MMS Project

Long-Term Integrity of Deepwater Cement Systems Under Stress/Compaction Conditions

Report 1

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CSI

CEMENTING SOLUTIONS, INC.

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Introduction

This project is conducting research to determine the properties that affect cement's capability to seal fluids and to develop correlations between cement properties and sealing performance under downhole conditions. Testing to this point has been performed on neat Class A cement. The testing has helped to refine and confirm the test procedures that will be used for the remainder of the project.

Thickening-Time Test

Following the procedures set forth in API RP 10B[1], a thickening-time test was performed on the neat Class A slurry. The test conditions started at 80°F and 600 psi, and were ramped to 65°F and 5,300 psi in 48 minutes. Data from the thickening time test can be seen in **Table 1**.

Table 1—Results from Thickening-Time Test

Time (hr:min)	Consistency (Bc)
3:05	40
3:58	70
4:38	100

Free-Fluid Test

The free-fluid testing that was performed on the Class A slurry came from API RP 10B[1]. The free-fluid procedure, also referred to as operating free water, uses a graduated cylinder that is oriented vertically. The free fluid for the slurry maintained at 65°F was measured to be 0.80% (by volume).

Compressive Strength

Table 2 presents compressive strength data for neat Class A cement. The compressive strengths were derived using the 2-in. cube crush method specified in API RP 10B[1]. The samples were cured in an atmospheric water bath at 45°F. The reported values were taken from the average of three samples.

Table 2—Crush Compressive Strength

Cure Time (days)	Crush Compressive Strength (psi)
7	2,735
10	4,065
12	4,385
14	4,035
17	4,470

Tensile Strength and Tensile Young's Modulus

Mechanical properties of the neat Class A cement were tested. Tensile strength was tested using ASTM C496[2] (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens). For this testing, the specimen dimensions were 1.5 in. diameter by 1 in. long. **Figure 1** shows a general schematic of how each specimen is oriented on its side when tested. The force was applied by constant displacement of the bottom plate at a rate of 1 mm every 10 minutes. Change in the specimen diameter can be calculated from the test plate displacement. The (compressive) strength of the specimen during the test can be graphed along with the diametric strain (change in diameter/original diameter) to generate the tensile Young's modulus.

Figure 1—Sample Orientation for ASTM C496-90 Testing

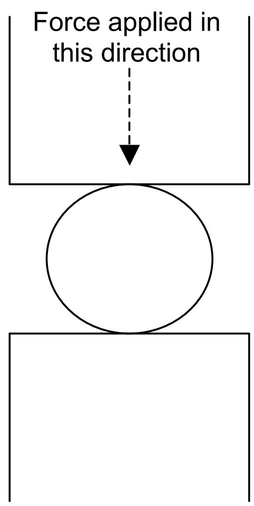


Table 3 shows the 14-day tensile strength and tensile Young's modulus of the cement. The samples were cured at atmospheric pressure in a water bath maintained at 45°F. The samples were cured under confined conditions (in the mold for the entire 14 days) and unconfined conditions (removed from mold after 24 hours and allowed to cure the remainder of the time outside of the mold).

Table 3—Splitting Tensile Strength and Tensile Young's Modulus Data

Curing Condition	Splitting Tensile Strength (psi)				Tensile Young's Modulus (10^4 psi)			
	Sample			Average	Sample			Average
	1	2	3		1	2	3	
Confined	409	406	368	394	20.43	19.20	17.83	19.15
Unconfined	163	278	198	213	7.88	8.35	8.25	8.16

For this project, rock mechanics personnel from Westport and Conoco will be discussing incorporation of a test method[3] from the International Society for Rock Mechanics (ISRM). The ISRM method calls for testing with a curved adapter that gives more contact area between the testing surface and the test specimen and results in less variation in results.

Some of the variation in the data could be attributed to settling of the cement slurry. The samples were cured in molds that were 5 in. long, and the individual 1-in. samples were then cut from the 5-in. specimen. For future testing, to avoid potential slurry settling, the slurry will be preconditioned for 20 minutes in an atmospheric consistometer and then be poured into individual, shorter molds so only one individual test sample will come from each mold.

Young's Modulus

Traditional Young's modulus testing was also performed using ASTM C469[4], Standard Test Method for Static Modulus of Elasticity (Young's Modulus) and Poisson's Ratio of Concrete in Compression. Young's modulus and effective compressive-strength were tested. The effective compressive strength is the equivalent unconfined compressive strength, which eliminates the effect of confining pressure. The diameter of each test specimen was 1.5 in., and the length was 3.0 in.

The following procedure is used for the Young's modulus testing.

1. Each sample is inspected for cracks and defects.
2. The sample is cut to a length of 3.0 in.
3. The sample's end surfaces are then ground to get a flat, polished surface with perpendicular ends.
4. The sample's physical dimensions (length, diameter, weight) are measured.
5. The sample is placed in a Viton jacket.
6. The sample is mounted in the Young's modulus testing apparatus.
7. The sample is brought to 100-psi confining pressure and axial pressure. The sample is allowed to stand for 15 to 30 min until stress and strain are at equilibrium. (In case of an unconfined test, only axial load is applied.)
8. The axial and confining stress are then increased at a rate of 25 to 50 psi/min to bring the sample to the desired confining stress condition. The sample is allowed to stand until stress and strain reach equilibrium.
9. The sample is subjected to a constant strain rate of 2.5 mm/hr.

10. During the test, the pore-lines on the end-cups of the piston are open to atmosphere to prevent pore-pressure buildup.
11. After the sample fails, the system is brought back to the atmospheric stress condition. The sample is removed from the cell and stored.

Samples that were cured in an unconfined condition (removed from mold after 24 hours and allowed to cure the remainder of the time outside of the mold) were tested at confining pressures of 0; 1,500; and 5,000 psi. Data from these tests are presented in **Table 4**. Testing at 0 confining pressure was also performed on samples that were cured in a confined condition (in the mold for the entire 14 days). Results from testing on the confined samples are presented in **Table 5**. All samples were cured for 14 days at atmospheric pressure in a water bath maintained at 45°F.

Table 4—Young's modulus data for samples cured in an unconfined condition

Confining Pressure (psi)	Young's Modulus (10^5 psi)	Effective Compressive Strength (psi)
0	8.13	4,118
	17.37	8,125
	15.99	9,166
1,500	12.39	7,912
	8.23	7,526
	12.59	9,046
5,000	8.22	8,553
	9.31	9,133
	9.67	9,007

Table 5—Young's modulus data for samples cured in a confined condition

Confining Pressure (psi)	Young's Modulus (10^5 psi)	Effective Compressive Strength (psi)
0	15.80	7,330
	17.50	6,823
	9.35	4,000

Figures 2 through 5 show Young's modulus plots for the different curing and testing conditions presented above. Young's modulus is the slope of the stress-strain curve. The highlighted portion of each curve shows the most linear segment where the Young's modulus is derived.

Figure 2—Young's modulus testing for samples cured in an unconfined condition and tested at a zero confining pressure

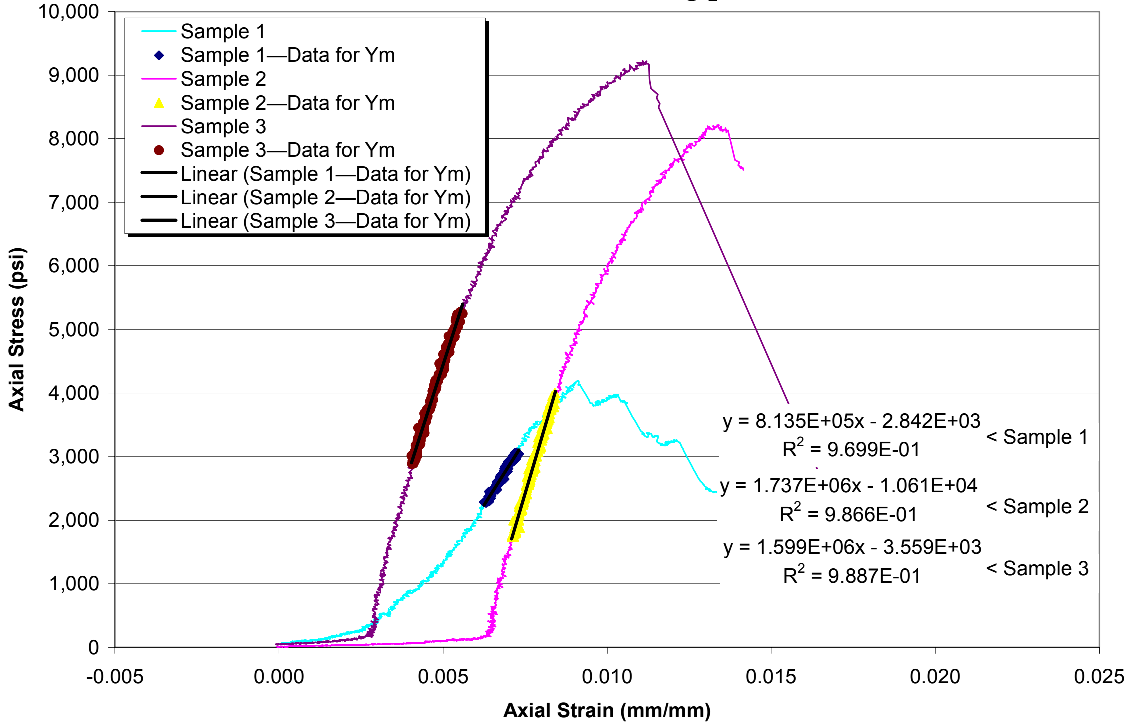


Figure 3—Young's modulus testing for samples cured in an unconfined condition and tested at a confining pressure of 1,500 psi

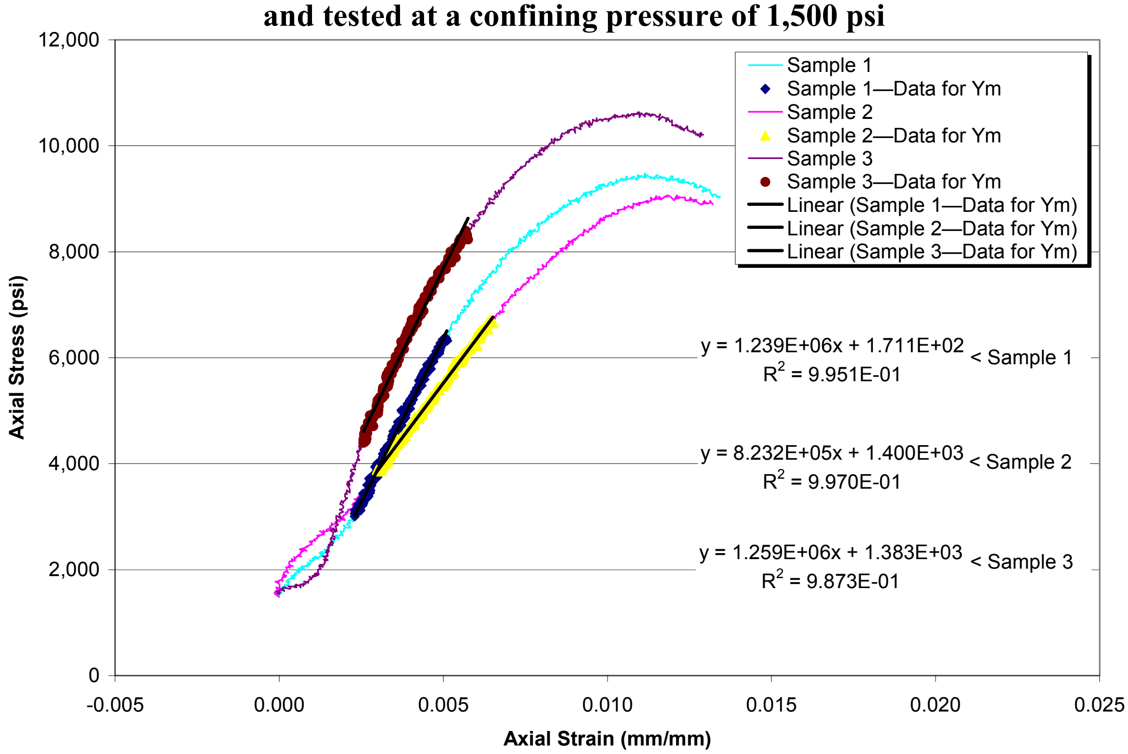


Figure 4—Young's modulus testing for samples cured in an unconfined condition and tested at a confining pressure of 5,000 psi

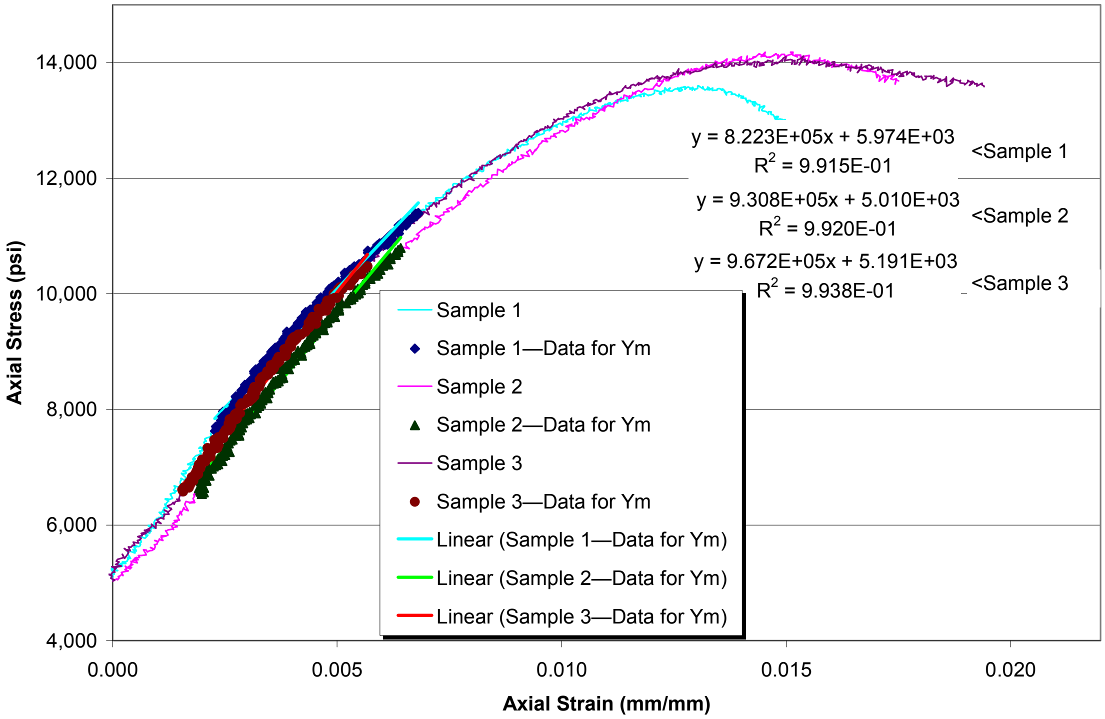
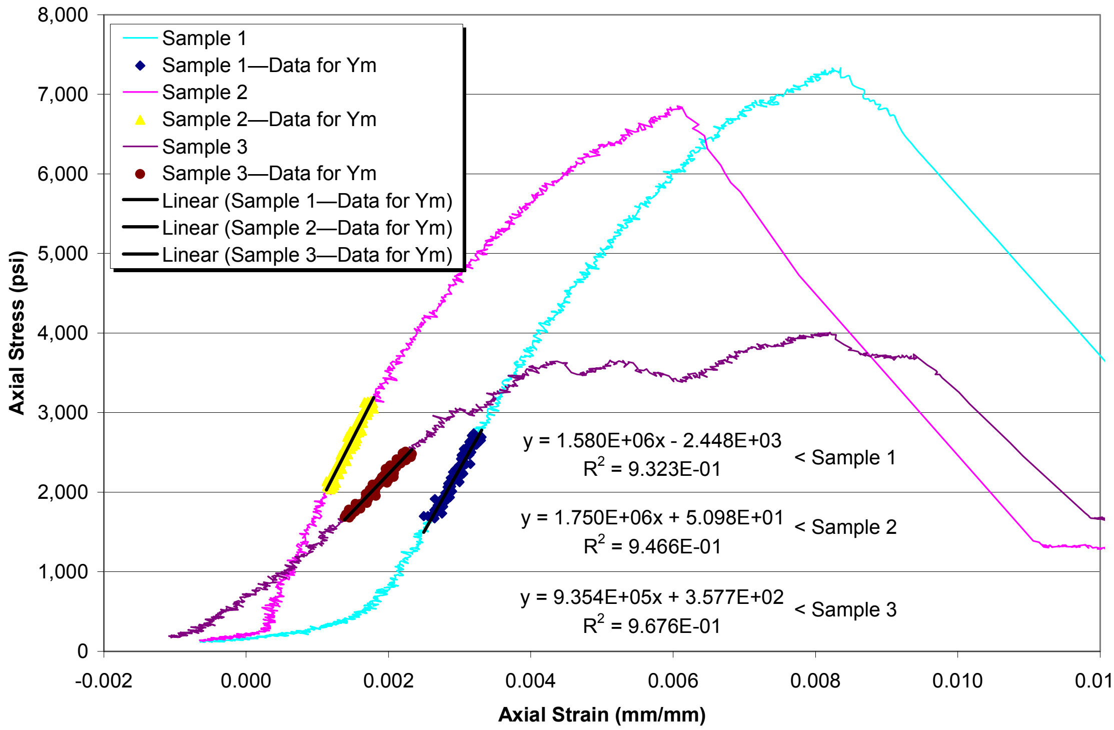


Figure 5—Young's modulus testing for samples cured in a confined condition and tested at zero confining pressure



Tests were also conducted to determine the effect that temperature cycling has on Young's modulus. The temperature cycling procedure was designed to simulate temperature conditions that might be encountered during production of a well. The samples are first cured for 14 days in a 45°F water bath at atmospheric pressure. They are then subjected to five days of temperature cycling. During each of these five days of temperature cycling, the cured samples are cycled as follows.

1. Samples are removed from 45°F water bath and placed in 96°F water bath for one hour.
2. Samples are placed in 180°F water bath for four hours.
3. Samples are placed in 96°F water bath for one hour.
4. Samples are placed back in 45°F water bath.

Table 6 presents samples that were cured at 45°F in an unconfined condition (removed from mold after one day and allowed to cure the remaining 13 days outside of the mold) and that were then temperature-cycled for five days. **Figures 6** and **7** graphically present the Young's modulus data.

Table 6— Young's modulus data for samples cured in an unconfined condition and then temperature-cycled for five days

Confining Pressure (psi)	Young's Modulus (10^5 psi)	Effective Compressive Strength (psi)
0	11.59	5,014
	5.48	4,084
	12.45	5,243
1,500	8.92	6,975
	10.48	6,642
	11.09	7,022

Figure 6—Young's modulus testing for samples cured in an unconfined condition and then temperature-cycled for five days and tested at zero confining pressure

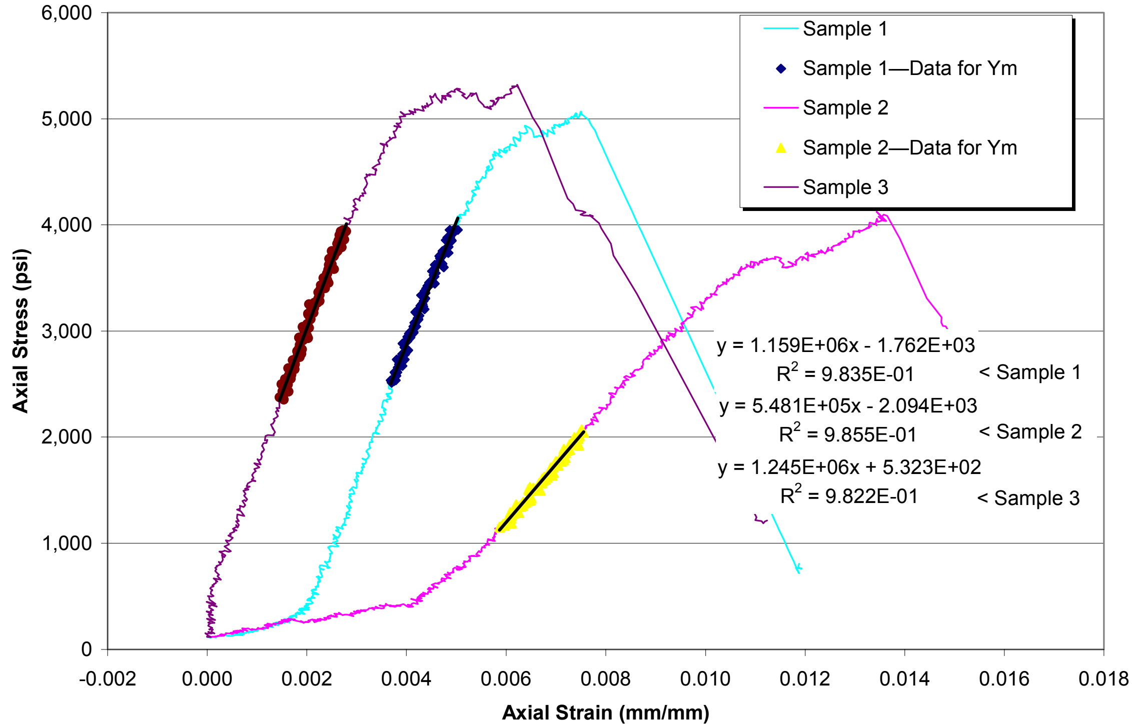
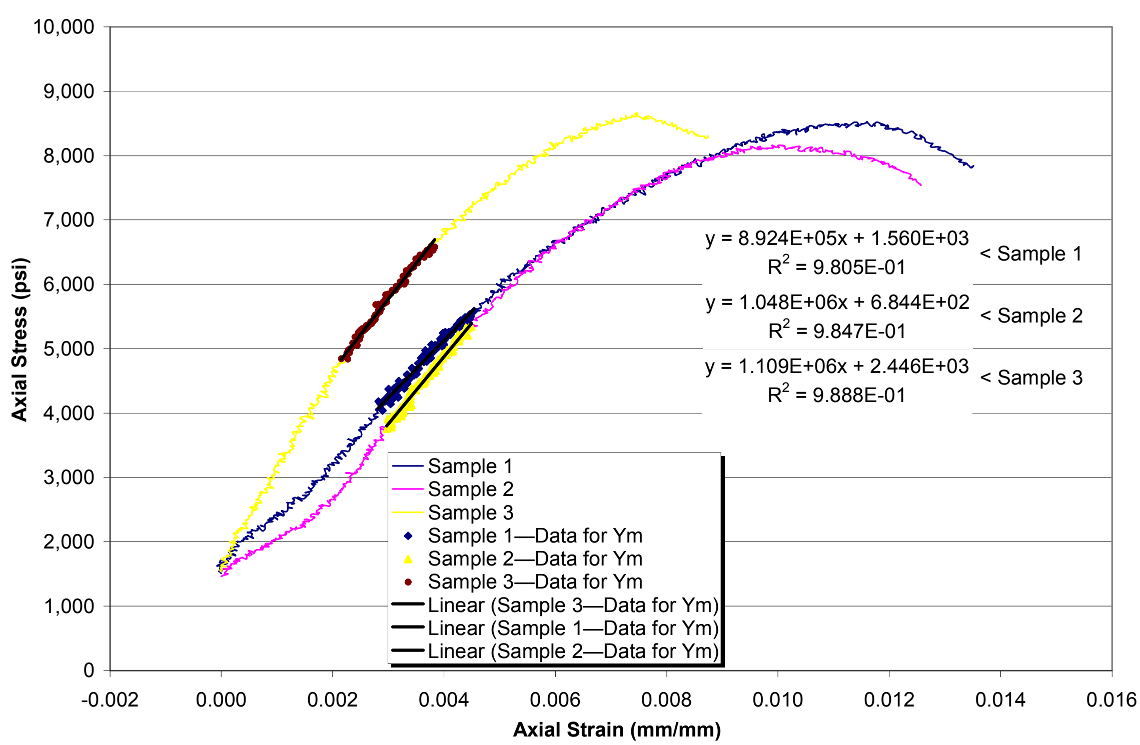


Figure 7—Young's modulus testing for samples cured in an unconfined condition and then temperature –cycled for five days and tested at a confining pressure of 1,500 psi



Some of the variation in the Young's modulus data could be attributed to settling of the cement slurry. The samples were cured in molds that were 10 in. long, and the individual 3-in. samples were then cut from the 10-in. specimens. For future testing, to avoid potential slurry settling, the slurry will be preconditioned for 20 minutes in an atmospheric consistometer and then poured into individual, shorter molds so only one individual test sample will come from each mold.

For future Young's modulus testing, it has been recommended to maintain a pore pressure that is 80% of the testing (final) confining load. The pore pressure will be ramped up at the same rate as the confining load and the pore pressure will be held and maintained once it reaches 80% of the testing confining load. This is believed to be a better simulation of the conditions that are experienced downhole.

Shear Bond Strength

Testing was also performed to evaluate shear bond strength of neat Class A cement. These studies investigate the effect that restraining force has on shear bond. Samples were cured in a pipe-in-pipe configuration (**Figure 8**) and in a pipe-in-soft configuration (**Figure 9**). The pipe-in-pipe configuration consists of a sandblasted internal pipe with an outer diameter (OD) of 1 $^{1}/_{16}$ in. and a sandblasted external pipe with an internal diameter (ID) of 3 in. and lengths of 6 in. A contoured base and top are used to center the internal pipe within the external pipe. The base extends into the annulus 1 in. and cement fills the annulus to a length of 4 in. The top 1 in. of annulus contains water.

For the pipe-in-soft shear bonds, plastisol is used to allow the cement to cure in a less-rigid, lower-restraint environment. Plastisol is a mixture of a resin and a plasticizer that creates a soft, flexible substance. This particular plastisol blend (PolyOne's Denflex PX-10510-A) creates a substance with a hardness of 40 duro.

The pipe-in-soft configuration contains a sandblasted external pipe with an ID of 4 in. A molded plastisol sleeve with an ID of 3.0 in. and uniform thickness of 0.5 in. fits inside this external pipe. With the aid of a contoured base and top, a sandblasted internal pipe with an OD of 1 $^{1}/_{16}$ in. is then centered within the plastisol sleeve. The pipes and sleeve are 6 in. long. The base extends into the annulus 1 in. and cement fills the annulus to a length of 4 in. between the plastisol sleeve and the inner 1 $^{1}/_{16}$ -in. pipe. The top inch of annulus is filled with water.

Figure 8—Cross-Section of Pipe-in-Pipe Configuration for Shear Bond Tests

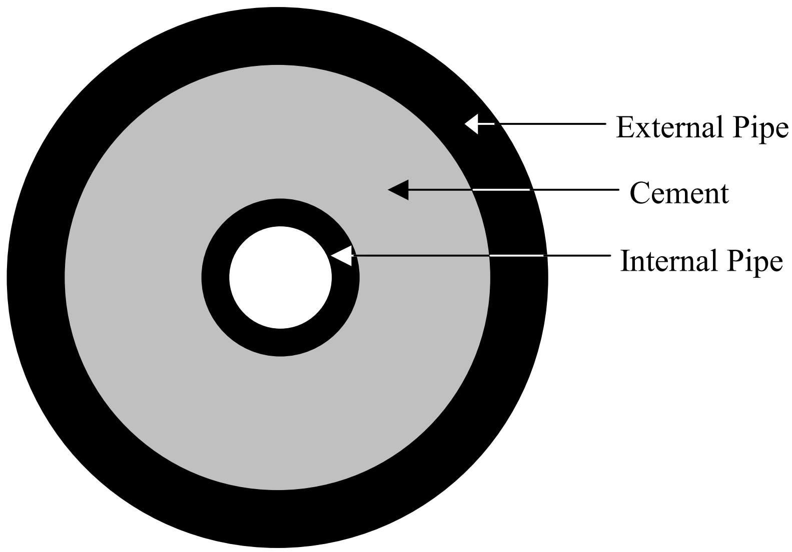
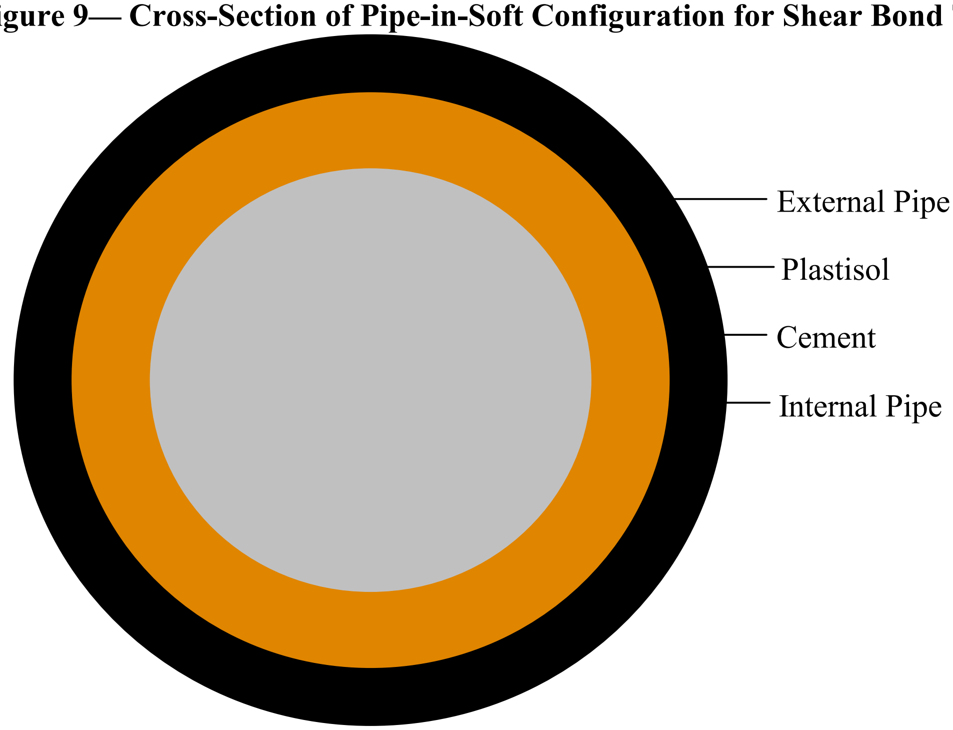


Figure 9— Cross-Section of Pipe-in-Soft Configuration for Shear Bond Tests



The shear bond measures the stress necessary to break the bond between the cement and the internal pipe. This was measured with the aid of a test jig that provides a platform for the base of the cement to rest against as force is applied to the internal pipe to press it through. (**Figure 10**) The shear bond force is the force required to move the internal pipe. The pipe is pressed only to the point that the bond is broken; the pipe is not pushed out of the cement. The shear bond strength is the force required to break the bond (move the pipe) divided by the surface area between the internal pipe and the cement. Future testing will also look at some other testing alternatives: (1) greasing the interior of the external pipe and (2) pressing out the external pipe first. These would help avoid the potential effects that the cement bond to the external pipe has on the measurement of shear bond of the cement to the internal pipe.

Figure 10—Configuration for Testing Shear Bond Strength

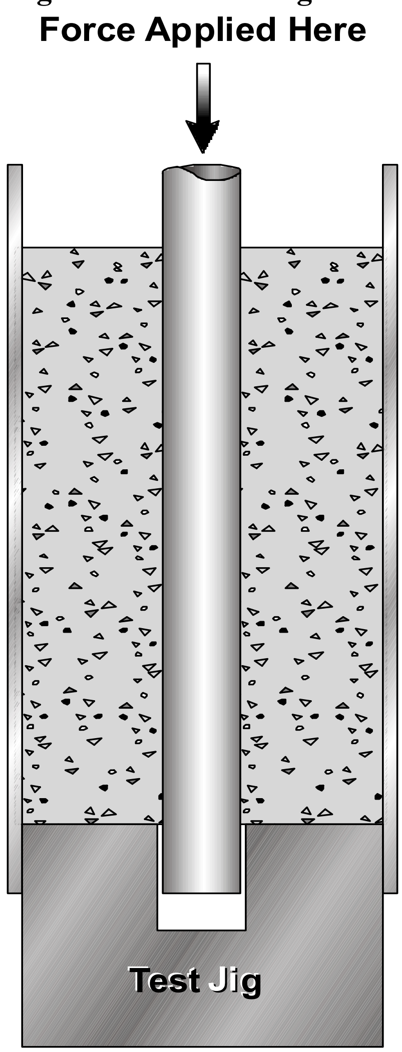


Table 7 presents the 14-day shear bond strengths of the cement samples in the pipe-in-pipe and pipe-in-soft configurations. They were cured at atmospheric pressure in a water bath maintained at 45°F.

Table 7—Shear bond strengths

Configuration	Shear Bond Strength (psi)			
	Sample			Average
	1	2	3	
Pipe-in-Pipe	1,200	1,233	945	1,126
Pipe-in-Soft	128	190	275	198

The effect that temperature cycling has on shear bond was also tested. The temperature cycling procedure was designed to simulate temperature conditions that might be encountered during production of a well. The samples are first cured for 14 days in a 45°F water bath at atmospheric pressure. They are then subjected to five days of temperature cycling. During each of these five days of temperature cycling, the cured samples are cycled as follows.

1. Samples are removed from 45°F water bath and placed in 96°F water bath for one hour.
2. Samples are placed in 180°F water bath for four hours.
3. Samples are placed in 96°F water bath for one hour.
4. Samples are placed back in 45°F water bath.

The results for the temperature-cycled shear bonds are presented in **Table 8**.

Table 8—Shear bond strengths for temperature-cycled samples

Configuration	Shear Bond Strength (psi)			
	Sample			Average
	1	2	3	
Pipe-in-Pipe	167	167	161	165
Pipe-in-Soft	68	65	82	72

Some variation in test results with the Young's modulus and tensile strength testing could be potentially attributed to settling of the cement slurry. For future testing, to avoid potential slurry settling with shear bond and other tests, the slurry will be preconditioned for 20 minutes in an atmospheric consistometer and then poured into individual, shorter molds so only one individual test sample will come from each mold.

Shrinkage Testing

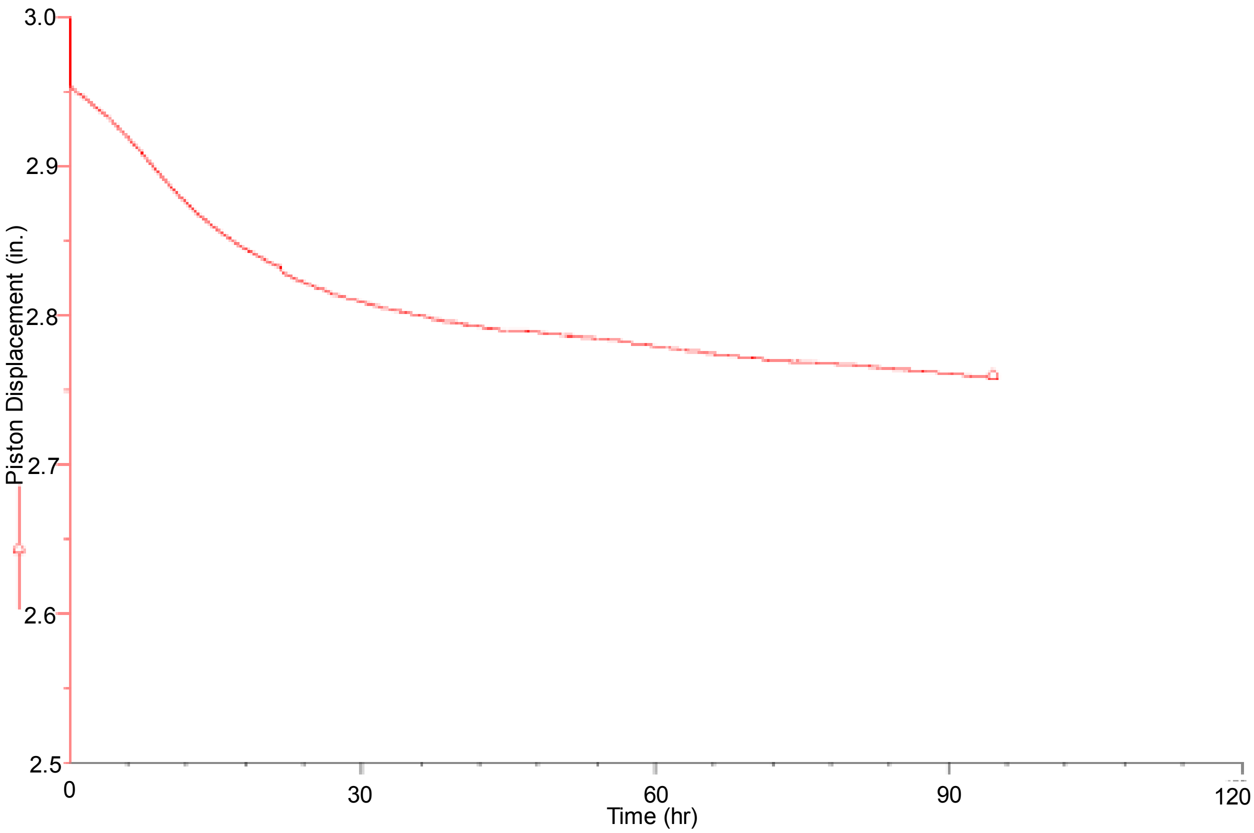
Using a modified Chandler Model 7150 Fluid Migration Analyzer, tests were performed to determine shrinkage of the neat Class A cement. The following procedures were used for performing the shrinkage testing.

1. Fill the test cell with 180 cm^3 of the cement slurry.
2. Place 40 mL of water on top of cement slurry.
3. Place the hollow hydraulic piston into the test cell and on top of the water.

4. Close off the test cell and attach the pressure lines and piston displacement analyzer.
5. Close all valves except valve on top of test cell cap. Purge air out of system.
6. Apply 1,000-psi hydrostatic piston pressure to the test cell and begin recording data (time, piston displacement, and pressure).
7. Run test and gather data for desired amount of time.

Figure 11 is a chart of the piston displacement that was recorded during the inner shrinkage testing. The piston displacement indicates the inner shrinkage of the cement.

Figure 11—Piston displacement during inner shrinkage testing of Class A cement



Changes in the cement volume are assumed to be overwhelmingly dominated by inner shrinkage, although any bulk shrinkage would also affect the volume. From the piston displacement data, the cement volume shrank by 6.8%.

Future testing will test for bulk (plastic state) shrinkage, which measures the external volume change of the cement. The Chandler Model 7150 Fluid Migration Analyzer can also be used for the plastic-state shrinkage testing. The procedures for the testing are as follows.

1. Grease the interior of the test cell for ease of piston movement.
2. Fill the test cell approximately halfway with cement slurry.
3. Place the hollow hydraulic piston into the cell and on top of the cement slurry.

4. Close off the test cell and attach the pressure lines and piston displacement analyzer.
5. Close all valves except valve on top of test cell cap. Purge the air above the piston with water until water passes through the release valve and then close the valve.
6. Apply 1,000-psi hydrostatic piston pressure to test cell and begin recording data (time, piston displacement, and pressure).
7. Run test and gather data for desired length of time.

Literature Review

A literature review is being conducted that is looking at some of the potential stressors on casing and cement such as compaction, temperature cycling, and pressure cycling. The literature discusses some of the resulting damage that can occur from the stressors, ways to model the stressors, and guidelines for minimizing or preventing the damage. The literature review is ongoing. Here is what has been done to date.

Production of a well leads to a decrease in downhole fluid pressure. With the pressure decrease, more of the weight of the overburden sediments must be supported by the rock matrix, which can lead to compaction. This subsurface compaction can also result in surface subsidence.[5]

Compacted reservoirs can lead to casing compression, buckling, shear, and bending.[5, 6] Companies have performed straightforward mathematical analysis and finite element modeling to determine the casing characteristics that best withstand the different aspects of compaction.[7, 8, 9, 10] Cement designs have also been based off of finite element modeling that was performed to simulate various stressors that can be seen by the cement.[11, 12, 13, 14]

Gas leaks in wells have also been attributed to cement shrinkage, which creates circumferential fractures that become paths for gas flow.[15] Baumgarte *et al*. looked at expanding cement (which is used to prevent some gas flow problems) and found that, although helpful in many situations, expanding cement can actually lead to a microannulus between the casing and cement when it is placed in soft formations.[16]

Jackson and Murphey examined the effect of casing pressure on annular cement seal. They used near-full-scale laboratory simulation and found that 5-in. casing that is pressure tested to 70% of its burst pressure could potentially lead to a loss of cement integrity and create a path for gas flow. They also tested for a reduced hydrostatic situation where the casing was pressured to 10,000 psi while the cement set and then the pressure was released; this situation also created a path for gas flow.[17]

Participants' Responses

Participants were asked to provide ideas on the factors that affect the integrity of the annular seal and flow of fluids. The following responses were received from the participants.

- Condition of the surface of the casing(s) – sandblasted, rusted, mill varnish, rough coat material, etc.
- Cement pumping rate – plug, laminar, or turbulent flow regime
- Hole cleaning spacer – type and volume
- Open hole lithology
- Fluid in hole before cement – water-based mud, oil-based mud, synthetic mud, clear fluid, water, liquid hydrocarbons, gas, etc.
- Wall cake – integrity, thickness, composition, etc.
- Borehole rugosity and tortuosity
- Pipe movement during cementing – rotation or reciprocation
- Casing jewelry – turbulators; wall scratchers; centralizer design, effectiveness, and spacing; etc.
- Cement sheath thickness/casing stand-off from hole wall
- Composition/type of cement slurry – neat, lightweight, foam, additives, gel and setting times, permeability of set cement, etc.
- Pore pressure in the cement and in the formation as a function of time. Maybe permeability, too.
- Shrinkage in the paste with increasing hydration - in the case where extra fluid is available and in the case where it is not (casing/permeable formation v. casing in casing or long liner lap)
- Decay in the hydrostatic pressure transmitted by the cement column with time
- Water/cement ratio
- Initial stress state in the cement
- Thermal expansion coefficients of formation, cement, casing
- Cement failure strain, cement failure envelope under triaxial conditions at widely different strain rates
- Cement work of fracture, fracture toughness
- Cement creep under complex stress and at temperature
- An oversimplistic belief that a 2-in. cube crush test tells anything about the cement mechanical properties in the annulus
- Inability to model (by FEA) the behavior of the sandwich of formation>mud cake>cement>microannulus>casing under complex stress from (say) compaction, tectonic displacements, fault movement, etc.
- Influence of temperature on all the above - on the property measurement and on the chemistry of the cement over time - years rather than hours
- Annular geometry and eccentricity
- Mud cake properties - formation>mud cake>cement>microannulus>casing
- Mud displacement efficiency % and geometry/extent of anything less than 100%
- Induced changes - thermal (e.g., production or cold completion brine)

- Induced changes - mechanical (e.g., pressure testing casing maybe at early age)
- Setting of pack-offs in wellheads, setting of integral liner top packers
- Inability to mix and pump the job as designed
- Cement
- Mud
- Formation fluids
- Cement slurry design
- Sheer incompetence
- Temperature cycling
- Out-of-gauge openhole large washouts
- Pipe centralization
- Cement slurry density variations
- Downhole fluid movements while cement sets
- Cement ability to develop gel strength rapidly
- Pressure cycling
- Positive pressure tests on casing after cement set
- Ineffective packer element design. (DV packer collars are not effective in sealing off gas)

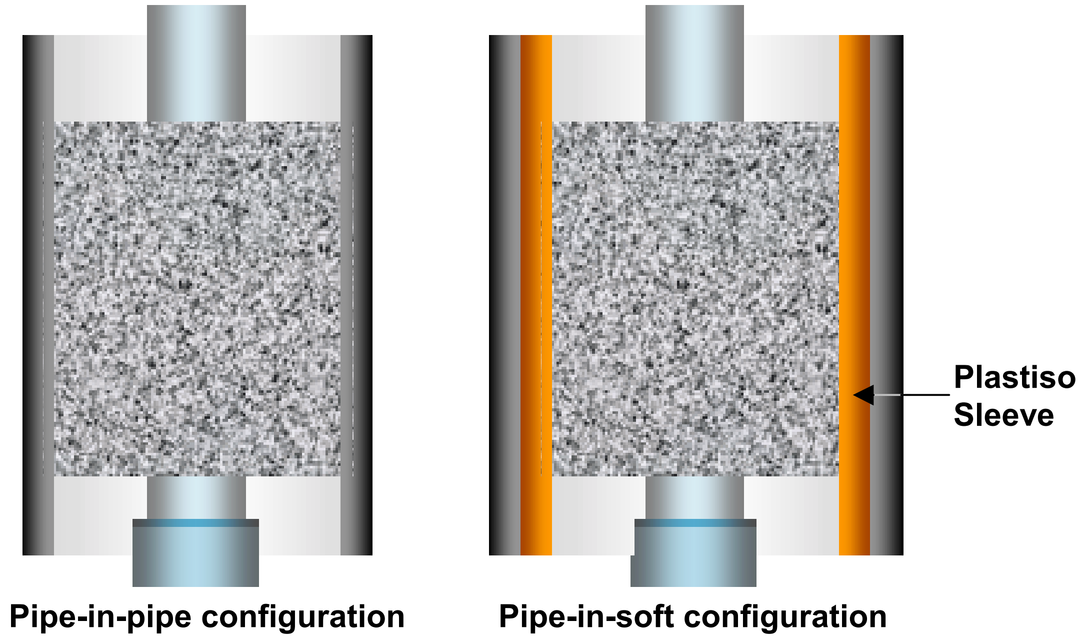
Future Testing

Casing Pressure Test

Future studies will investigate the effect that casing pressure tests have on annular seal. Many people feel that casing pressure tests expand the casing and create pressures on and increase the inner diameter of the surrounding cement. The stresses and physical changes can adversely strain the cement and potentially deform the cement irrecoverably.

A laboratory model has been developed to simulate casing pressure tests (**Figure 12**). The model can be made in two different configurations– pipe-in-pipe and pipe-in-soft. This is to simulate high-restraint and low-restraint formations. This can help to identify differences between hard formation and loosely consolidated formation. The pressure testing will be initiated after different times of cement curing to determine the effects of curing time before pressure testing. Multiple cycles of pressure testing will be performed.

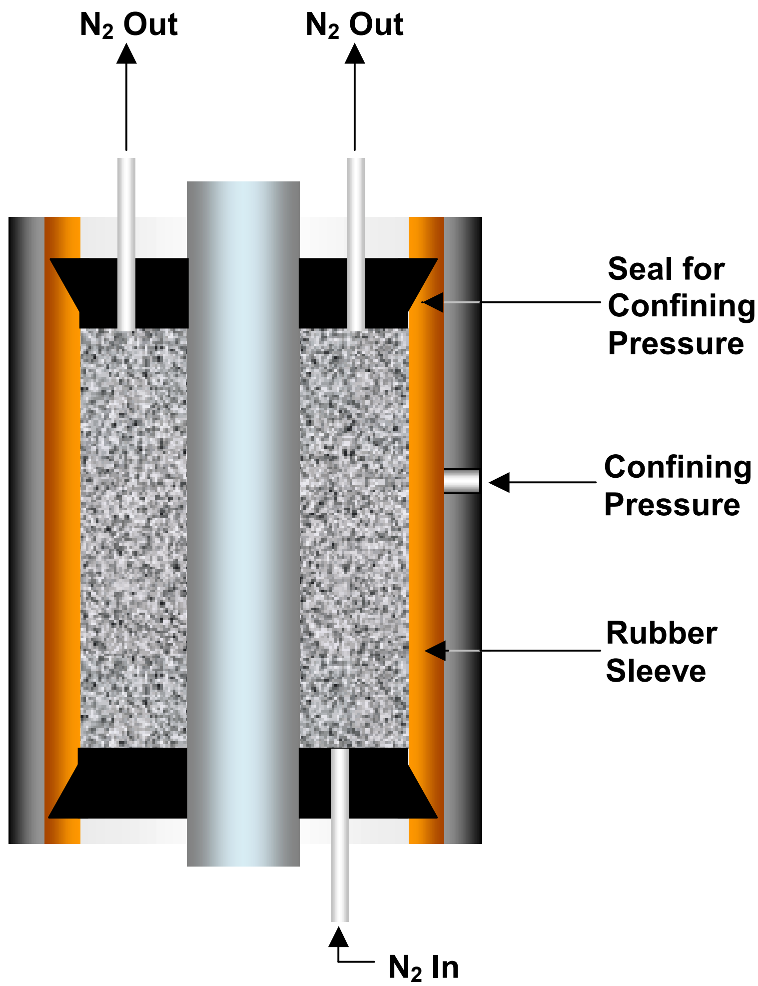
Figure 12—The two different configurations for the casing pressure test



Annular Seal Test

A key factor of this project is investigating cement's capability to maintain its seal under downhole stresses. An annular seal model is being developed that can measure bulk permeability across a cement system that has been stressed from temperature or pressure cycling. As with some of the other testing, the annular seal test model will have pipe-in-pipe and pipe-in-soft configurations to simulate high and low restraints, respectively. **Figure 13** is a schematic of the pipe-in-soft configuration of the annular seal model.

Figure 13—Cross section of annular seal model for pipe-in-soft configuration



The inner pipe of the model will be the main conduit for the stressing medium. For instance, the inner pipe can contain heated fluids while the remainder of the system is at a different temperature; this simulates the hotter formation fluids that can be experienced during production. The inner pipe of the model can also be pressured up to 5,000 psi, simulating casing pressure testing which is believed by many to lead to loss of annular seal because of the expanding and contracting casing.

The annular seal testing will be performed after each time the interior conduit pipe is pressurized. For the temperature cycling, the model will be subjected to five complete temperature cycles and then annular seal testing will be done. The model will again be temperature cycled five times and then annular seal testing performed. This will continue with annular seal testing after every fifth temperature cycle until annular flow is detected or after 20 temperature cycles, whichever comes first.

In the pipe-in-soft configuration, the rubber sleeve surrounding the cement is able to withstand 25 psi. During the annular seal test, pressure can then be applied to the outside of the rubber sleeve, allowing the sleeve to make a fluid-tight seal on the outside of the cement. Pressurized nitrogen gas (<25 psi) can then be applied axially across the cement and the only paths for fluid flow is through cement or along the interface between the cement and the inner pipe. Any exiting nitrogen flow rate can be monitored and measured. There is no need for the rubber sleeve or the exterior confining pressure in the pipe-in-pipe configuration.

Testing on Other Cement Designs

After finalizing some of the test procedures, testing will be started on specific cement slurries. The first four slurries to test after the Class A cement slurry include foamed cement (20 to 25% foam quality), latex cement (1 gal/sk), high-strength fumed silica cement (with carbon fibers), and cement with lightweight hollow spheres.

Mathematical Modeling

Progress is also being made to contract with the University of Houston to perform finite element analysis (FEA) of the laboratory models being used in the project (temperature and pressure cycling models). The results from the laboratory experiments will be compared to the mathematical modeling. These studies will then be compared with other FEA work that has been presented in the literature.

The mathematical modeling will be analyzed to determine if the stresses associated with the temperature and pressure cycling will result in loss of annular seal. This can be compared with the annular-seal testing that will physically test the cement systems for annular seal.

References

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