Simulated Field Oil Well with Piezoresistive Smart Cement Performance Monitored Over Seven Years

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Abstract

For optimizing the well cementing, it is important to develop technology to monitor drilling and cementing operation in real time during the well installation to minimize operation delays, failures and ensure safety. In this study, the potential of using the smart cement in installation of a field well was tested for real time monitoring using a field model for a period of 7.5 years. The field well model of 40 ft. deep were instrumented and being monitored for changes in electrical resistivity, during curing and applied stresses over period of 7.5 years (2700 days). The piezoresistivity of the smart cement response was related to the casing pressure using a nonlinear relationship. Electrical resistance was used as real time monitoring parameter for long term cement condition prediction. The smart cement used to cement the field well was very sensitive to the applied pressure, piezoresistive cement. Using the Vipulanandan p-q stress-piezoresisitive model the change in electrical resistivity of smart cement was related to the applied pressure in the casing.

Introduction

In oil well cementing, cement is poured in and flows up, reinforcing the space between the wellbore and the casing. This cement reinforcement is critical to the integrity of the well. Over $40 billion in damages, 4 million barrels of oil spilled into the Gulf of Mexico, and 11 Workers were killed with the 2010 Oil Spill. One of the main contributing factors that caused this event was the cementing, which did not set properly in the oil well.

As deepwater exploration and production of the oil and gas expands around the world, there are unique challenges in well construction beginning at the seafloor. 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. Moreover, the environmental friendliness of the cements is a critical issue that is becoming increasingly important (Durand et al., 1995; Thaemlitz et al., 1999; Dom et al., 2007). Lack of cement returns may compromise the casing support and excess cement returns cause problems with flow and control lines. 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.

Vipulanandan et al., (2014) have developed smart cement with real time monitoring ability. They have used electrical resistivity as the sensing property to quantify changes in the cement due to pressures, temperatures, contaminations, corrosion and cracking.

Cementing operation during oil well installation is important to provide effective inter-zonal isolation and protect casing string from fluid formation. It will serve the production of oil economically and safely over the well's lifetime. Real time monitoring of the cementing is necessary to prevent failures in the oil wells.

Several nondestructive methods have been used by researchers to monitor and characterize the behavior of cementitious materials, such as impact-echo, pulse-echo, ultrasonic pulse velocity, wave reflection, resonant frequency, acoustic emission and microwave adsorption methods (Panzera et al., 2011). Use of these methods has two major drawbacks. Firstly, these methods only give snapshot of the data and do not provide any kind of real time monitoring. Secondly, implementation of all these techniques require temporary stopping of the well operations. Recently, nondestructive real time monitoring system with monitoring the cement sheath from outside the casing using instrumentation was developed by using electrical resistivity measurements (Vipulanandan et al., 2015).

The well cement was monitored using cement bond logs and ultrasonic cement evaluation (Spoerker et al., 2002). Cement bond logs can give a reasonable estimate of bonding and a semi-quantitative idea of presence or absence of larger cement channels but will not certify pressure or fluid isolation of a zone. Cement bond logs have been proven to miss a percentage of smaller channels in cement, even under ideal conditions (Hill, 1990). Bond logs have failed to show bond in many wells that proved to be well isolated in a differential pressure test. Error within the application and interpretation of cement bond logs has resulted in numerous workovers to repair cement that was not faulty, resulting in higher costs and a decrease in the well integrity by unnecessary perforating and attempts to block using squeeze cement (George, 2012).

The smart cement can be used for real-time monitoring while it sustains its structural properties. Electrical resistivity has been considered as a monitoring parameter since it is a material property, which is sensitive to the changes inside the material, during setting and hardening (McCarter et al., 1990).

There is emerging interest in characterizing and determination of performance properties of cements under various conditions. Some modifications such as introducing additives can be done to improve the physical and sensing properties of oil well cement. Preparation of smart cement material sensitive to stresses, temperatures, cracks, contaminations enables us to monitor the changes in the material with high accuracy over long period of time. Hence, it is important to optimize the composition of the materials and also experimentally characterize these materials.

Oil and Gas Well Drilling and Cementing

The Oil and gas industry has emerged as one of the most powerful branches of world economy. More than four billion metric ton of oil is produced around the world annually. The United States is the largest producer, generating over 12 percent of the world's total oil production.

The United States likely surpassed Russia and Saudi Arabia to become the world's largest crude oil producer earlier in 2018 with production close to 12 million barrels per day. The global oil consumption is experiencing ever increasing demand with an increase from 70 million barrels a day in 2000 to 95 million barrels a day in 2015. This increase is leading to increase of deep-water explorations with about 272 wells in 2014 and 169 wells in 2015. Cementing of these oil wells at higher depth is leaving new challenges. It is attributed that about 60% of the oil and gas failures a result of poor cementing job. One of such consequence is the recent BP Oil spill in 2010. $40 Billion in damages, 4 Million barrels of oil spilled into the Gulf of Mexico, and 11 Workers killed with the 2010 BP Oil Spill. One of the main contributing factors that caused this event was the cement, which did not set properly in the BP's oil wells. All these incidents magnify the importance for the improvement of cementing operations and its monitoring. Oil well cementing is defined as the process of placing of the cement in the annulus between casing and well bore. This oil well cementing is part of process of preparing the well for further drilling, production or abandonment.

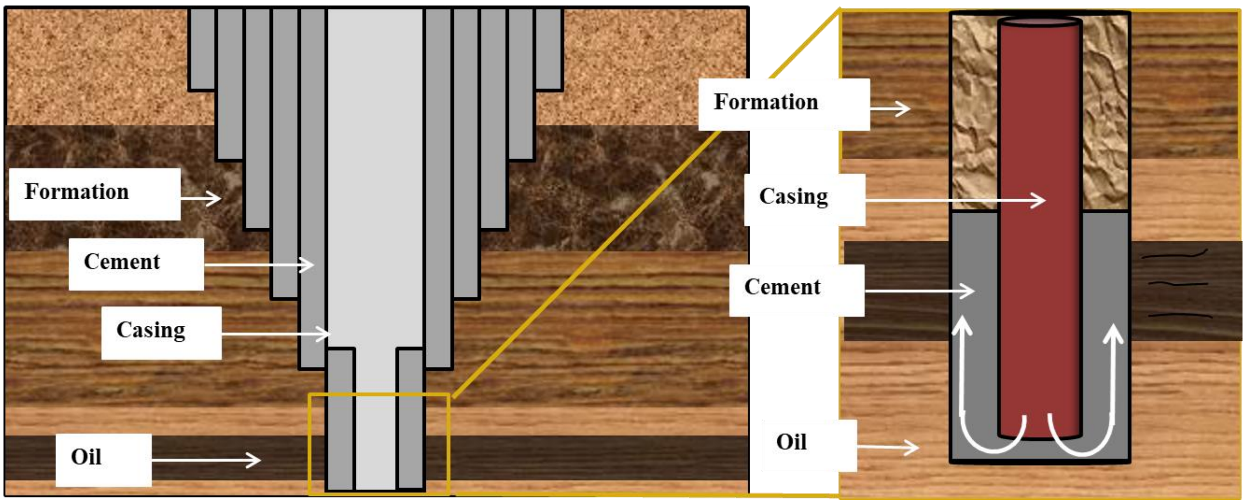

Figure 1 Oil well Cementing.

The cementing is generally used for number of uses, mainly serving as protection and sealing for the wellbore. Most commonly, cementing is used to permanently shut off water penetration into the well. Additionally, cementing is used to seal a lost circulation zone, or an area where there is a reduction or absence of flow within the well. In directional drilling, cementing is used to plug an existing well, in order to run a directional well from that point. Also, cementing is used to plug a well to abandon it.

Cementing is performed when the cement slurry is deployed into the well via pumps, displacing the drilling fluids still located within the well, and replacing them with cement (Figure 1). The cement slurry flows to the bottom of the wellbore through the casing and then flows up. From there it fills in the space between the casing and the actual wellbore and hardens. This cement reinforcement is critical for the integrity of the well. This creates a seal so that outside materials cannot enter the well flow, as well as permanently positions the casing in place. The creation and life of a well can be divided up into four stages: (a) Planning, (b) Drilling, (c) Completion, (d) Production.

Production

The production stage is the most important stage of a well's life; when the oil and gas are produced. By this time, the oil rigs and work over rigs used to drill and complete the well have moved off the wellbore, and the top is usually outfitted with a collection of valves called a Christmas tree or production tree. These valves regulate pressures, control flows, and allow access to the wellbore in case further completion work is needed. From the outlet valve of the production tree, the flow can be connected to a distribution network of pipelines and tanks to supply the product to refineries, natural gas compressor stations, or oil export terminals.

As long as the pressure in the reservoir remains high enough, the production tree is all that is required to produce the well. If the pressure depletes and it is considered economically viable, an artificial lift method mentioned in the completions section can be employed.

The production stage is the most important stage of a well's life, when the oil and gas are produced. Enhanced recovery methods such as water flooding, steam flooding, or CO_2 flooding may be used to increase reservoir pressure and provide a "sweep" effect to push hydrocarbons out of the reservoir (Zitha et al., 2011). Such methods require the use of injection wells (often chosen from old production wells in a carefully determined pattern) and are used when facing problems with reservoir pressure depletion, high oil viscosity, or can even be employed early in a field's life. In certain cases – depending on the reservoir's geomechanics – reservoir engineers may determine that ultimate recoverable oil may be increased by applying a water flooding strategy early in the field's development rather than later. Such enhanced recovery techniques are often called "tertiary recovery.” The Oil well cannot be monitored for leaks and other structural damages occurring in the cement during its lifetime (Syed, 2017).

Improving Cementing and Monitoring

With some of the reported failures and growing interest in environmental and economic concerns in the oil and gas industry, integrity of the cement sheath is of major importance (Vipulanandan et al., 2014). Due to the Hazards and the number of unsuccessful events, researchers are reviewing on the feasibility of monitoring of the installation process and as well as the cement during its lifetime. Cement reinforcement between piping and earth is a standard for all downhole operations in the oil and gas industry, including drilling, fracking, and natural gas storage. And when this cement fails, the environmental consequences can be severe. The oil well operators are required to monitor their wells to prevent the occurring of disasters.

Today, this is achieved through a process called wireline testing which was developed in the 1970’s and has been the industry standard for downhole monitoring ever since. The general type of wireline testing includes Cement Bond logs, Sonic and ultrasonic logs and Triple Combo.

However, the wireline testing has two fundamental problems. First, to get well data using wireline testing, operators have to drop measurement tools into a well. But to do this, they must temporarily shut down that well. This costs millions of dollars over the lifetime of an operation because they aren’t producing in that time. The second problem is that it can only provide data while those tools are dropped in the well. So, once they take the tools out and start producing again, operators no longer have any idea how the cement is doing. In other words, they can’t really monitor their well, they can only check in on it.

Real time monitoring of the cement during its installation and through the life of the well is hence gaining importance. The structural integrity of the civil infrastructure is essential for the safety, productivity and quality over the life of the well (Chung et al., 2003). Thus, there is need for monitoring damage nondestructively, so that timely repair of the oil wells takes place. Real time monitoring gives information on the time, load condition or other conditions at which damage occurs, thereby facilitating the evaluation of the cause of the damage.

Structural Health Monitoring Materials

The damage in cement-based materials is most commonly studied by destructive mechanical testing; however, there is an increasing interest in nondestructive testing of materials. Electrical resistivity measurement has been used by many researchers to characterize the cement concrete and in other applications.Concrete is a poor electrical conductor and hence it requires the presence of conductive particle or fibers that are added to attain stable and accurate conductive properties. The design formulation of conductive cements is based on the "Electrical Percolation" principle by which the cement matrix conductivity increases with increasing conductive particles and reaches a critical value. The commonly used additives for making cement matrix conductive include carbon fibers, steel fibers, carbon black, coke breeze, ferrous compound, high carbon fly ash and other materials (Garas et al., 2003; Chung et al., 2003; Vipulanandan et al.,2014; Naik et al., 2010; Wei et al., 2008) . From the recent studies, it was observed that about 60% use carbon fibers as their conductive particles. The cement matrix with electrically conductive properties makes it smart material that has important applications in self health monitoring systems. The fibers enhance the damage sensing ability of the cement matrix.

The conventional methods of measuring the electrical resistivity of cementitious materials can be categorized into direct current (DC) methods and alternating current (AC) methods, where of both electrodes are needed for the measurements (Vipulananadan et al., 2014). The DC methods can be categorized into two or four probe methods. About 60% of the researchers use DC four probe method. The use of AC two probes was limited to very few researchers. The number of studies on electrical characterization of foam cement was very limited (Sugama et al., 2004) and was only to extent of impedance characterization. Some of the recent studies aimed at microstructural evolution in hydrating cement-based material systems using non-contact electrical resistivity methods (Wei et al., 2008). Use of electrical resistivity measurements for sensitivity has been proven advantageous at microscopic level. The presence of electrically conductive fibers in the cement-based materials is necessary for the piezoresistivity to be sufficient in magnitude and in reversibility.

A material is said to be piezoresistive if resistivity of that material changes under applied stress. Piezoresistivity has been proven to be a good sensing property in the literature (Carmona et al., 1987; Vipulanandan et al., 2015). It can be used to sensing of stress/strain, damage and thermoelectric properties and monitor health of the structure and more. Development and characterization of piezoresistive smart structural materials led a new path to study on Piezoresistive Structural Sensors (PRSS). The researchers have studied electrical resistivity with curing time, changes in electrical resistivity with loading, fiber content and impedance characterization under electrical characterization of cement-based materials. (Vipulanandan et al., 2004 & 2021).

Smart Cement

Primary energy consumption continues to accelerate globally despite several years of slow economic growth. With increased consumption, production of oil continues to grow surpassing record level of 90 million barrels per day worldwide. Not only does the oil industry need to produce more to meet ever increasing demand, it also needs to overcome existing well production declines. All active wells ultimately decline in production as resources are tapped, though there is an opportunity for technology to slow or in some cases even temporarily reverse those decline rates. In addition, as existing wells decline, more and more new wells need to be drilled to keep up with demand. This is leading to exploration of oil at very large depths where the formations are very weak, fragile with lost circulation zones. Hence the need for cement monitoring system during its installation and the life of the well are the driving factors for the study.
Use of smart cement ensures the following:

- Safe Installation: The installation process of the cement sheath can be monitored continuous and this gives the scope for monitoring the quality of cementing during the installation process.
- Monitor Cement Profile: The smart cement technology enables us to know exactly the level of the cement and the drilling muds which helps in monitoring any formation failures. The cement sheath can be monitored as it is curing over its lifetime. This enables us to monitor or detect any failures or changes in the cement.
- Monitor Cement Quality: The quality of the cement can be monitored using resistivity measurements. The effect of fracturing or any mechanical operations on cement can be identified.
- Monitor the Cement sheath bonding: The bond between cement and casing is critical for zonal isolation. Smart cement technology helps us monitor the integrity of the well by monitoring the bond.
- Monitor the Stresses: Smart cement monitors both the physical and thermal stresses coming on to the oil well system and notifies the possible damage that can occur in the well in advance to provide scope for repair and reconstruction.
- Prevent Failures like Macondo, 2010: Enhanced smart monitoring system can help prevent accidents as it is the most sensitive technology available to monitor the stresses.

Figure 2 and **Error! Reference source not found.** show the typical stress-strain and piezoresistive behavior of the neat cement and smart cement. Cement generally fails at 0.2% strain. Monitoring this low strain needed very accurate measurements of the data which is not easy.

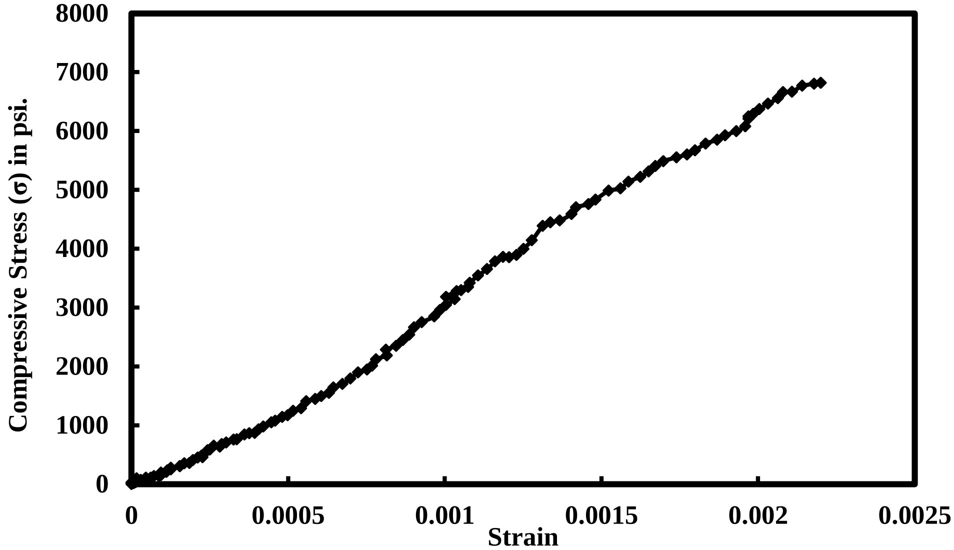

Figure 2 Typical Compressive Stress Strain Behavior of Cement.

The smart cement technology can monitor the changes in the cement at very high magnification of about 2500 times after one day curing (Vipulanandan et al., 2014). The main property of interest is piezoresistivity, the change in the resistivity of the cement with the application of the stress. Also, the rheological properties were not affected by the addition of conductive filler (Vipulanandan et al., 2014).

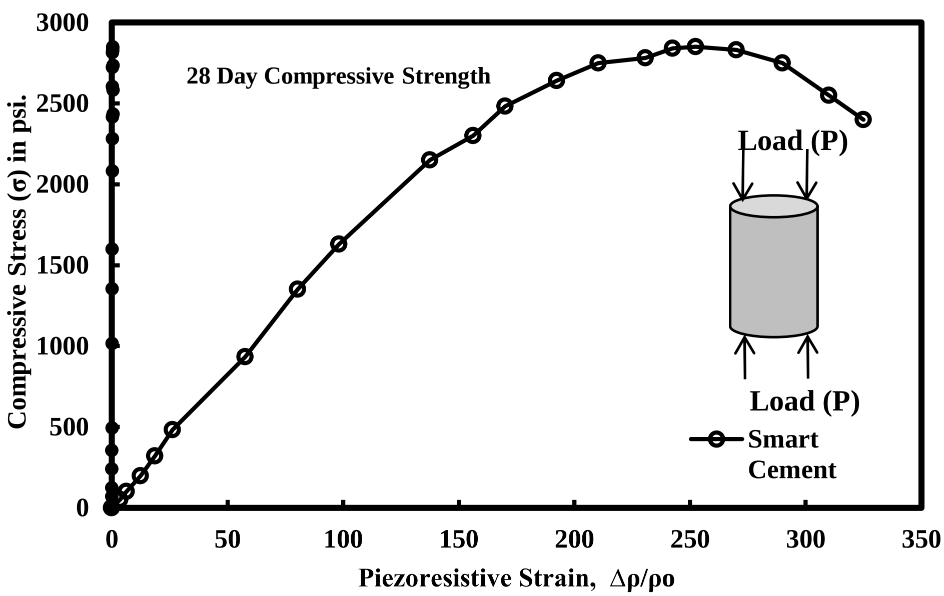

Figure 3 Typical Piezoresistive Behavior of Smart Cement

2. Objective

The overall objective is to continuously monitor the smart cemented well. The specific objectives are as follows:

1. Evaluate the monitoring setup in the field to determine the durability and fuctioality of the smart cement.
2. Collect data on resistances using the two probe method and AC current, strain gages and thermocouples.
3. Perform pressure tests to evaluate the piezoresistivity of the smart cement in the field.

3. Materials

Materials

Cement

To study the effect of smart cement, the class H oil well cement was used.

Smart Cement

Commercially available oil well cement (Class H cement) was modified with conductive fillers to make it a piezoresistive material. The Cement was modified by adding about 0.1% of conductive filler (CF), by weight, and the water to cement ratio was 0.38.

4. Field Testing

Field Model Well

- Resistivity of smart cement: The LCR meter was used to measure the impendence (resistance, capacitance and inductance) in the frequency range of 20 Hz to 300 kHz. Based on the impedance (z) – frequency (f) response it was determined that the smart cement was a resistive material (Vipulanandan et al., 2013). Hence the resistance measured at 300 kHz using the two-probe method was correlated to the resistivity (measured using the digital resistivity device) to determine the K factor for a time period of initial five hours of curing. This K factor was used to determine the resistivity of the cement with the curing time.

- Piezoresistivity test: Piezoresistivity describes the change in electrical resistivity of a material under stress. Since oil well cement serves as pressure-bearing part of the oil and gas wells in real applications, the piezoresistivity of smart cement (stress – resistivity relationship) in these wells is obtained by application of pressure in the central casing for the lab model and in the aluminum pipes for the field model. To eliminate the polarization effect, AC resistance measurements were made using a LCR meter at frequency of 300 kHz (Vipulanandan et al., 2013).

Test Site and Soil Characterization

After careful reviewing, Energy Research Park (ERP) at University of Houston was selected to install the field well. The selected site had swelling clays with fluctuating moisture conditions (active zone) which represents nearly the toughest conditions encountered. The top 20 ft. of the soil was swelling clay soil with liquid limit over 50%. Based on the ASTM classification the soil was characterized as CH soil. The water table was 20 ft. below the ground and soil below the water table was also clay with less potential swelling and the liquid limit was below 40%. Based on ASTM classification, this soil was characterized as CL soil (Figure 4).

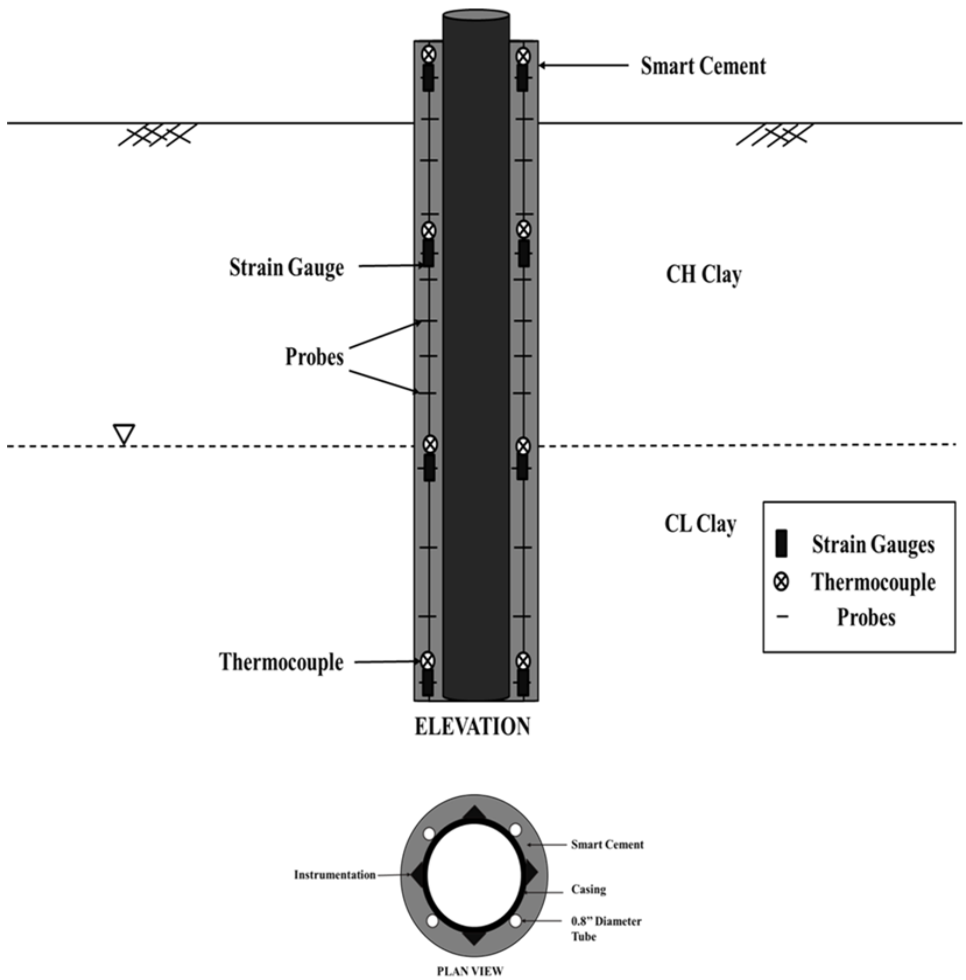

Figure 4 Profile of Strain gauges, thermocouples and resistivity probes in the model.

Electrical Resistance

The smart cement was mixed in the field and used for cementing the field well. It is important to identify the measurable parameters in the cement sheath and determine the changes with time and depth. Fiber optics are used for monitoring and it depends in the changes in the strain in the cement sheath. The strain in the cement will be influenced by the cement curing, stress and temperature in the cement sheath. Over the past 7.5 years (over 2700 days) thousands of data has been collected on the monitoring parameters. It is important to quantify the changes in the measuring parameters with important variable such as depth. In order to investigate the changes with depth, top level (CH soil), middle level (above the water table, CH soil) and the bottom level (below the water table, CL soil) were selected for investigation.

Top Level

Resistance (R): The top level was about 1 ft. below the ground surface. The initial resistivity of the smart cement measured using the two probes was 1.03 Ω.m comparable to the laboratory mixed cement of 1.05 Ω.m. The resistance in the top level changed from 22 Ω to 318 Ω, about 13.5 times (1350%) change in the resistance (Figure 5). The changes in the cement sheath resistance were not uniform but overall showed continuous increase. The rapid increase in the cement resistance was due to the lowering of the environmental temperature and losing of moisture in the cement. The rapid decrease in the cement resistance was due to increase in the environmental temperature and saturation of the cement due to flooding.

Temperature (T): The temperature continuously fluctuated with time with no clear trend. Over the 7.5 years the minimum and maximum measured temperature in the cement sheath was 68^{o}F (20.1^{o}C) and 97.2^{o}F(36.2^{o}C), maximum change of 42.8% (Figure 5). The average temperature at the top level was about 77.7^{o}F (25.4 ^{o}C), a 14% decrease from initial temperature of 90.3^{o}F (32.4^{o}C) which was due to the cement column hydration.

Strain (S): The strain gauge resistance increased from 123 Ω to 133 Ω during the period of 4.5 years with some fluctuations. The change in strain gage resistance was about 8.1%. The tensile strain at the top level was about 3.3xE-6.

Based on the measured monitoring parameters in the cement sheath, change in electrical resistance showed the largest change compared to the changes in temperature and strain. Hence it is important to develop models to predict this change with time for monitoring the well.

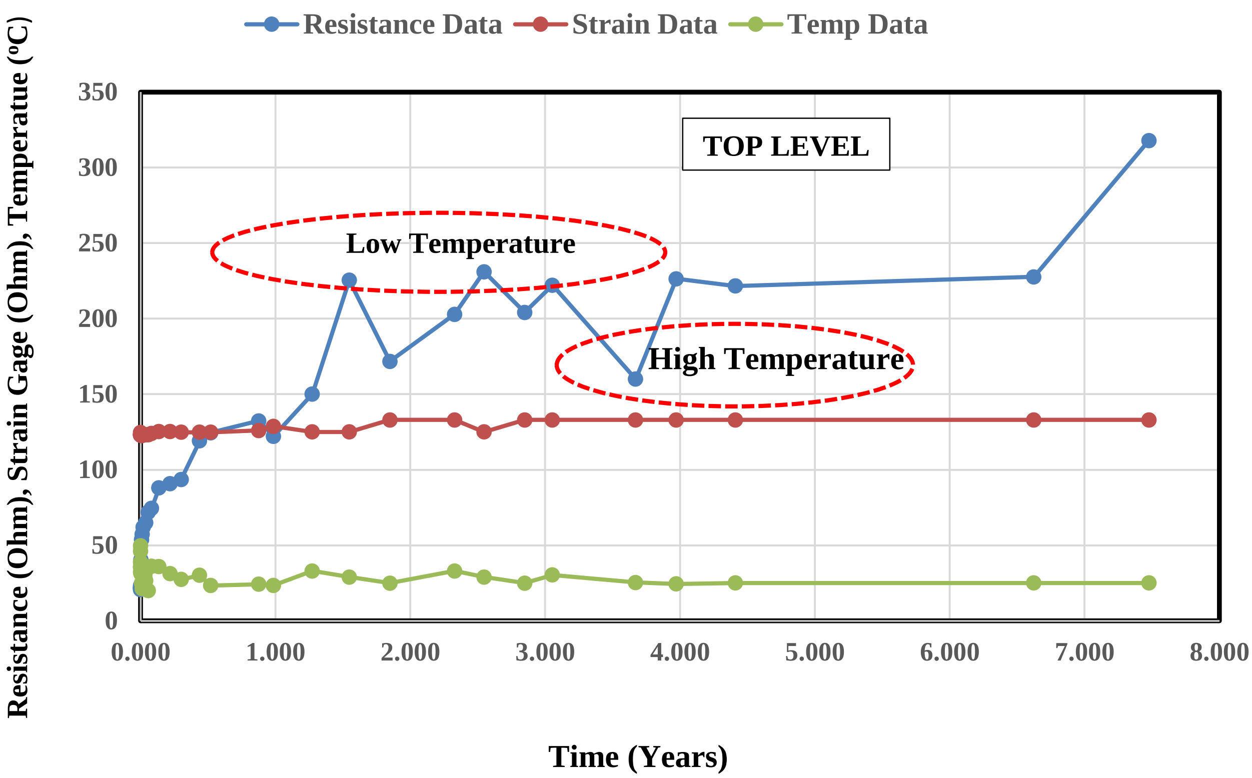

Figure 5 Changes in the Electrical Resistance, Strain and Temperature variation in Top Level over 7.5 years

Middle Level

Resistance (R): The middle level was about 15 ft. below the ground level and above the water table. The initial resistivity of the smart cement measured using the two probes was 1.24 Ω.m higher than top level of 1.03 Ω.m and the laboratory mixed cement of 1.05 Ω.m. The resistance in the top level changed from 26.5 Ω to 193 Ω, about 6.28 times (628%) change in the resistance (Figure 6). The changes in the cement sheath resistance were not uniform but overall showed continuous increase. The rapid increase in the cement resistance was due to the lowering of the environmental temperature and losing of moisture in the cement. The rapid decrease in the cement resistance was due to increase in the environmental temperature and saturation of the cement due to rising of the water table because of flooding.

Temperature (T): The temperature continuously fluctuated with time with no clear trend. Over the 7.5 years the minimum and maximum measured temperature in the cement sheath was 70.9ºF (21.6ºC) and 95.5ºF(34.7ºC), maximum change of 34.7% (Figure 6). The average temperature at the middle level was about 78.8ºF (26 ºC), a 18% decrease from initial temperature of 96.4ºF (35.8ºC) which was due to the cement column hydration.
Strain (S): The strain gage resistance increased from 124 Ω to 132 Ω during the period of 4.5 years with some fluctuations. The change in strain gage resistance was about 6.5%. The tensile strain in the middle level was 3.65xE-6.

Based on the measured monitoring parameters in the cement sheath, change in electrical resistance showed the largest change compared to the changes in temperature and strain. Hence it is important to develop models to predict this change with time for monitoring the well.

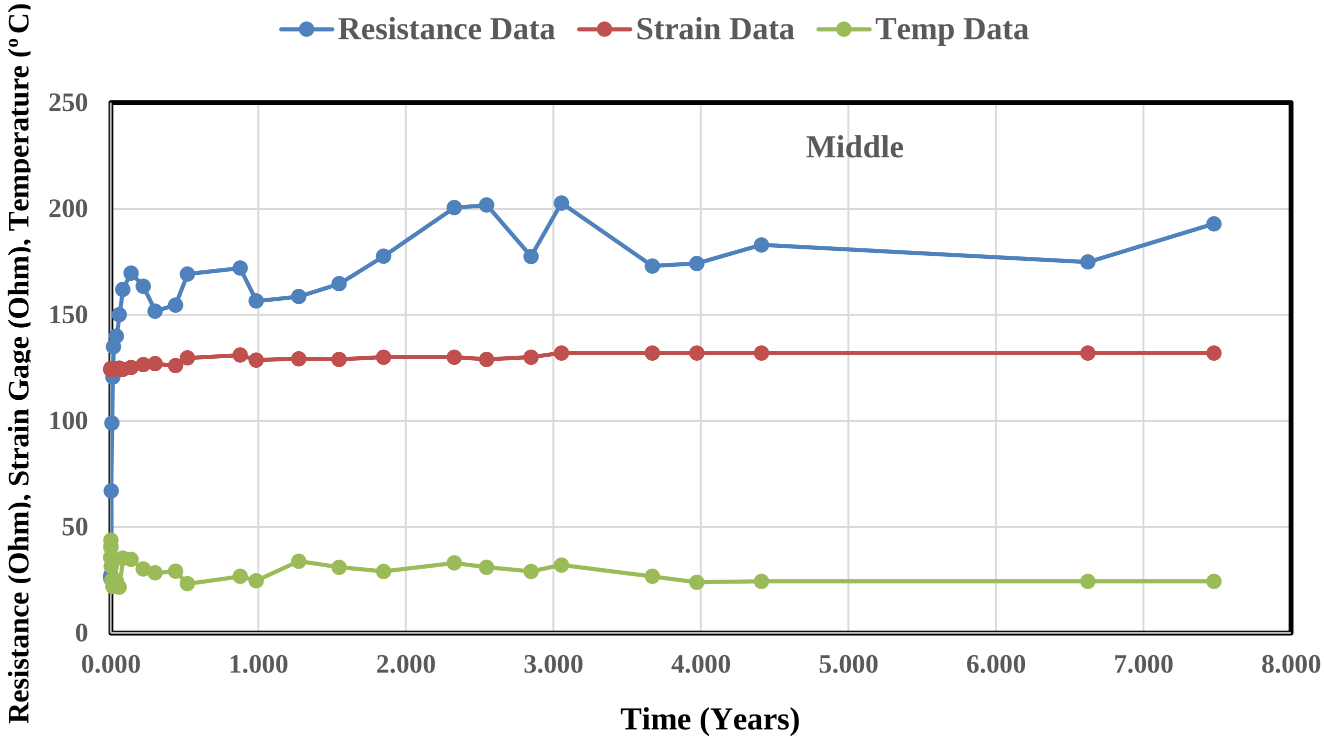

Figure 6 Changes in the Electrical Resistance, Strain and Temperature variation in Top Level over 7.5 years

Bottom Level

Resistance (R): The bottom level was at 36 ft. below the ground and was under the water table. The initial resistivity of the smart cement measured using the two probes was 1.32 Ω.m higher than top level of 1.03 Ω.m and the laboratory mixed cement of 1.05 Ω.m. The resistance in the bottom level changed from 28.2 Ω to 105.9 Ω, about 2.76 times (276%) change in the resistance (**Error! Reference source not found.**). The changes in the cement sheath resistances were uniform and overall showed continuous increase. The minor fluctuations are due to changes in water table level due to flooding.

Temperature (T): The temperature fluctuated with time but was much less than the middle and top levels. Over the 7.5 years the minimum and maximum measured temperature in the cement sheath was 71.1°F (21.7°C) and 91.4°F (33°C), maximum change of 28.6% (**Error! Reference source not found.**). The average temperature at the bottom level was about 77°F (25°C), a 15.8% decrease from initial temperature of 91.4°F (33°C) which would have been influenced by cement hydration.

Strain (S): The strain gage resistance increased from 124 Ω to 133 Ω during the period of 7.5 years with some fluctuations. The change in strain gage resistance was about 8.6%. The tensile strain at the bottom level was 4.8xE-6.

Based on the measured monitoring parameters in the cement sheath, change in electrical resistance showed the largest change compared to the changes in temperature and strain. Hence it is important to develop models to predict this change with time for monitoring the well.

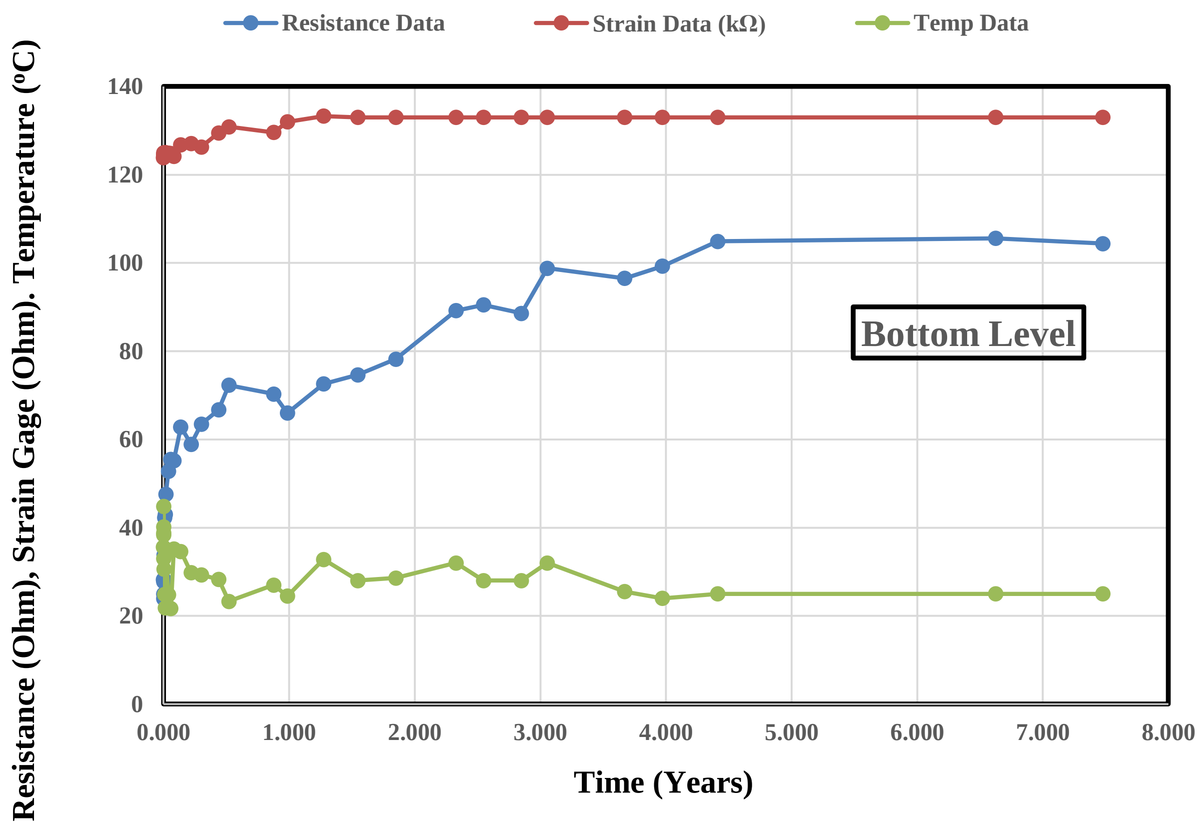

Figure 7 Changes in the Electrical Resistance, Strain and Temperature variation in Bottom Level over 7.5 years

Pressure Test

It is important to demonstrate the piezoresistivity of smart cement in the field. Also, it is important to show the sensitivity of smart cement for small pressure changes. Hence the test was performed at 10 psi (0.07 MPa) increments up to 80 psi (0.55 MPa). The maximum value of piezoresistive strain for smart cement after 7.5 years of curing was 13.5% at a stress of 0.55 MPa (Figure 8). This is a clear demonstration of sensitivity of the smart cement. The piezoresistivity per unit stress was 0.17%/psi for field model after 2700 days of field curing. Also, by measuring the piezoresistive strain in the smart cement it will be possible predict the pressure in the casing using the models. The value of model parameters p_2 and q_2 for piezoresistivity model are 0.025 and 0.417. The model had a of 0.02 Ω-m. with a coefficient of determination of 0.99 (**Error! Reference source not found.**).

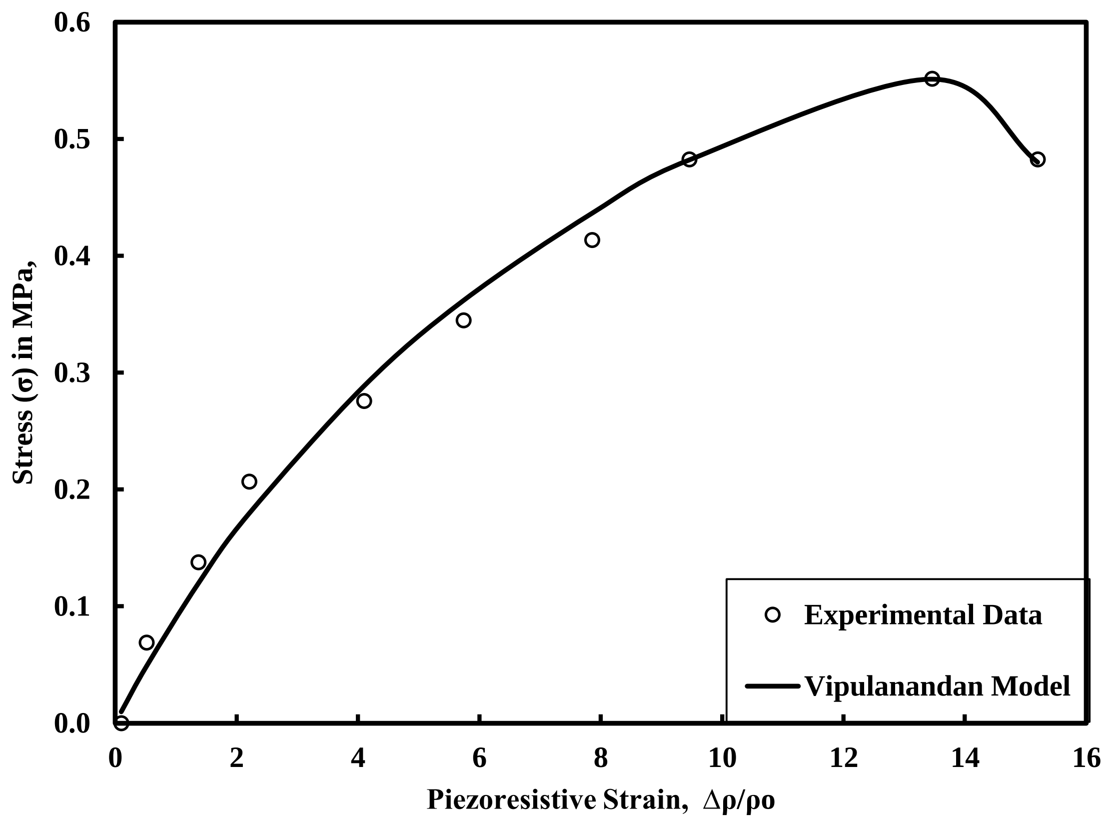

Figure 8 Piezoresistive Strain for smart cement in the field after 7.5 years of curing.

5.Conclusions

Based on the resistand, strain gage and thermocouple monitoring of the field test following conclusions are advanced.

i) The two-probe method was effective in measuring the bulk resistance of the smart cement column at all levels.. The resistance increased at all levels by varying percentages. The changes in strain and temperatures also varied with the depth.

ii) The smart cement used to cement the field well was very sensitive to the applied pressure, piezoresistive cement. Using a nonlinear p-q model the change in electrical resistivity of smart cement was related to the applied pressure in the casing.

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