A METHOD FOR STUDYING PRESSURE CYCLING EFFECTS ON CEMENT INTEGRITY IN AN ANNULUS

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ABSTRACT

In a wellbore, the cement sheath is subjected to pressure changes from various well operations, including pressure testing, fracturing, and remedial operations. Pressure changes can also occur with changes in the densities of displacement fluids. Failure of the cement sheath in the annulus due to pressure changes can lead to debonding from the formation or the casing and cause a microannulus to form and produce cracks in the cement matrix, thereby providing flow paths for fluids such as oil, water, or gas. Such failures lead to expensive remedial operations in a producing well or continuous monitoring in an abandoned well.

Designing cement slurries that can withstand cyclic pressure changes contributes to extended periods of trouble-free operation. However, experimental techniques are not available to measure the resistance of set cement in an annulus to failure from pressure changes.

This paper presents a method of testing cement compositions using wellbore models with pipe-in-pipe (PIP) configuration in which cement was circulated in the annulus, cured, and subjected to cyclic pressure loads by pressuring and depressurizing the inner pipe. The failure of the cement was measured by the flow rates during pressurization and depressurization cycles of a dyed fluid through the cement column as a function of applied pressure. The method was applied to several low-density cement formulations. The failure mode at the end of the tests was investigated by cutting the models into several segments and inspecting the cement under fluorescent light. Effects of experimental parameters, such as temperature at the time of failure testing, annulus pressure, and slurry design were tested. The results and their implications in designing slurries for long-term cement performance are discussed.

INTRODUCTION

The oil and gas industry is exploring and producing oil and gas under extreme conditions, such as high-pressure and high-temperature (HPHT), deepwater, shallow gas, and accelerated-production rate wells. The stresses exerted on the cement sheath from these extreme operating conditions can be severe and can damage the cement sheath. Examples of well operations that might exert stress on the cement sheath include:

- Cement hydration.
- Changeover from displacement fluid to completion fluid.
- Hydraulic stimulation.
- Hydrocarbon production.
- Fluid injection.
- Gas lift.

These types of operations could change the pressure and temperature of the cement sheath after the slurry is placed in the annulus. The cement sheath can be damaged if the magnitude of pressure or temperature change is great and the stresses in the cement sheath exceed its key values. The key values are measured values that vary depending on the cement slurry formulation.

Some major consequences of damage to the cement sheath, such as sustained pressure on the annulus side or damage to the casing, can force well shutdown or result in high remedial costs.

Other consequences of damage to the cement sheath, such as loss of hydrocarbon production, production of unwanted fluids (e.g. water), and growth of wellhead, can negatively affect the safety and economics of oil and gas assets because remedial jobs are expensive and even impossible in some cases. Hence, the integrity of the cement sheath should be considered during the early stages of well construction and designed for uninterrupted, safe, and economic production of hydrocarbons.

A detailed engineering analysis should be conducted to evaluate how the different well operations affect the integrity of the cement sheath. In other industries, for example, in bridge construction, applying engineering analysis is a common way to optimize material properties. The oilfield is slowly adopting these techniques. This adoption has occurred because of a combination of increased risk to cement sheath integrity in expensive wells operating under extreme conditions and more stringent safety standards.[1-7]

A three-step approach should help operators construct a well that can produce hydrocarbons safely and economically. Step 1 is the engineering analysis. The outcome of the engineering analysis is to help provide the optimum cement sheath properties needed to withstand the well operations. Step 1 has been discussed by Bosma *et al*., Ravi *et al.*, and others.[8-12]

Step 2 is cement slurry design and testing to provide a cement system that can match or exceed the cement sheath properties evaluated in Step 1. Examples of cement sheath properties that should be tested in Step 2 are:

- Tensile strength
- Young's modulus
- Poisson's ratio
- Plasticity parameters

To help achieve effective zonal isolation, Steps 1 and 2 should be followed by Step 3—effective cement slurry placement and monitoring during the life of the well. Step 3 has been presented by Ravi *et al.*, Biezen *et al.*, and other authors.[13,14]

The laboratory-measured values become a part of the input variables for the engineering analysis (Step 1) to evaluate the cement sheath integrity. In addition, the capability of the cement sheath to sustain cyclic stresses experienced during the life of the well can be determined by the engineering analysis and laboratory testing. The engineering analysis evaluates how much useful life, or capacity (of the original capacity), is left in the material to resist failure. This capacity is called "remaining capacity." The remaining capacity is an indicator of the ability of the cement sheath to sustain cyclic stresses. A direct measurement of the resistance of cement formulations under laboratory conditions was reported recently.[15] In this study, cement samples were subjected to cyclic stresses in the axial direction on cylindrical samples. In the current study, the same cement formulations are placed in an annular environment in a model built with PIP configuration and subjected to cyclic stresses by pressurizing and depressurizing fluid inside the inner diameter (ID). The response of the material is evaluated by measuring the flow rate of water containing a fluorescent dye, as well as by examining cut portions of the wellbore model for failure modes, particularly cracks and debonding from pipe surfaces. Results from both methods are compared.

EXPERIMENTAL PROGRAM

Cyclic Loading

If a material is repeatedly stressed, the number of stress cycles that the material can withstand will depend on the stress magnitude and the material properties. In other industries, this is called the "endurance limit," and it is defined as the stress below which the material can withstand a large number of stress cycles. Measuring the stress value to which a cement sheath can be repeatedly subjected without failing can help ensure that it can withstand a large number of cycles and provide zonal isolation during the life of the well. Laboratory tests were conducted to determine the number of cycles that a cement sheath can withstand before failure.

Cement Systems, Curing, and Testing

All cement formulations had a density of 12 lb/gal and were tested for conventional properties such as stability, rheology, mixability, and compressive strength by crushing the cubes. A liquid defoamer was used in all slurries except the foamed slurry.

In addition, test specimens were poured for tensile strength, confined and unconfined triaxial tests, and cyclic tests. All the slurries were prepared according to API procedure. The cube samples for compressive-strength measurements, the dog-bone samples for tensile-strength measurements, and the 2-in. × 5-in. cylindrical samples for load vs. displacement measurements were cured under a pressure of 3,000 psi for 72 hr at 190°F, with the exception of Cement System 1, which was cured in a water bath at 190°F for 72 hr. In the unfoamed samples, the pressure and temperature of the autoclave were decreased gradually over four hours after curing.

Pipe-in-Pipe Model

The following are the dimensions for PIP models.

- Inner Pipe:
  - ID—6.5 in.
  - OD—7 in.
  - Length—4.5 ft

- Outer Pipe:
  - ID—8.92 in.
  - OD—9 5/8 in.
  - Length—4.0 ft

The outer pipe was provided with an inlet and an outlet for slurry entrance and exit, and the inlets and outlets were provided with open/close valves. The bottom end of the outer pipe also had a bottom inlet (approximately 1 inch above its bottom edge) and a top outlet for water entrance and exit. One outlet was used to contact the cement column with an external water source (dye water) and another was used for water to exit when a conduit was established during cyclic testing or before the beginning of testing. The bottom opening of the inner pipe was sealed with a metal plate, and the top opening was sealed with a metal plate containing two fluid connections with open/close valves. The inner pipe was sealed into the outer pipe such that ½ in. of the inner piper extended beyond the outer pipe on the bottom side. The fluid volume of the annulus was about 5 gallons (**Fig. 1**).

Sand was poured into the space below the slurry inlet point on the outer pipe and rinsed with water such that the sand and water mixture filled the volume below the slurry entry point. Cement slurry (20 gallons) was mixed for 15 minutes in a tub with a paddle mixer and a circulating pump until a homogeneous slurry was obtained. Slurry line connections between the slurry tub and the wellbore model were made to provide continuous circulation between the two units. After 15 minutes of circulation, the slurry inlet and outlet valves of the model were closed. The slurry circulation was performed with a pump pressure of 100 psi. The inner pipe was filled with water, and the valves on the top end were left partially open to relieve pressure during the curing phase. The model was kept in a 190°F autoclave room for 7 days, at which time the model was taken out and allowed to cool to room temperature overnight.

The water inlet on the outer pipe was connected to a fluorescent dye solution reservoir pressurized to 100 psi. The water inlet on the inner pipe was connected to a Sprague pump and the outlet was closed.

The model was allowed to stand with just the pressure on the dye solution for 15 minutes to determine if the dye solution would break through before any pressure cycling was started. After this period, the water pressure on the inside pipe was increased to 250 psi, and held at that pressure for 5–15 minutes. Any flow of the dye solution through the cement was collected in a graduate cylinder for small volumes and the flow rate was measured. After this pressurization period, the pressure was released to 0 psi and the flow rate of the dye solution was measured. After 5 minutes of depressurization, the same pressure (250 psi) was applied for 5 minutes and the flow rate of dye solution was measured. Then, the unit was depressurized to and held at 0 psi for 5 minutes while measuring the flow rate. After a total of 10 to 15 cycles of pressurization to 250 psi and depressurization to 0 psi, the pressure was increased to 500 psi and pressurization and depressurization was repeated for 10 to 15 cycles, then increased to 750 psi. The final pressures used ranged from 5,000 to 6,000 psi. After the final cyclic sequence and simultaneous measuring of the fluid flow rates, the top and bottom portions containing the valve connections were sawed off and the remaining model was cut into four segments. The middle two segments were 1 foot in length, and the top and bottom segments were 1/2-foot long. Photographs were taken of the exposed surface under regular light as well as under UV black light (**Figs. 2** and **3**).

For foam cement, an additional metal cylinder with an inlet on the bottom end and a screw-type lid with an outlet on the top end was connected with the previously described model, and the total volume of the two units and all the connections were measured by filling the unit with water. The weight of the base slurry of 16.4-lb/gal density and the foaming surfactant required to provide a foamed slurry of 12.0-lb/gal density sufficient to fill the total volume of the model, the cylinder, and the hoses was calculated. The base slurry was prepared in the slurry tub and circulated through the model (as usual) until the model was full. The remaining base slurry and the foaming surfactants were added to the cylinder. The filled model, the spare cylinder, and the pump were connected in a closed loop, and the foamed slurry was circulated until the assembly was filled. The empty cylinder was placed on a weighing scale and the weight of the cylinder was measured after circulation until it reached a constant weight.

Cement Systems

- Cement System 1 consisted of a base slurry with a density of 16.4 lb/gal, which was prepared from cement and water and subsequently foamed to 12 lb/gal. Appropriate surfactants were used to generate and stabilize the foam structure.
- Cement System 2 consisted of cement, sodium silicate, and water.
- Cement System 3 consisted of cement, Class F fly ash, lime, and a small amount of bentonite.
- Cement System 4 consisted primarily of cement, fumed silica, and glass beads of specific gravity 0.6. Polymeric additives for fluid-loss control, mixability, and set-time control were included in the slurry as needed.
- Cement System 5 consisted primarily of cement, ultrafine-particle-sized cement, and cenospheres, which were pre-crushed under a pressure of 6,000 psi. Polymeric additives to control fluid loss and set time were included in the cement slurry as needed.
- Cement System 6 consisted of cement, Class F fly ash, silica fume, and a small amount of bentonite.

The compressive strengths and tensile strengths for these cement systems are presented in **Table 1.** The results from the measurement of compressive strengths, Poisson's ratio, and Young's modulus by stress-strain method are also provided in Table 1.

Stress-Strain and Cyclic Testing

In addition to the typical testing (e.g., crushing cubes), uniaxial and triaxial stress-strain tests were performed on cylindrical samples to determine Young's modulus, Poisson's ratio, and plasticity parameters. Tests were performed as proscribed in ASTM D 3148–02 (Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression) and D 2664–95a (Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements). Dualaxial extensometers and a circumferential chain extensometer were used to measure strains on samples. Cyclic compression tests were performed to determine the resistance of the cements to the repeated stress cycling they could be subjected to during the life of the well.

The cyclic tests were designed to provide data about the cement response to initial load cycles starting at 50% of compressive strength and increasing by 10% of the compressive strength per cycle to the final level. The final level was set at the lower value of two standard deviations below the compressive strength, or 90% of the compressive strength. The low stress level was set at the larger value of 100 psi, or 10% of the compressive strength. The details are shown in **Table 2.** One thousand (1,000) cycles were run at the final level unless the sample failed earlier. Samples that survived 1,000 cycles were then stressed to failure.

The cyclic test program was constructed to complete a 1,000-cycle test in less than 14 hours so that tests could be completed overnight. The initial partial-load cycles were performed under displacement control at a displacement rate of 5 E-5 inches per second, to match the displacement rate of the stress-strain tests. The cyclic portion of the tests were run under force control with the first 10 cycles at 4 minutes per cycle, the next 50 cycles at 2 minutes per cycle, the next 190 cycles at 1 minute per cycle, and the last 750 cycles at 30 seconds per cycle. A final load cycle to failure was performed under displacement control at a displacement rate of 5 E-5 inches per second. The details are shown in **Table 3.**

DISCUSSION

Cyclic Stresses in Axial Direction

The discussion in this paper and the data provided in Tables 1 and 3 indicate that no single parameter measured, including compressive or tensile strength, Young's modulus, or Poisson's ratio, can explain the behavior of different formulations under axial cyclic loading conditions.

Stress-strain testing has shown that not all the cement sheaths behave as linear elastic solids in the full range of measured compressive strength. Cement System 4, containing glass beads, had reportedly high compressive strength but showed significant deviation from a linear stress-strain relationship (**Fig. 4**). While this cement shows a brittle failure under unconfined compression, it undergoes ductile plastic deformation failure under confined conditions (**Fig. 5**). The question of whether the nonlinear behavior before failure is elastic or plastic is answered by the stress-strain behavior during the initial partial-loading cycles of the cyclic tests described in the following paragraphs. **Fig. 6** clearly shows permanent plastic deformation after the first load cycle to 50% of the compressive strength and additional plastic deformation for each increasing load cycle. Similar nonlinear deformation was seen for the other five nonfoamed cements. Cement System 1 showed reasonably linear elastic behavior with a ductile failure in the unconfined testing (**Fig. 7**) and also in the confined testing (**Fig. 8**). The initial partial-loading cycles of the cyclic test shown in **Fig. 9** confirm elastic behavior below 90% of the compressive strength.

Examination of the initial partial-load cycles showed that five of the six slurries had permanent plastic deformation after the first load cycle to 50% of compressive strength and that plastic deformation increased at each increasing load cycle. When full load levels were reached, plastic deformation increased with each cycle until failure occurred. Only Cement System 1 behaved as a reasonably linear elastic material. Cement System 1 showed a very small plastic deformation during the initial partial-load cycles. No further plastic deformation was observed for approximately 70 full cycles. After 70 cycles, a gradual increase in plastic deformation was observed to 1,000 cycles. The plastic deformation of Cement System 1 after 1,000 cycles was significantly lower than the nonfoamed cements after 1 cycle. A plot of plastic strain vs. number of cycles for one sample of each slurry was prepared by subtracting the axial strain when the stress reached the cycle minimum on the first compression cycle to 50% from the axial strain at each cycle minimum (**Fig. 10**).

These tests indicate that a linear elastic model is a reasonable model for Cement System 1 at repeated loading to near 90% of compressive strength (**Fig. 11**). The nonfoamed cements tested do not behave as linear elastic materials for stresses at or above 50% of compressive strength and may have poor-to-fair resistance to repeated high-stress cycles. An example of this behavior is shown by a cyclic test of Cement System 4 (**Fig. 12**). For these cements, further cyclic testing at lower load levels will be required to determine the stress level that will allow repeated loading without failure. In addition, the yield value (compressive strength) of some of these cement systems may be less than what is usually reported, based on crush strength tests. A combination of modifying how the yield values are determined and cycling at a lower percentage value of the yield could result in a better understanding of how these systems behave when they are stressed. This work is in progress and will be reported in subsequent publications.

Cyclic Stresses in Annular Environment Behind Casing

The results from water flow rate measurements during pressurization and depressurization steps are shown separately in **Figs. 13** and **14.** Only two formulations, Cement Systems 3 and 5, showed complete failure even with no pressure imposed on the inner pipe. The rest of the formulations showed either no fluid flow or less than 10 ml/min. It is assumed that these slurries are competent formulations with respect to resistance to cyclic stresses due to pressure changes in the wellbore. Flow rate response to pressurization and depressurization steps is probably an indicator of the presence of a microannulus between the cement and inner casing. It may indicate, to a lesser extent, the presence of cracks serving as a conduit to fluid because the pressure differential on either side of the inner casing must be transmitted to the inner core of the cement sheath to affect closure of the open cracks. This may happen at a high pressure differential, which is a function of the magnitudes of the stresses carried by the casing and the stresses transmitted to the cement sheath. Most likely, the pressurization effect is due to a combination of the presence of a microannulus, as well as internal cracks that may be interconnected. Both Cement Systems 3 and 5 responded to pressurization at high pressure values, especially Cement System 3. The flow rate in the case of Cement System 3 remained the same when the pressure was taken off, suggesting that no additional fluids were created due to the cyclic process. For System 5, the flow rate increased after cycling at high pressures (Fig. 14), indicating potentially further breakage of brittle hollow spheres under pressure. Cement System 2 failed catastrophically only at very high pressures. The flow rates increased suddenly when applied pressure reached 5,000 psi and the flow rate remained high with pressure on or off.

Examination of the cut sections, especially the middle section showed dye flow at the interface between the casing inner surfaces as well as inside the matrix to different degrees except in the case of Cement System 1. Cement System 5, which had high flow rates, showed a wide concentric fracture that communicated with the microannuli between the inner casing, as well as outer casing and the cement matrix. For Cement System 4 with glass beads, a few radial cracks were noted in the pictures taken in daylight (Fig. 2), and a microannulus and dye penetration into the matrix in the picture taken under UV black light (Fig. 3). The fact that the flow rates were low for this formulation suggests that the cracks and/or the microannulus did not communicate through the entire length of the model. Examination of the mechanical properties of the formulations and the flow rates did not provide any meaningful correlations.

Correlation Between Direct Axial Stress Cycling and Indirect Radial Stress Cycling in Wellbore Model

There was no obvious correlation between the average number of cycles that survived (1) the axial stress-strain cycling method, wherein pressure was applied directly on the cement sample and (2) the flow rates observed in the model testing, wherein the cyclic stresses were transmitted to the cement by the casing. However, examination of the permanent deformation results observed during the cyclic loading (Figure 10) showed a definite correlation between the magnitude of permanent deformation and the fluid rates. The two cement compositions with the highest irrecoverable permanent deformation were Cement Systems 3 and 5, and the lowest deformation was observed for Cement System 1. This correlation suggests that cement systems that are nonlinear, elastic solids are more likely to be affected by pressure cycling. In a wellbore situation, the deformation tendency may manifest as a microannulus if the cement debonding from casing is more facile than when the cement-to-bond is stronger, in which case the irrecoverable deformation may manifest as internal cracks caused by shear failure.

CONCLUSIONS

1. Cyclic stress resistance of cement compositions is measured by repeated pressurization and depressurization of cement samples in the axial direction directly by application of a load on cylindrical samples, or in radial direction indirectly by application of pressure to the inner casing in a PIP wellbore model.
2. The cyclic resistance is indicated by the number of cycles survived in the direct cyclic stress method and by the fluid flow rates through the cement column due to cyclic stresses in the wellbore model method.
3. The results from both methods do not provide unequivocal correlations between mechanical properties and the cyclic resistance of the compositions.
4. The susceptibility of the cement compositions to plastic deformation appears to be critically important in predicting their behavior under cyclic stress conditions for both methods.
5. The results from the wellbore model testing agree with the trends in plastic deformation observed from the direct axial cyclic stress method.
6. In general, cement compositions that behave as linear elastic solids have a greater survival rate when exposed to cyclic stresses.

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Table 1
Mechanical Properties of Cement Formulations

Cement System	Compressive Strength Crush Test (psi)	Tensile Strength (psi)	Compressive Strength Load vs. Displacement Analysis (psi)	Young's Modulus	Poisson's Ratio
1	1,190	190	1,050	8.08E+05	0.151
2	320	50	340	8.20E+04	0.084
3	1,030	80	1,010	3.28E+05	0.139
4	4,160	350	5,970	1.12E+06	0.207
5	2,710	380	4,590	1.07E+06	0.220
6	1,210	90	1,800	4.64E+05	0.194

Table 2
Cyclic Test Level from Unconfined Compressive Strength (UCS)

Slurry	Samples Tested for UCS	Average UCS (psi)	Standard Deviation (psi)	Cyclic Test Final Level	Percent of UCS
1	4	1017	90	837	82.3
1 Repeat	4	1015	74	866	85.4
2	5	337	15	303	90.0
3	5	1008	46	907	90.0
4	5	5155	147	4640	90.0
5	5	4136	93	3722	90.0
6	5	1772	41	1595	90.0

Table 3
Cyclic Testing Summary

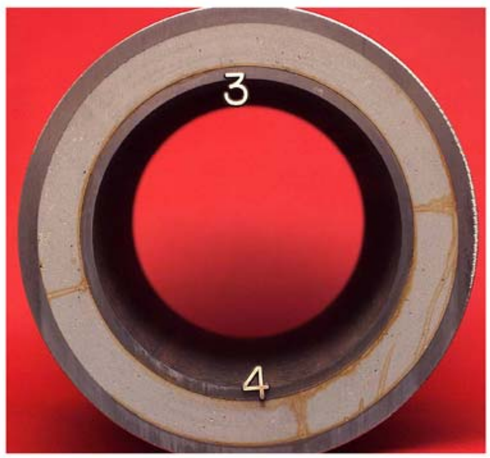
Slurry	Samples Tested	Samples Survived 1,000 Cycles	Samples Failed before 1,000 Cycles	Average Cycles Survived*	Earliest Failure*	Latest Failure*	Average UCS after 1,000 Cycles (psi)
1	8	6	2	486	157	816	1,307
2	5	0	5	88	17	197	
3	5	1	4	120	11	354	1,042
4	5	0	5	35	2	89	
5	5	0	5	53	34	72	
6	7	0	7	16	1	58	

*If failed before 1,000 cycles

Figure 1—Pipe-in-Pipe Wellbore Model

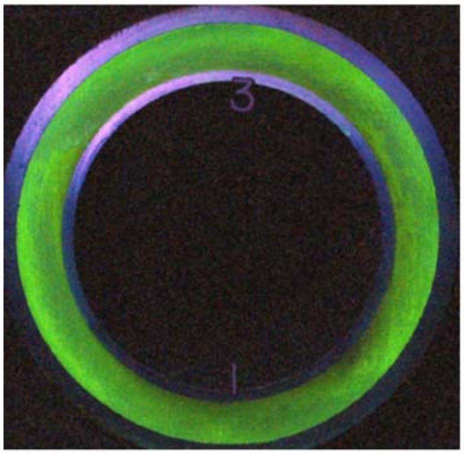
Cement System 1

Cement System 5

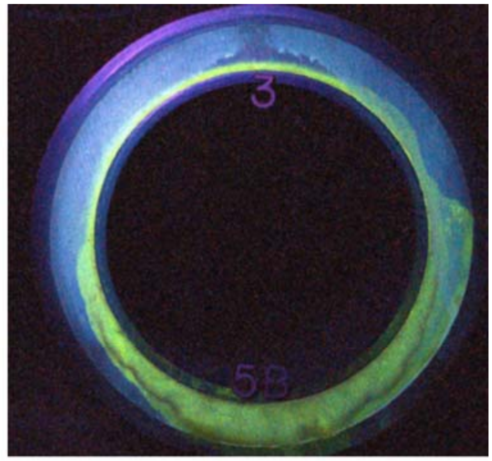


Cement System 4

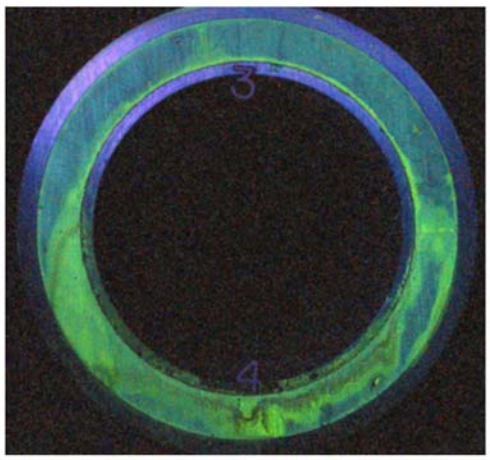
Figure 2—Photographs taken in daylight of cut sections of wellbore models.



Cement System 1



Cement System 5



Cement System 4

Figure 3—Photographs taken in UV black light of cut sections of wellbore models.

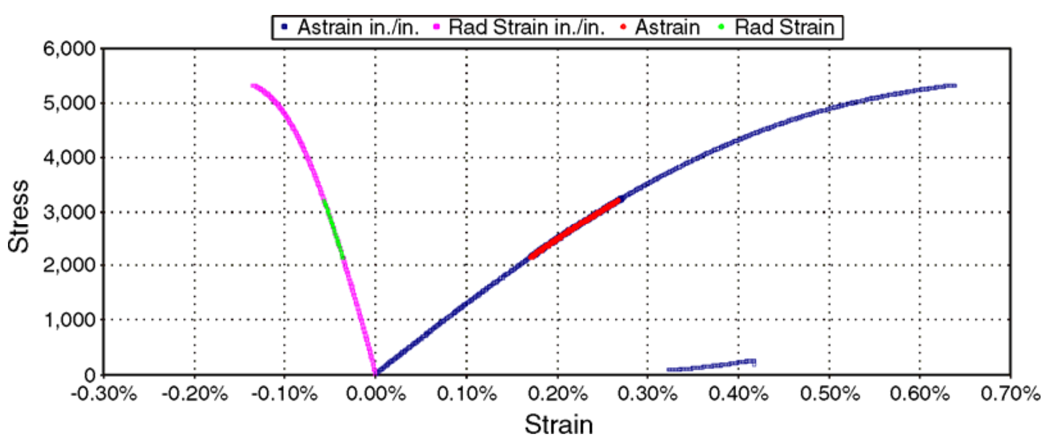


Figure 4—Stress-strain Curve for Cement System 4, Unconfined

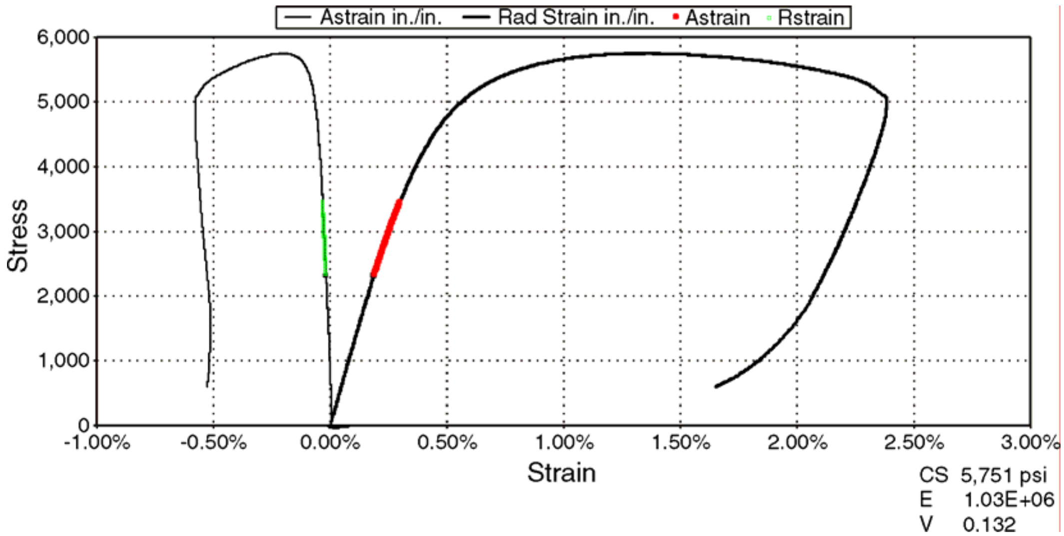


Figure 5—Stress-strain Curve of Cement System 4, Confined

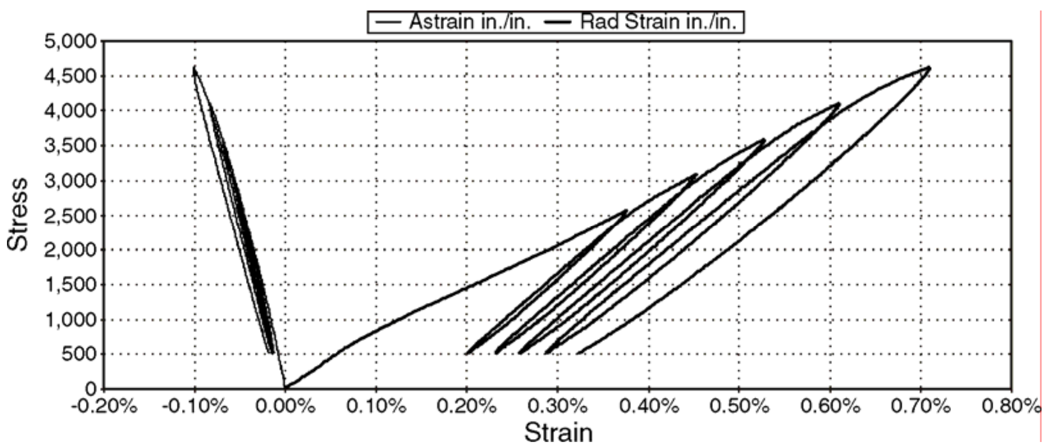


Figure 6—First Partial-cyclic Tests for Cement System 4

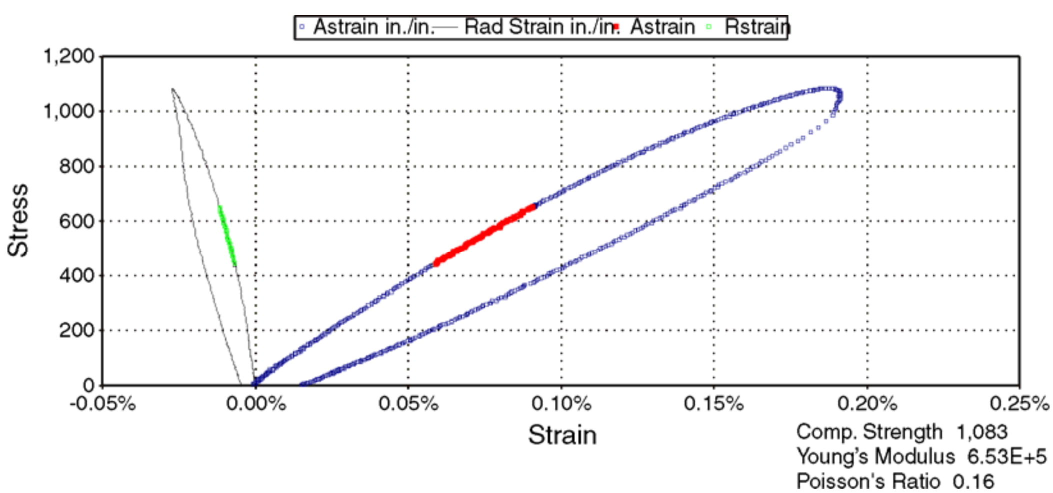


Figure 7—Stress-strain Curve for Cement System 1, Unconfined

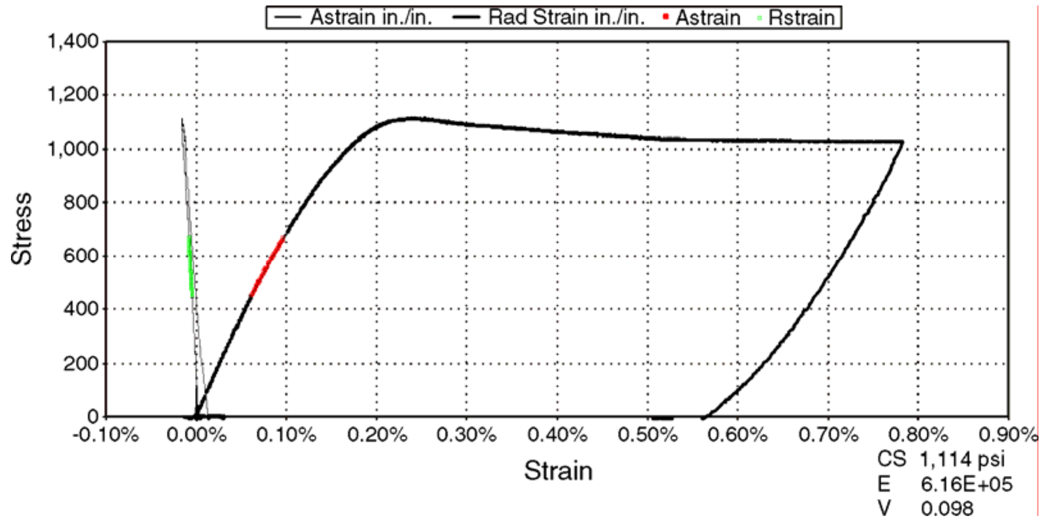


Figure 8—Stress-strain Curve for Cement System 1, Confined

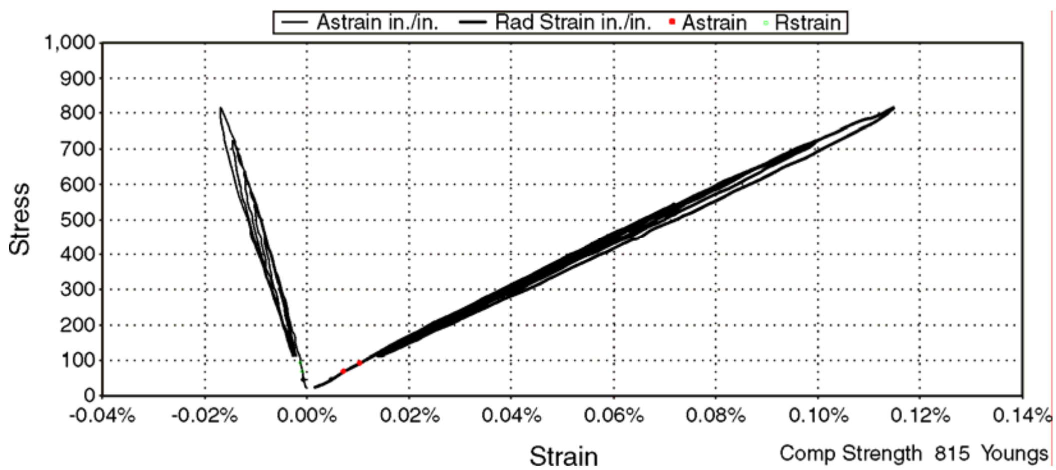


Figure 9—First Partial-cyclic Tests for Cement System 1

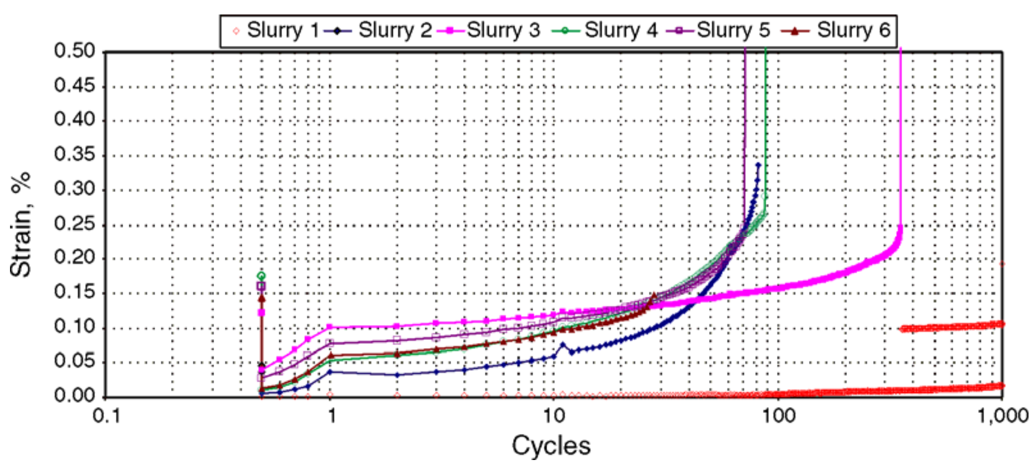


Figure 10—Plastic Strains of Various Cement Systems

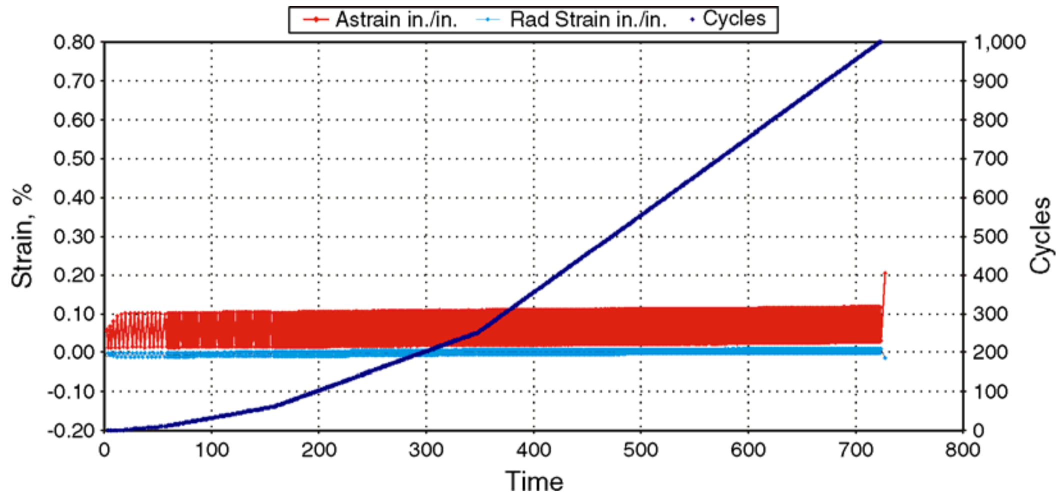


Figure 11—Cyclic Tests for Cement System 1

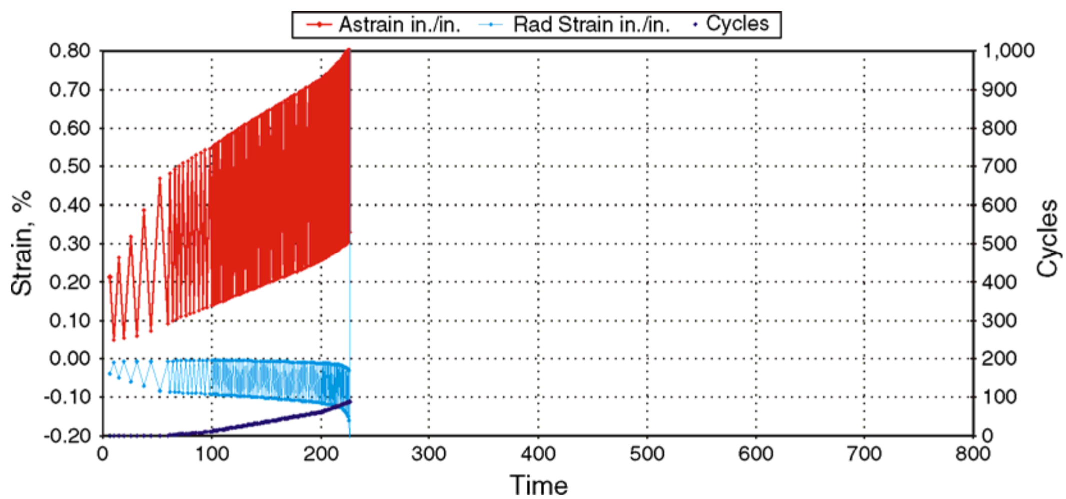


Figure 12—Cyclic Tests for Cement System 4

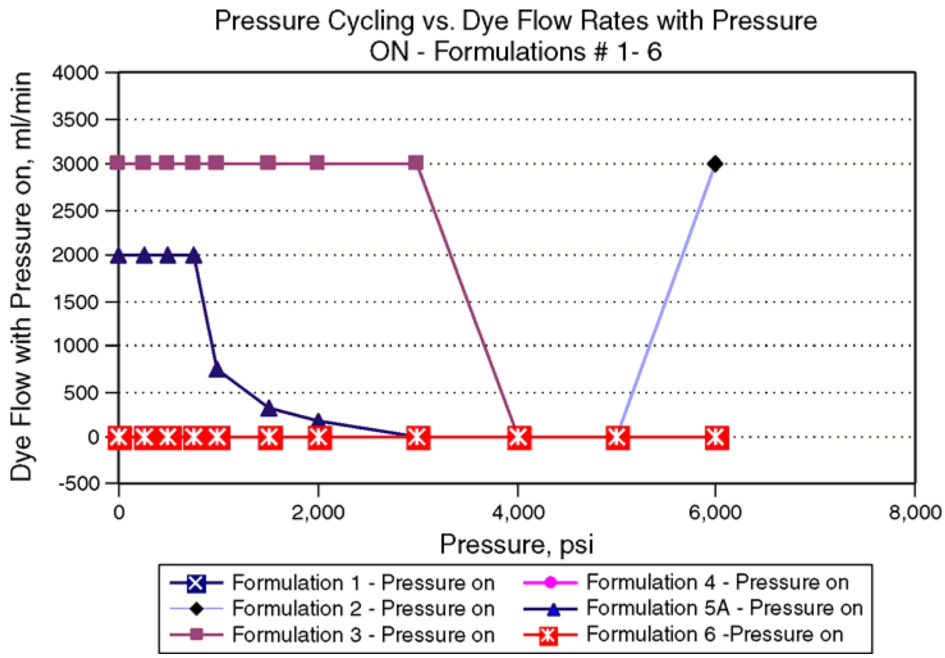


Figure 13—Fluid flow rates through the wellbore while the pressure is on.

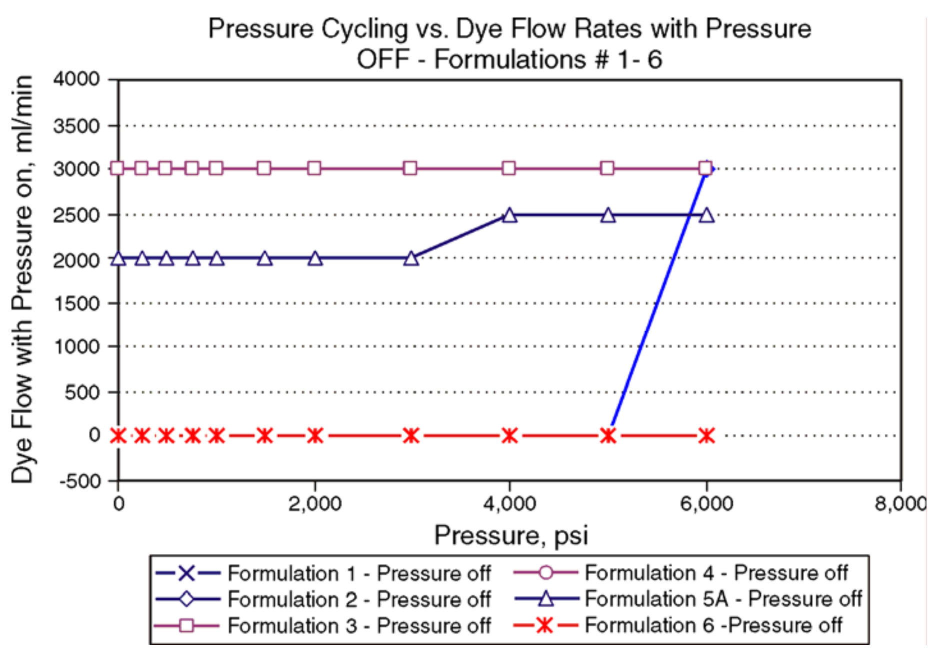


Figure 14—Fluid flow rates through the wellbore model with pressure off.