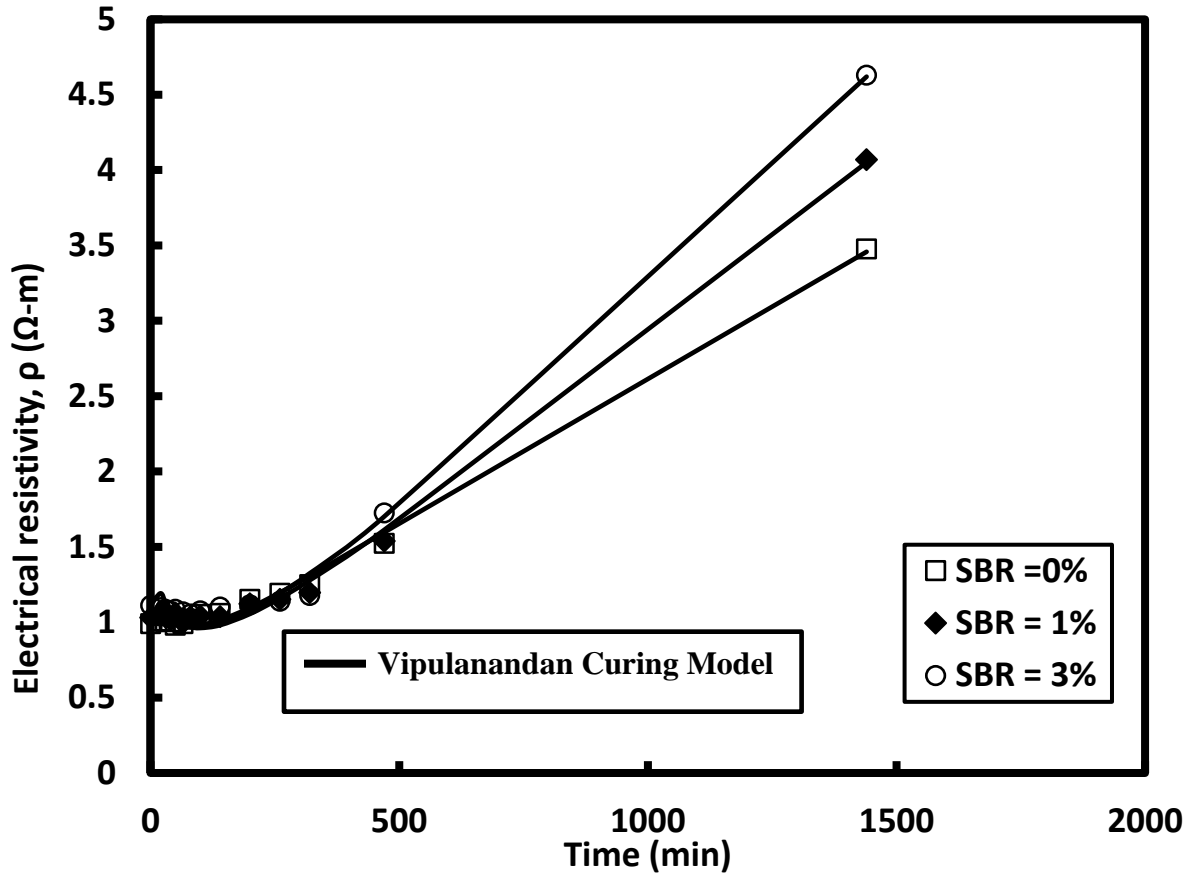


Figure 2. Variation of Resistivity with Curing time for Smart Cement With and Without SBR.

Compressive Strength

The compressive strength of the smart cement increased with the SBR polymer addition. The smart cement average compressive strength after 1 day of curing was 1400 psi. With the addition of 1% SBR polymer the strength increased to 1650 psi, 18% increase. With the addition of 3% SBR polymer the 1 day compressive strength increased to 1850 psi, 32% increase in strength.

Piezoresistivity Behavior

It is important to characterize the sensing property, resistivity change, of the smart cement with and without polymer. For the smart cement slurry application of a compressive stress Of 800 psi reduced the resistivity by 14% indicating even the cement slurry is piezoresistive (Vipulanandan et al. 2017).

The piezoresistive responses (stress-resistivity relationship) for the smart cement with and without polymer are shown in Fig. 3. The piezoresistivity of the smart cement at failure after 1 day of curing $\left(\frac{\Delta\rho}{\rho_o}\right)_f$ was 171%, as summarized in Table 2. The addition of 1% and 3% of SBR polymer to the smart cement decreased the electrical resistivity at failure $\left(\frac{\Delta\rho}{\rho_o}\right)_f$ to 125% and 104% respectively, as summarized in Table 2. But the smart cement with SBR polymer are piezoresistive and the responses were over 500 times compared to the compressive failure strain of cement of 0.2%.

Vipulanandan p-q piezoresistivity model

The Vipulanandan p-q piezoresistivity model was used to predict the observed trends for the smart cement with and without SBR (Vipulanandan et al. 2014). The Vipulanandan p-q piezoresistive model is defined as follows:

$$\sigma = \frac{\frac{x}{x_f} * \sigma_f}{q_2 + (1 - p_2 - q_2) \frac{x}{x_f} + p_2 \left(\frac{x}{x_f}\right)^{\left(\frac{p_2}{p_2 - q_2}\right)}} \tag{4}$$

where σ is the stress (MPa); σ_f : compressive stress at failure (MPa); $x = \left(\frac{\Delta\rho}{\rho_o}\right) * 100$ is percentage of change in electrical resistivity due to the stress; $x_f = \left(\frac{\Delta\rho}{\rho_o}\right)_f * 100$ is the percentage of change in electrical resistivity at failure; $\Delta\rho$: change in electrical resistivity; ρ_o : initial electrical resistivity ($\sigma = 0$ MPa) and p_2 and q_2 are piezoresistive model parameters. Both parameters were sensitive to the polymer content in the smart cement (Table 2). As summarized in Table 2, model parameter p_2 increased with polymer content while q_2 decreased.

Table 2. Piezoresistive Model Parameters for Smart Cement with and without SBR Polymer

Mix Type	p_2	q_2	Max Change in Resistivity, (%)	Compressive Strength, (σ_c psi)	R^2	Piezoresistivity/Stress
SBR = 0%	0	1.25	171	1400	0.99	0.12
SBR = 1%	0.12	0.301	125	1650	0.96	0.08
SBR = 3%	0.43	0.467	104	1850	0.99	0.06

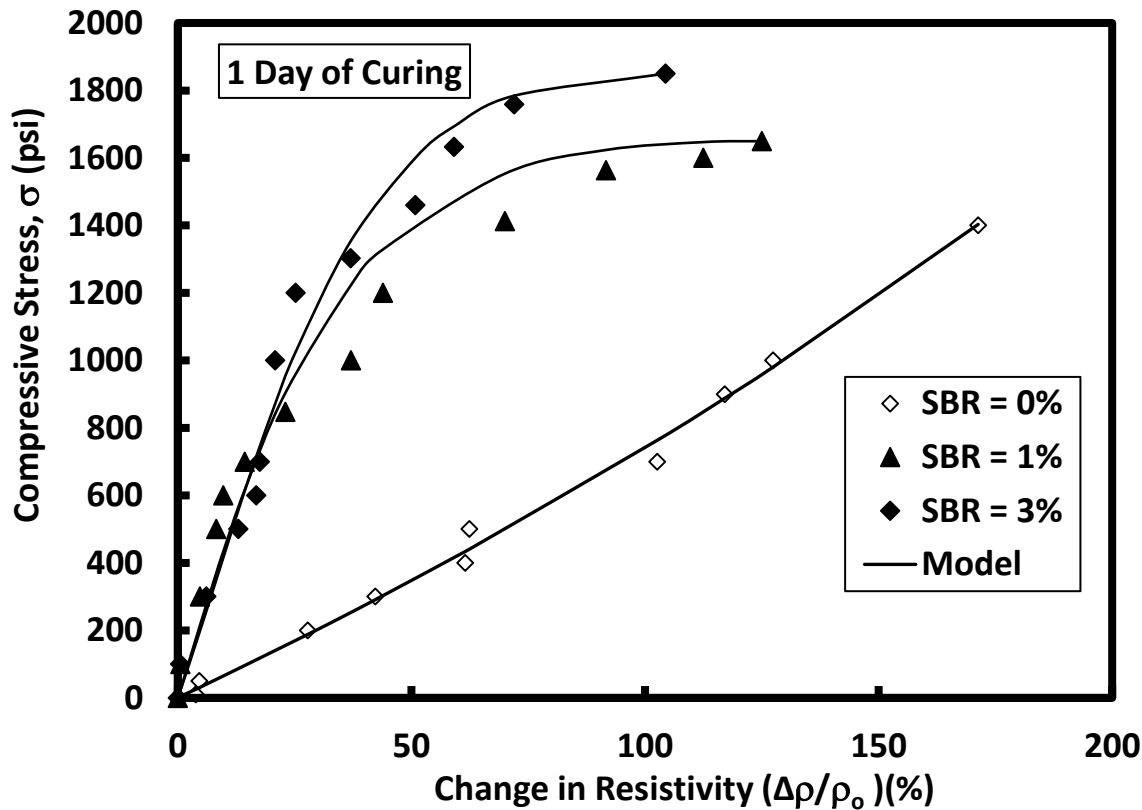


Figure 3. Piezoresistive Behavior of Smart Cement With and Without SBR.

FLUID LOSS

One reason for adding polymer to the cement slurry is to reduce the fluid loss. Styrene Butadiene polymer reduces the fluid loss when added into smart cement. Fluid loss observed for smart cement without and with 3% polymer was 141 mL and 67 mL respectively (Figs. 4 and 5). Hence the adding 3% of SBR polymer reduced the fluid loss by 52%. Gas Migration was observed after an initial fluid loss 46 mL and 25mL respectively in smart cement without and with 3% polymer. So the gas leak occurred 33% and 37% of the total fluid loss without polymer and with 3% polymer. This is also a clear indication of the importance of fluid loss model predictions.

Reduction in the amount of fluid loss is a clear indicator that the styrene butadiene polymer fills the pores of cement slurry and also retains the water. When the fluid loss test was done after 24hours, the observed fluid loss for smart cement without and with 3% polymer was 26 mL and 15 mL respectively.

Static model (API Model)

In this model the filter cake properties are assumed to be constant with time and the relationship is as follows:

$$FL_f - FL_o = M * \sqrt{t} \tag{5}$$

where:

FL_f : volume of fluid loss (cm^3).

FL_o : initial volume of fluid loss (spurt) (cm^3).

t: time.

M: model parameter ($mL/(min)^{0.5}$).

From Eqn. (5), the maximum fluid loss (FL_u) when $t \rightarrow \infty \Rightarrow FL_u = \infty$ (6)

The API model predictions are compared to the experimental results in Figs. 4, 5, 6 and 7. Also the model parameter M is summarized in Table 3. The coefficient of variation was 0.97 to 0.99 and the Root Mean Square Error (RMSE) varied from 0.44 to 0.67 mL.

Vipulanandan fluid loss (FL) model

Taking into account of the changes in the permeability and cake thickness with time Vipulanandan Fluid Loss Model was developed and the relationship is as follows (Vipulanandan et al. 2014):

$$FL_f - FL_o = \frac{t}{D + E * t} \tag{7}$$

where:

D (min/mL) and E (mL^{-1}): model parameters.

From Eqn. (7),

the maximum fluid loss (FL_u) when $t \rightarrow \infty \Rightarrow FL_u = \frac{1}{E} + FL_o$ (8)

The Vipulanandan Fluid Loss model predictions are compared to the experimental results in Figs. 4, 5, 6 and 7. Also the model parameter D and E are summarized in Table 3. The coefficient of variation was 0.99 and the Root Mean Square Error (RMSE) varied from 0.12 to 0.40 mL. In all cases the RMSE for the Vipulanandan Model was lower than the API Model hence it shows a better prediction of the test results.

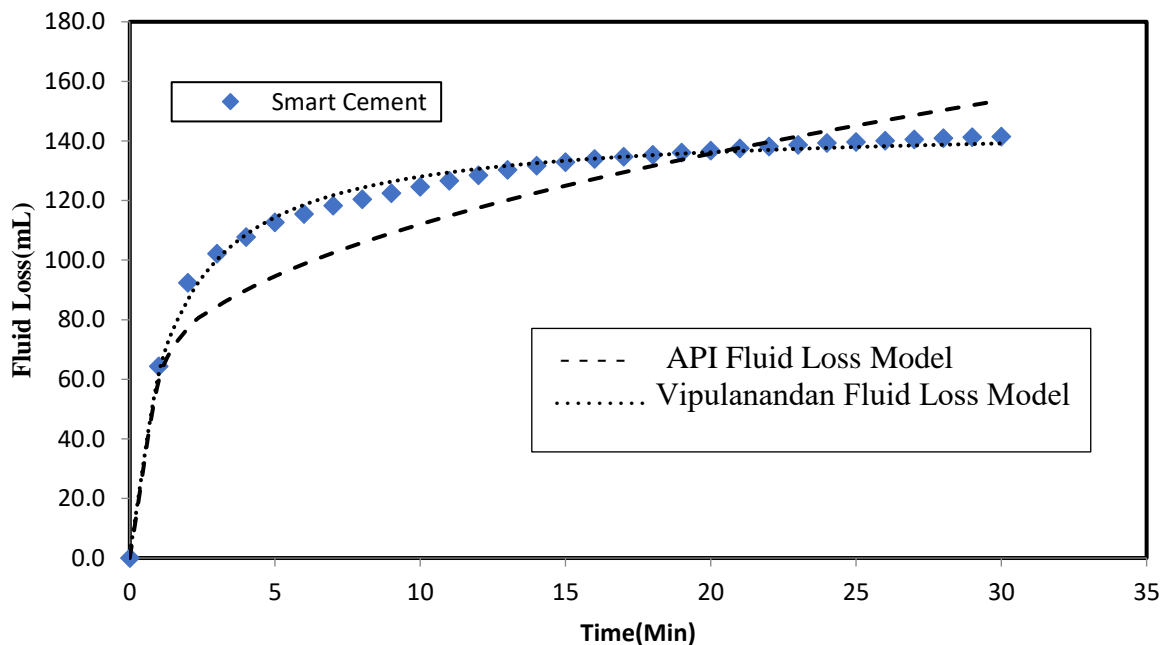


Figure 4. Fluid Loss in Smart Cement after 30 minutes of Curing.

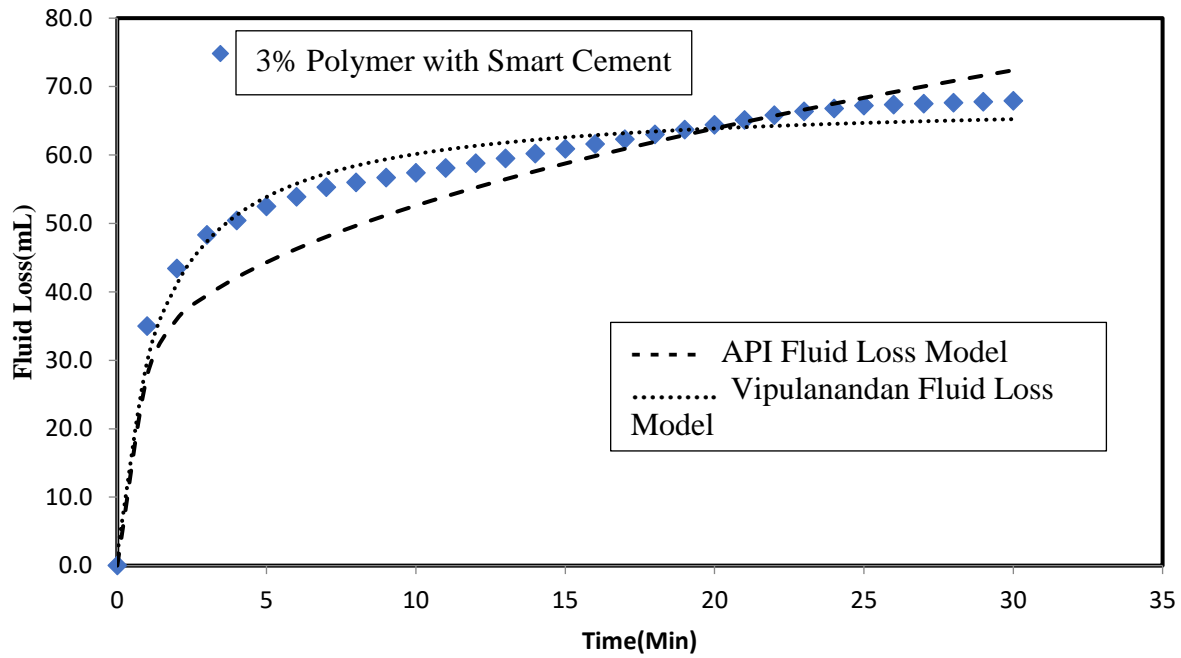


Figure 5. Fluid Loss in Smart Cement with 3% SBR Polymer after 30 minutes of Curing.

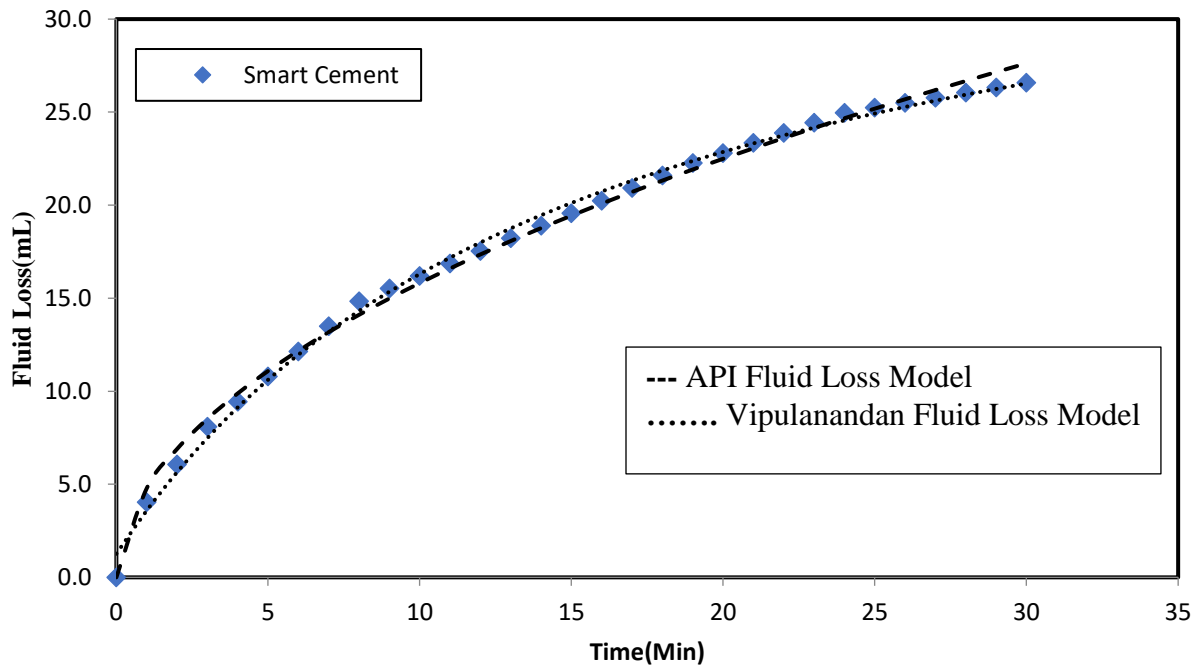


Figure 6. Fluid Loss in Smart Cement after 24 hours of Curing.

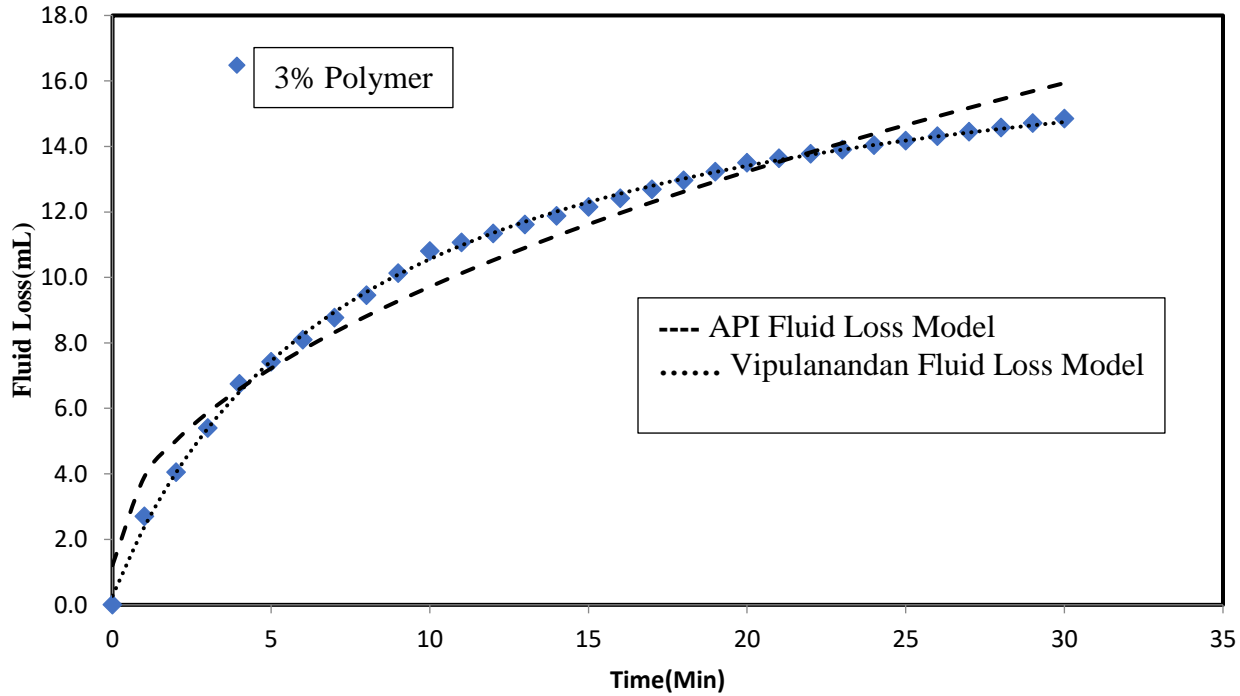


Figure 7. Fluid Loss in Smart Cement with 3% SBR Polymer after 24 hours of Curing.

Table 3. Vipulanandan and API Fluid Loss Model Parameters for Smart Cement and 3% Polymer Modified Smart Cement.

Time(Hrs)	Cement Type	API Fluid Loss Model			Vipulanandan Fluid Loss Model				Figure
		M	RMSE (mL)	R ²	D	E	RMSE (mL)	R ²	
0.5	Smart Cement	5.74	0.65	0.99	.32	.02	0.35	0.99	4
0.5	3% Polymer with Smart Cement	2.68	0.67	0.97	.42	.05	0.12	0.99	5
24	Smart Cement	5.11	0.44	0.99	0.41	0.2	0.40	0.99	6
24	3% Polymer with Smart Cement	2.68	0.67	0.97	.42	0.5	0.12	0.99	7

Gas Leak

The smart cement with and without 3% polymer was tested for gas leak aft 1 hour of curing (slurry) and after 24 hours of curing (solid). The tests were performed to investigate the sensing characteristics of the smart cement during gas leak. Maximum pressure gradient of 2100 psi/ft was use in this study. The pressure gradient was increased and the discharges were measured using the HPHT test facilities (Fig. 1). The resistance changes were monitored continuously during the test. In Fig. 8, the discharge velocity (volume discharge per unit area) for smart cement without and with 3% polymer addition is compared for

specimens cured for one hour. Polymer addition reduced the discharge velocity of gas at all the pressure gradients tested. The maximum reduction in discharge velocity was about 18%. The velocity of discharge and pressure gradient relationship was non linear and hence Darcy’s Law cannot be used. In Fig. 9 the gas leak velocities with pressure gradients are compared in smart cement with and without 3% polymer and the relationship was nonlinear. With the 3% Polymer addition, the maximum gas velocity reduction was about 33%.

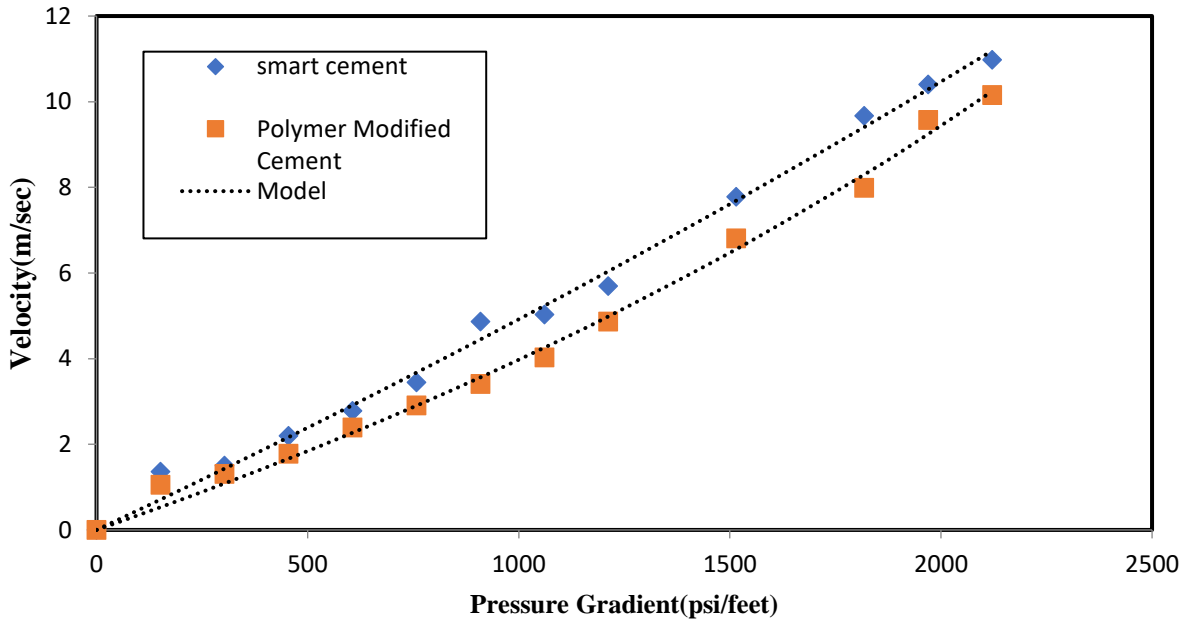


Figure 8. Variation of Gas Discharge Velocity with Pressure Gradient after One Hour of Curing.

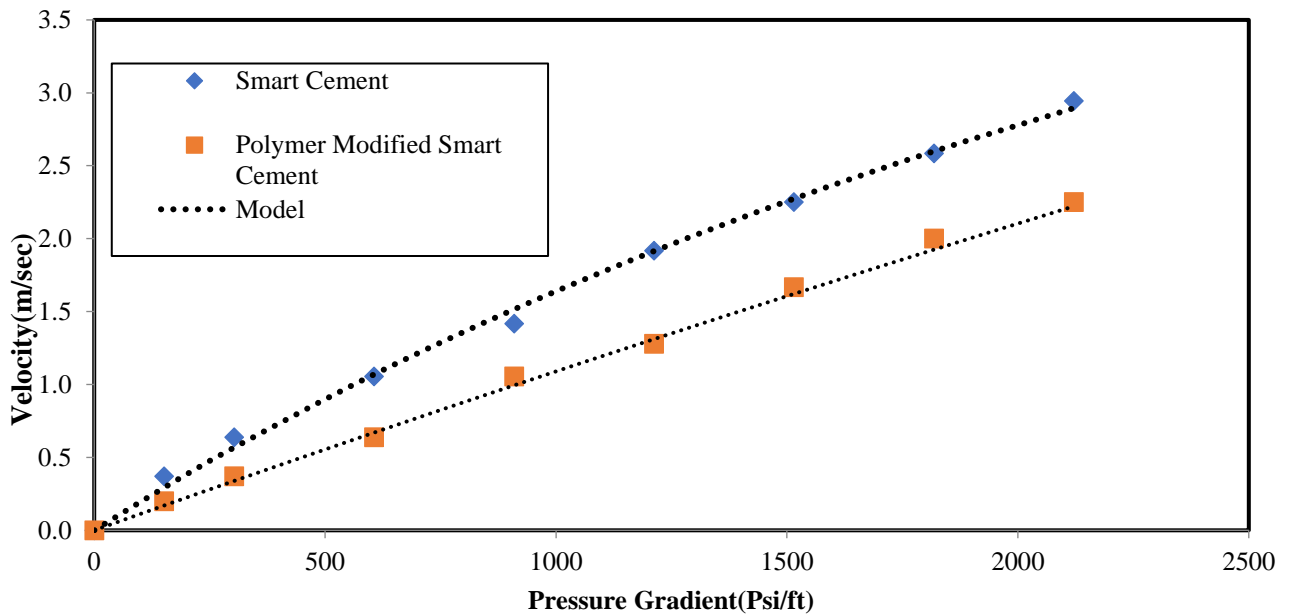


Figure 9. Variation of Gas Discharge Velocity with Pressure Gradient after 24 Hours of Curing.

Table 4. Vipulanandan Gas Flow Model Parameters for Smart Cement with and without SBR Polymer

Cement	Time(hr)	A	B	R ²	RMSE	Figure
Smart Cement	1	215.56	0.01	0.99	0.27	8
3% Polymer with Smart Cement	1	291.27	0.03	0.99	0.23	8
Smart Cement	24	500.44	0.109	0.99	0.09	9
3% polymer with Smart Cement	24	884.1	0.03	0.97	0.13	9

To quantify the gas leak occurring in cement at different pressure gradients and curing time, a new Vipulanandan Fluid Flow Model was developed and represented as follows:

$$V = \frac{\Delta P}{A + B\Delta P} \tag{9}$$

- V = Discharge Velocity (m/sec)
- ΔP=Pressure Gradient (psi/ft)
- A (psi.sec/ft²) =Model Parameter 1
- B (sec/ft) =Model Parameter 2

The model parameters are summarized in Table 4 with the coefficient of determination and RMSE. The Vipulanandan Fluid Flow Model predictions are compared to the experimental results in Figs. 8 and 9 and the predictions were very good.

Sensing Gas Leaks

In the smart cement slurry without and with 3% polymer and cured for one hour due to gas leak the resistivity increased as shown in figure 10. The resistivity increased by 45% and 32% for the smart cement slurry and smart cement with 3% polymer. In the case of hardened cement, the trends were opposite to that of slurry cement. In the smart cement cured for 24 hours, with the addition of pressure the resistivity increased by +80% for compressive stress of 700 psi (Fig. 3) but with gas leaks the resistivity reduced by -35% (Fig. 11). This is a clear indication of sensing characteristic of smart cement. In the case of smart cement with 3% polymer the maximum resistivity change was -12%. By monitoring the resistivity change .gas migration in cement can be detected and quantified.

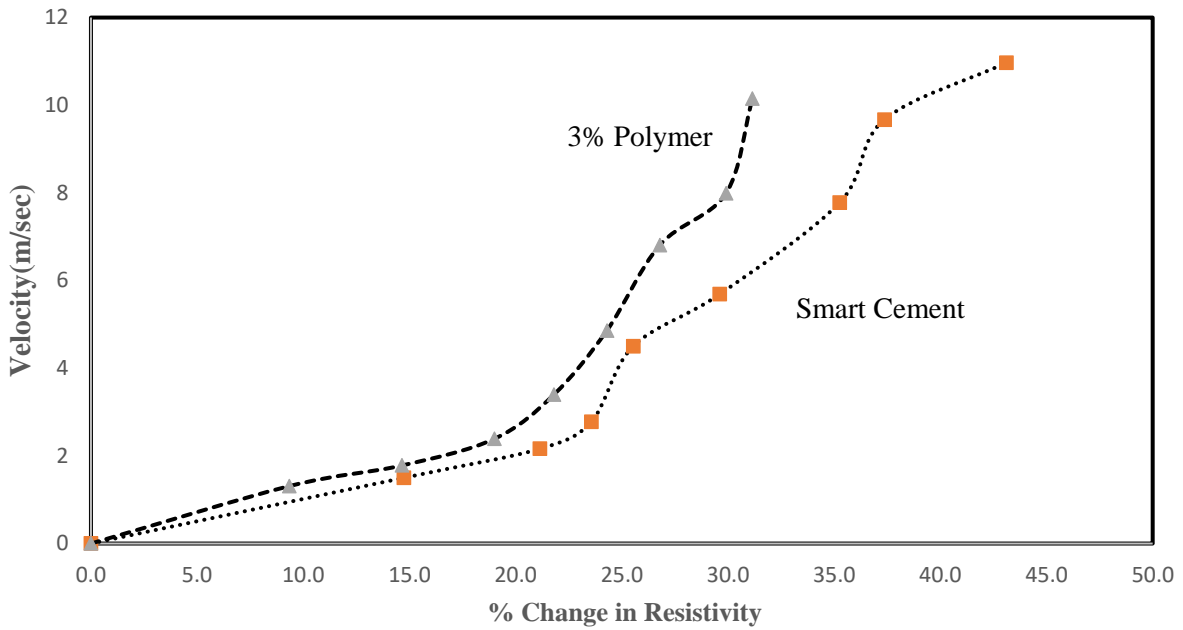


Figure 10. Resistivity Change with Gas Leak for One Hour Cured Smart Cement With and Without 3% SBR.

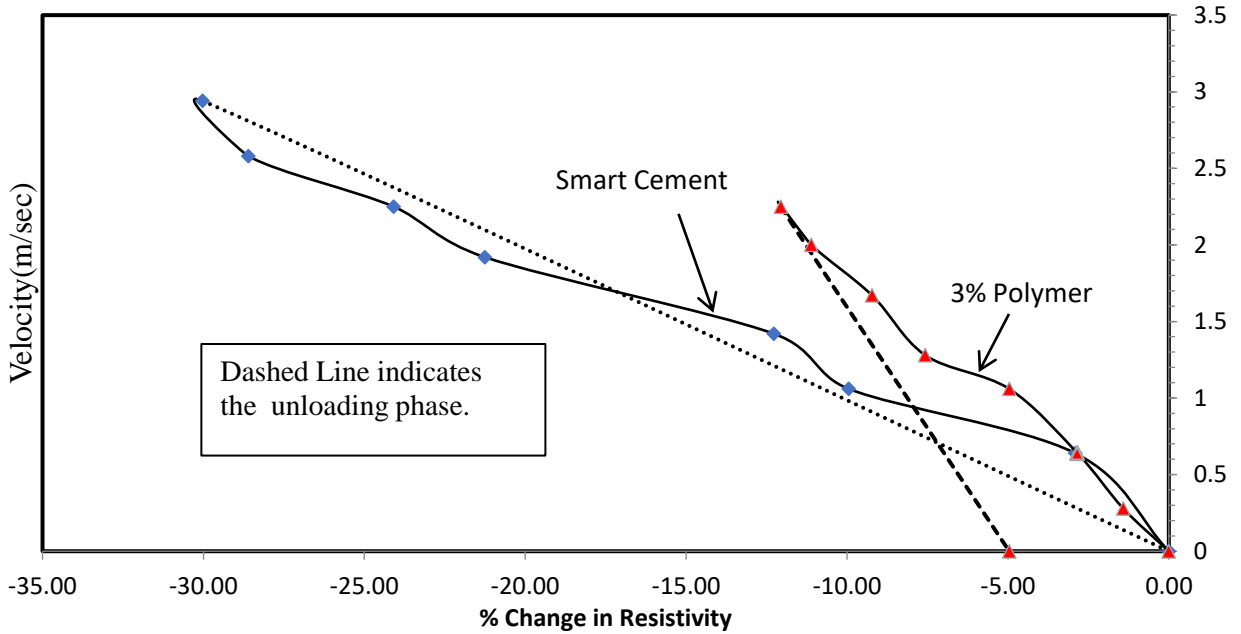


Figure 11. Resistivity Change with Gas Leak for Twenty Four Hours Cured Smart Cement With and Without 3% SBR.

Conclusions

Based on the experimental and analytical study on the smart cement with and without SBR polymer

addition up to 3%, (by weight of cement) the following conclusions are advanced:

1. Addition of SBR polymer increased the initial resistivity of the smart cement. Addition of 1% polymer increased the initial resistivity by 4% and adding 3% polymer increased the resistivity by 12%. Hence resistivity could be a good quality control parameter in the field. Vipulanandan curing model predicted the trends very well.
2. Addition of polymer increased the compressive strength of smart cement after 24 hours of curing. The compressive strength increased by 32% with 3% addition of polymer.
3. With the addition of polymer the smart cement was piezoresistive. The resistivity change at peak stress with 3% polymer addition was over 100% after 24 hours of curing. Vipulanandan p-q piezoresistive model predicted the behavior very well.
4. Fluid loss was reduced with the addition of polymer. With the addition of 3% SBR polymer, the fluid loss for the 30 minutes cured cement slurry was reduced by 52%. Vipulanandan fluid loss model predicted the test results very well.
5. Addition of polymer reduced the gas leak. Smart cement resistivity changes were highly sensitive to the gas leak and can be used to detect and quantify gas leaks.

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