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Field Evaluation of Pre-Job Test Protocol for Cement Pulsation

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ABSTRACT

Cement pulsation is a relatively new technology to counteract the problem of flow after cementing by delaying the development of gel strength and suppressing the loss of wellbore pressure that can cause flow after cementing. A cement testing protocol for cement pulsation and our experience applying it to an actual, instrumented, cement pulsation job in the field are described. The protocol uses conventional mud and cement lab test equipment to measure the mud and cement properties that determine the feasibility of, and allow simple performance predictions for, cement pulsation for a particular field application.

INTRODUCTION

Cement pulsation (CP) is the application of pressure pulses to a recently cemented annulus while the cement is curing. It was originally proposed by Haberman[1] as a potential means of suppressing the problem of flow after cementing. Recent full-scale experiments in a test well have demonstrated that the application of pulsation can prevent the development of gel strength in high gel strength, non-Newtonian fluids[2]. Recent field trials[3,4] have demonstrated that cement pulsation delivers pressure pulses that can be detected by pressure sensors installed at the bottom of a cemented annulus and that can delay the development of cement gel strength and therefore can delay or prevent the loss of wellbore pressure that can cause flow after cementing.

Cooke et al[5] measured pressures in the annuli of several wells during and following cement jobs. Those tests proved that pressure in a cement column typically decreases as the cement cures. This decrease in hydrostatic pressure is widely accepted as the cause of flow after cementing. The loss of pressure is generally understood to result from the combination of decreasing downhole cement volume due to filtrate losses and/or hydration and increasing cement gel strength opposing fluid movement to restore downhole pressure. The results of this phenomenon may be insignificant, may be flow after cementing that requires remedial cementing to restore wellbore integrity, or in the worst cases, results in a surface or underground blowout.

John Haberman[1,6] the inventor of cement pulsation, described the process and its early applications. Recent research to both develop and evaluate the effectiveness of the cement pulsation process has been documented by Newman et al[3,4]. They provide detailed descriptions of the process, its practical application in instrumented field trials on actual primary cement jobs, and the results of those trials. Analytical modeling of the cement pulsation process to provide improved job design, job monitoring, and post-job analysis has been described by Manowski and Wojtanowicz[7], Kunju and Wojtanowicz[8], and Chimmalgi[9]. Although this modeling requires fluid rheology parameters to predict or analyze the performance of a pulsation job, a protocol to measure such parameters did not exist. Therefore the work and the resulting protocol described herein was conducted to correct that shortcoming. The protocol was developed as part of an overall effort to both conclusively evaluate and to develop the cement pulsation technology.

PROPOSED CEMENT TESTING PROTOCOL

A cement testing protocol for cement pulsation is proposed which is analogous to the pre-job tests performed for conventional primary cementing operations. The protocol uses conventional mud and cement lab test equipment to measure the mud and cement properties that determine the feasibility of, and allow simple performance predictions for, cement pulsation for a particular application. The most important properties are a pulsation-specific definition of yield point, conventional gel strength measurements, and the expected pulsation time analogous to thickening time. The cement test methods can also be used to demonstrate how pulsation delays and controls the development of cement gel strength.

Objectives

The proposed tests have two general purposes. The first is to verify the feasibility of cement pulsation and that up to 30 minutes of downtime to hook up and begin pulsation will not cause excessive mud and cement gelation. The second is to predict job parameters. The most important parameter is the approximate maximum depth of treatment. Fluid properties for use with the cement pulsation model described by Chimmalgi[9] are needed for more precise prediction and monitoring of a pulsation job's progress. Additional job parameters that can be determined are the length of time that treatment will be effective for each slurry and the effect of pulsation on controlling the development of cement gel strength versus time. The rheological properties of both the mud and the cement versus time are required to accomplish these objectives. The specific procedures for measuring these properties are included in the Appendix: Proposed Test Protocol.

Tests of Mud Properties

The annulus in a typical primary cement job for a production casing is only partially cemented. Therefore the pulses used in the CP process must be transmitted through the mud column above the cement. Consequently, the rheological properties of the mud in the annulus influence the effectiveness of cement pulsation unless the annulus has been cemented to the surface.

The critical mud properties that must be measured for use with CP are the plastic viscosity, the yield point, and the gel strength versus time. However, given that the velocity of the movement in the annulus during pulsation is much less than the velocity during normal circulation, the rotational speeds used for viscometer measurements should be equivalent to this lower range of annular velocities. An upper limit on the viscometer speed for mud was selected by analogy to a typical maximum annular velocity at the surface in a 10,000 foot well due to a typical 100 psi pulse with a 20 second total period. This velocity is equivalent to the velocity at the face of the bob in a standard Fann viscometer at 84 rpm. Therefore 100 rpm was selected as a reasonable upper limit on the viscometer speed. Use of 3 and 6 rpm readings for determining YP was based on these being the lowest speeds available on a typical 6 speed Fann viscometer and were validated by previously reported work on full-scale testing of cement-like fluids[2]. Therefore pulsation specific rheology parameters have been defined for these low velocity conditions as:

$$\boldsymbol{YP}_{3,6\boldsymbol{M}} = \theta_3 - (\theta_6 - \theta_3)$$

$$\boldsymbol{PV}_{\boldsymbol{CPM}} = 3 \times (\theta_{100} - \boldsymbol{YP}_{3,6\boldsymbol{M}})$$

The gel strength for the mud is measured using conventional definitions and procedures for drilling fluids[10].

Tests of Cement Properties

The critical cement properties that must be measured for use with CP are also the plastic viscosity, the yield point, and the gel strength versus time. However for cement, all of the properties vary with time and prior shear history. Nevertheless, some relatively simple measurements can provide useful insights into cement behavior in the well.

Viscometer Measurements

The rotational speeds used for the viscometer measurements were selected in a manner similar to that described for the drilling fluid. However a typical cement column is much shorter than 10,000 feet. Therefore the upper limit on viscometer speed for cement tests was based on a typical annular velocity at the top of a 3000 foot long cement column with the same pulse characteristics described for mud. The average velocity of fluid at the top of the cement column for this situation would be about 4.6 cm/second. This velocity is equivalent to the velocity at the face of the 1.2276 cm radius bob in a modified Fann viscometer at 36 rpm. Therefore 30 rpm was selected as the viscometer speed closest to representing a maximum cement velocity at the top of a moderately long cement column during pulsation, which requires use of a twelve speed viscometer.

The 1.2276 cm radius viscometer bob was selected to allow measurement of shear stress higher than the 300 lb/100sf that can be measured with a standard bob and spring. In addition, the surface of the bob is knurled to minimize the effect of slippage when measuring cement rheology[11]. Due to its smaller diameter, the shear stress on the surface of this bob is a factor of 2.11 higher than the stress on a standard bob at the same dial reading. Therefore this 2.11 correction factor is applied to all of the dial readings using the modified viscometer. In addition, the velocity at the face of the smaller bob is a factor of .71 times the velocity on the face of a standard bob at the same rpm. Therefore the PV is estimated using an adjustment of 1.47 times the measured shear stress difference. The 3 and 6 rpm readings were selected for determining YP using the same logic described for the mud.

Therefore, pulsation specific rheology parameters when measured with a knurled, 1.2276 cm radius bob and standard F1 spring in a Fann viscometer are defined as:

$$\boldsymbol{YP}_{3,6\boldsymbol{C}} = 2.11 \times (\theta_{3\boldsymbol{k}} - (\theta_{6\boldsymbol{k}} - \theta_{3\boldsymbol{k}}))$$

$$\boldsymbol{PV}_{\boldsymbol{CPC}} = 29.7 \times (\theta_{30\boldsymbol{k}} - (\boldsymbol{YP}_{3,6\boldsymbol{C}} / 2.11))$$

$$\boldsymbol{Gel\ Strength} = 2.11 \times \theta_{3\boldsymbol{k},\boldsymbol{peak}}$$

Macs Analyzer Measurements

The MACS Analyzer is a consistometer-like device used for measuring static gel strength of a cement slurry at downhole conditions[12]. The static gel strength is the shear stress measured at a very low shear rate as a continuously measured estimate of gel strength.

A new proposed application for the MACS Analyzer is the simulation of pulsation applied during cement curing to determine the maximum pulsation time. The cement movement due to pulsation is simulated by operating the device at a rotational speed to give a velocity at the edge of the paddle that is the same as the maximum velocity expected at the top of the cement column during pulsation. A speed of 8 rpm was selected as an even number that is roughly equivalent to this velocity. The consistometer output in consistency units (Bc) is used as an approximate indicator of shear strength development in the cement. Although no rigorous relationship exists between consistency units and shear stress, a preliminary consistency limit of 25 to 35 Bc at 8 rpm in the MACS Analyzer is proposed for determining maximum cement pulsation treatment time based on the tests conducted to date. The actual static gel strength can be measured when the consistency reaches this level by stopping rotation and switching the device to its static gel strength measuring mode. As described in the section below on practical applications, the maximum gel strength to prevent pulsation can be calculated and compared to the measurement to verify the likelihood of success for continued pulsation.

The measurement of conventional static gel strength versus time under normal conditions is also potentially useful. Comparing the consistency versus time under simulated CP with static gel strength versus time can give an approximate indication of whether pulsation does in fact suppress gel strength development for a particular slurry.

The MACS Analyzer readings may also be useful as a substitute for viscosity measurements at downhole conditions that would otherwise require use of a HTHP rheometer. However, the device was not designed for this purpose and to date we have been unable to develop a reliable basis for estimating PV and YP using MACS Analyzer measurements.

Practical Applications

The results of the mud and cement tests can be used to estimate several useful job parameters. These include the maximum allowable mud gel strength and cement YP for successful cement pulsation and the maximum expected depth of treatment at the beginning of a pulsation job. The equations for determining these job parameters were based on the full-scale experiments conducted by Martin et al[2] and the simple, static model that they proposed. A maximum pulse amplitude of 100 psi was assumed in developing these equations.

The maximum mud gel strength is defined as the strength that would prevent pulsation from affecting the cement. It is based on pulse strength attenuation due to the YP of the mud and the assumption that the gel strength of the mud acts on only a characteristic length of about 200 feet when opposing fluid motion.

The same logic was used in determining the maximum cement YP, which is defined as the YP that would prevent pulsation from affecting more than the first 200 feet of the cement column. Similar, but more complicated calculations could be used to estimate the maximum gel strength or YP for which pulsation at the top or the bottom of the tail slurry would be effective.

This logic is used again for determining a simple estimate of the maximum depth of treatment. Treatment is defined for these purposes as occurring at any depth in the mud or cement column where the amplitude of the pressure pulse is greater than zero psi when a 100 psi pulse is applied at the surface.

The calculation of maximum treatment depth may be optimistic in the case where significant gel strength has developed in the cement before pulsation begins because it assumes that the effect of cement gel strength is minor compared to the effect of YP and can be ignored.

$$\textbf{\textit{Max Allowable Mud Gel Strength}} \quad (\boldsymbol{lb}/100\boldsymbol{sf}) \\ = ((\boldsymbol{D}_2 - \boldsymbol{D}_1)\times 150) - ((\boldsymbol{L}_{\boldsymbol{TOC}} \times \boldsymbol{YP}_{3,6\boldsymbol{M}})/200)$$

(Note: Mud gel strength must be less than this maximum when pulsation begins.)

$$\textbf{\textit{Est. Max Depth of Treatment}} = \boldsymbol{L}_{\boldsymbol{MAX}} \ (\boldsymbol{ft}) \\ = \boldsymbol{L}_{\boldsymbol{TOC}} + ((300 \times (\boldsymbol{D}_2 - \boldsymbol{D}_1)/\boldsymbol{YP}_{3,6\boldsymbol{C}}) \\ \times (100 - ((\boldsymbol{L}_{\boldsymbol{TOC}} \times \boldsymbol{YP}_{3,6\boldsymbol{M}})/(300 \times (\boldsymbol{D}_2 - \boldsymbol{D}_1)))))$$

$$\textbf{\textit{Max Allowable}}\ \boldsymbol{YP}_{3,6\boldsymbol{C}} \quad (\boldsymbol{lb}/100\boldsymbol{sf}) \\ = ((\boldsymbol{D}_2 - \boldsymbol{D}_1)\times 150) - ((\boldsymbol{L}_{\boldsymbol{TOC}} \times \boldsymbol{YP}_{3,6\boldsymbol{M}})/200)$$

Note that a cement yield point (or gel strength if cement pulsation has stopped) greater than this maximum will prevent effective pulsation of any of the cement in the annulus below the depth where the cement has this yield point. Also, if the maximum depth of treatment is equal to or greater than the depth to the base of a lead slurry, the length of the lead slurry can be added to the formula. Then the pressure lost in the lead slurry can be subtracted from the term that begins with 100 to calculate the estimated depth of treatment into the tail slurry.

EXAMPLE FIELD APPLICATION

The proposed protocol was used on field samples of mud and cement for comparison to measured job parameters for a production casing cement job that was instrumented downhole. The job was similar to but preceded the one described by Newman et al[3,4]. Predictions of downhole pressure response to pulsation based on these test results are evaluated by comparison with actual pressure measurements in the well annulus during pulsation. Figure 1 is a plot of the pressures measured at the surface and at two subsurface pressure sensors during pulsation. Note the separate scales used for surface and downhole pressures. This plot clearly shows the response of downhole pressure when surface pressure pulses are applied. It also shows how gelation of the cement eventually suppresses transmission of pressure pulses and hydrostatic pressure through the lead cement allowing downhole pressure to decline at the middle sensor, which was located near the bottom of the lead slurry.

Results from Viscometer Measurements

The mud properties that were measured and calculated for samples of mud from the field are summarized in Table 1. These properties appear to provide an appropriate basis for simple predictions of job performance.

One indicator of the relevance of these properties is that the calculated $YP_{3,6M}$ of 1.5 lb/100sf, when used with the simple static equation proposed by Martin et al[2], indicates that the pulse strength should be attenuated about 13 psi by the depth of the top pressure sensor in the field test. The actual attenuation reported in the field was 12 psi. The difference of less than 10 per cent is well within the accuracy of measuring such small shear stresses with a rotational viscometer and of this simple model.

The cement properties that were measured and calculated for samples of the lead slurry from the field are summarized in Table 2. These properties also appear to provide an appropriate basis for simple predictions of job performance.

The $YP_{3,6C}$ of 17 lb/100sf was used with the simple static equation to estimate attenuation of 25 psi for pulsation through the lead slurry at the beginning of the job. Using this attenuation together with the 13 psi estimated for the mud, allows prediction of pressure pulse amplitude at the middle pressure sensor which was located at a depth of 7627 feet near the bottom of the lead slurry. The total estimated attenuation at that depth is 38 psi, which is again within 10 per cent of the actual attenuation which was reported to be 36 psi.

In addition to these simple analyses, the YP defined herein can be used as the yield stress required for diagnosis of a pulsation job as proposed by Kunju[8] and the PV and YP can be used with the predictive, analytical model proposed by Chimmalgi[9].

Properties for the tail slurry were also measured, but these are not reported here because the pressure sensor at the base of the tail slurry failed on the trip in the hole. Therefore a quantitative evaluation of the effect of tail slurries properties on the success of this job was not possible.

The calculated job parameters for the mud and cement are summarized in Table 3. The job results clearly demonstrate that pulsation was transmitted effectively through the mud during the entire job as expected based on the measured mud gel strength and yield point being much lower than the calculated maximum allowable. Likewise, pulsation was transmitted effectively through the lead slurry at the beginning of the job, and for more than two hours thereafter. This is also expected given that the calculated 10,187 foot maximum depth of treatment was greater than the well depth. This field example does not allow rigorous, quantitative conclusions about the validity of these parameters. However, additional discussion of the significance of the maximum allowable cement gel strength is included in the next section.

Results from MACS Analyzer Measurements

Two tests were performed on the lead slurry using the MACS Analyzer. Both began by conditioning the cement samples for one hour to simulate the actual cement pumping time with a pressure and temperature schedule representing the actual temperatures and pressures recorded with surface and subsurface sensors in the field.

A static gel strength test was conducted by service company lab personnel in Lafayette. The results of that test are shown in Figure 2. The static gel strength after 10 minutes was approximately 25 lb/100sf. This compares to the 10 minute gel strength of 36 lb/100sf measured with an atmospheric viscometer. Given the evaporation that occurs with an open viscometer at the temperature used, a higher reading with the viscometer was expected. The static gel strength increased fairly steadily, reaching a value of about 316 lb/100sf at 145 minutes. Consequently, pulsation would be expected to be ineffective if it were not initiated before 145 minutes after pumping ceased. As shown in figure 1, pulsation was initiated within 4 minutes, continued for about 210 minutes, and was effective at transmitting some pressure to the middle sensor at the bottom of the lead slurry for just over 180 minutes.

A separate test using the MACS Analyzer at LSU was conducted to evaluate its use for predicting maximum pulsation time and for comparison of gel strength development under conditions of simulated pulsation with conventional SGS measurements. The test was conducted by running the device at a repeating sequence of 8, 4, and 0.139 rpm for 10 minutes each while recording either consistency units or shear stress. This specific experimental test was relatively unsuccessful because cement fouled the magnetic drive bearing mechanism during the test and caused unrealistically high readings. Nevertheless, it showed that simulating pulsation by running the device at 4 or 8 rpm did suppress the development of gel strength. The consistency readings were fairly constant until a rapid increase began after about 175 minutes as opposed to the continuous buildup seen in the SGS tests. This is very similar to the 180 minute time period after which pulses ceased to reach the middle pressure sensor in the actual well. At 210 minutes, the consistency readings had reached a level where we expect pulsation would be completely ineffective, a static gel strength value of over 500 lb/100sf was measured, and the test was terminated.

An additional, similar test was performed on the tail slurry. Although this test had some of the same complications as the test on the lead slurry, it did provide one interesting and important result. The gel strength of the tail slurry developed more slowly under pulsation than the lead slurry did. This means that gelation of the lead slurry prevented pressure transmission to the tail slurry which was still fluid. This combination should logically encourage flow after cementing as bottom hole pressure drops and the slurry opposite the formation is still fluid.

These tests did not provide quantitatively useful results and did not follow the proposed protocol exactly. However, the tests do reinforce the expectation that a MACS Analyzer can be used to simulate the effect of pulsation on cement during the curing process. The tests can also be an indicator of how long pulsation might effectively transmit pressure through the cement and a check on whether the lead slurry may build gel strength more rapidly than the tail slurry, which would create an undesirable tendency to encourage flow after cementing.

SUMMARY AND CONCLUSIONS

1) The fluid property definitions proposed herein provide a reasonable basis for simple predictions of cement pulsation feasibility and performance. Specifically, the proposed YP criteria for the drilling fluid and cement can be used to predict attenuation and therefore pulse amplitude during cement pulsation. These criteria and gel strength also provide a basis for quick estimates of treatment depth and pulsation feasibility.

2) The proposed applications for the MACS Analyzer are not as well proven. However, the MACS Analyzer should be applicable for measuring cement static gel strength versus time under realistic conditions, as it was designed to do. In addition, it can apparently be used at low rpm to simulate pulsation, to determine maximum pulsation treatment time, to show the effect of pulsation on suppressing gel strength development, and to determine which slurry will stop transmitting pressure first. It may also prove to be useful as a substitute for a HTHP viscometer for cement pulsation, but that application has not been satisfactorily evaluated.

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NOMENCLATURE

D_1 outside diameter of casing, in

D_2 internal diameter of outer pipe or hole, in

L_{MAX} maximum depth of treatment, ft

L_{TD} desired treatment depth (usually total depth), ft

L_{TOC} depth to top of cement, ft

θ_n dial reading at n rpm with standard Fann viscometer, lb/100sf

θ_{nk} dial reading at n rpm with modified Fann 35 viscometer, lb/100 sf

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APPENDIX: PROPOSED TEST PROTOCOL

The specific test procedures proposed for this protocol are described in this appendix.

Drilling Fluid (Mud):

1) Measure and record dial readings at 3, 6, 100, 200, 300, 600 rpm with standard Fann viscometer and calculate $YP_{3,6M}$ and PV_{CPM}. Use either the $YP_{3,6M}$ to make a quick prediction of pressure losses in mud column in annulus above cement or both for predictions using the CP model.

2) Measure and record 10 second, 10 minute, and 30 minute gel strengths.

Cement:

1) Measure cement rheology -- Prepare a sample of each slurry following API Specification 10A. Condition each sample in an atmospheric consistometer with a temperature schedule versus time to simulate pumping time for proposed job. Remove sample from the consistometer and pour into a pre-heated, modified, twelve-speed Fann viscometer. The viscometer should be modified by using a knurled, 1.2276 cm radius bob with a standard F1 spring (an F2 spring and the appropriately revised equations can be used to double the maximum shear stress that can be measured, up to approximately 1500 lb/100sf if desired). Measure 3, 6, 30, 60, 100, 200, 300 rpm dial readings and calculate $YP_{3,6C}$ and PV_{CPC}. Use either the $YP_{3,6C}$ to make a quick prediction of pressure losses in cement column in the annulus or both for predictions using the CP model. Measure and record 10 second and 10 minute gel strengths.

2) Measure static gel strength -- Prepare a sample of each slurry following API Specification 10A and condition each sample in a MACS Analyzer using the consistometer mode with temperature and pressure schedule and time to simulate pumping time for proposed job. Switch to the static gel strength (SGS) mode and measure SGS versus time, using a temperature schedule appropriate for cement curing. Continue for 30 minutes or until SGS = 500 lb/100sf, whichever occurs first. Optionally, measurements may continue beyond 30 minutes if SGS is less than 500 lb/100sf and a static gel strength measurement versus time is desired.

3) Optional measurement of maximum treatment time -- Prepare a sample of each slurry following API Specification 10A and condition each sample in a MACS Analyzer using the consistometer mode with a temperature and pressure schedule versus time to simulate pumping time for proposed job. Remain in the consistometer mode, but decrease rotational speed to 8 rpm, and follow a temperature schedule as used for cement curing. This speed simulates pulsation. When the consistometer reading is consistently in the range of 25 to 35 Bc, the maximum treatment time has probably been reached. This can be confirmed by switching the MACS Analyzer over to measure static gel strength. A static gel strength of approximately 500 lb/100sf confirms that the cement has effectively become a solid and that this time can be recorded as the maximum length of time anticipated for treatment to be effective in that slurry in the field.

Measured Mud Properties	Value
θ_3	2 lb/100sf
θ_6	2.5 lb/100sf
θ_{100}	14 lb/100sf
30 second gel strength	3 lb/100sf
10 minute gel strength	4 lb/100sf
30 minute gel strength	5.5 lb/100sf
$YP_{3,6M}$	1.5 lb/100sf
PV_{CPM}	37.5 cp

Table 1 - Mud Properties for Field Example

Measured Cement Properties	Value
θ_{3k}	11
θ_{6k}	14
θ_{30k}	17
$\theta_{3k\ peak}$ after 10 minutes static	17
$YP_{3,6C}$	17 lb/100sf
PV_{CPC}	276 cp
10 second gel strength	30 lb/100sf
10 minute gel strength	36 lb/100sf

Table 2 - Lead Slurry Cement Properties for Field Example

Calculated Job Parameters	Value
Maximum Allowable Mud Gel Strength to Initiate or Resume Pulsation	307 lb/100sf
Maximum Allowable Cement YP or Gel Strength to Initiate or Resume Pulsation	307 lb/100sf
Est. Maximum Depth of Treatment	10,187 ft

Table 3 - Calculated Job Parameters for Field Example

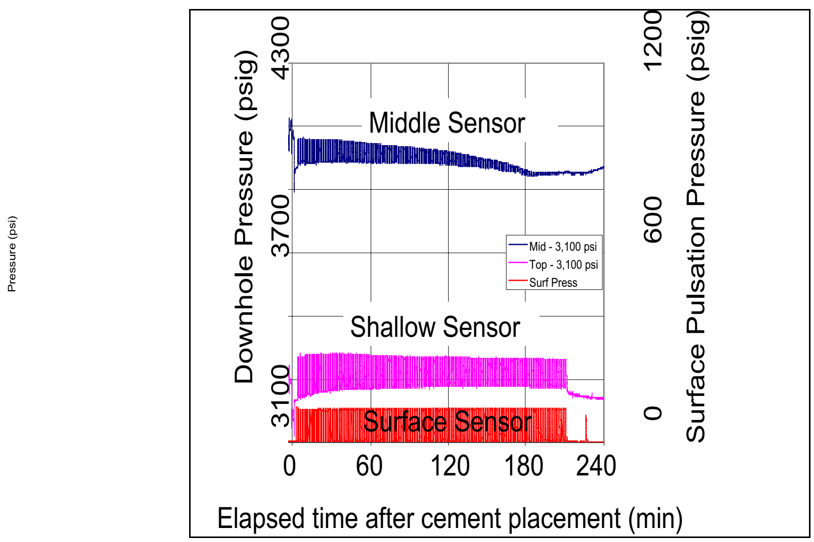

Figure 1 - Pressure Pulsation Record for Field Example

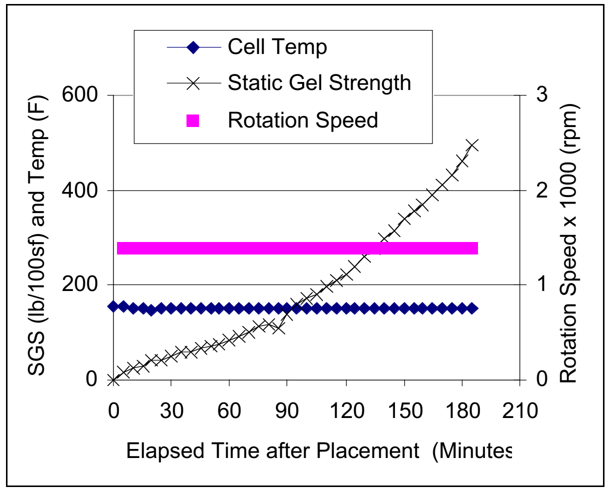

Figure 2 - Static Gel Strength Test on Lead Slurry for Field Example