Long-term Cement Integrity of HPHT Cement Systems

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Deep Trek, a U.S. Department of Energy program, seeks to improve HPHT well economics by improving drilling and completion technology. As part of the Deep Trek effort, CSI Technologies is attempting to improve the economics of deep-well completions with the development of a "supercement" capable of providing long-term, HPHT sealing integrity.

Industry growth in the United States finds drillers moving into deeper and hotter frontiers in search of oil and gas. Remediation of failed cement jobs in deep hot wells costs the industry more than $100 million each year. While additives and well-designed placement techniques can increase chances for achieving long-term zonal isolation in high-pressure, high-temperature (HPHT) wells, a high incidence of gas pressure on deep hot wells because of inadequate placement and mechanical failure of cements, continues to be reported.

Although applications and methods may vary, Portland cements have been used worldwide and are recognized as the industry standard for well sealants. Temperature and pressures encountered through production and intervention can induce high stresses in the wellbore, exceeding the resistance capabilities of conventional Portland cement systems. Short-term fluid migration of water and gas also affects the performance of wellbore cement, and mechanical cement failure is exaggerated in wells with narrow annuli because of higher stress on the cement sheath.

With current completion technology, a supercement designed for long-term sealing integrity in HPHT wells is needed to alleviate escalating costs associated with annular seal loss and associated remedial repair. Remedial procedures for restoring seal integrity are expensive and multiple applications often are required during the well's life. Annular seal loss in HPHT wells can result in well abandonment, and potential environmental and safety issues.

Deep Trek, a U.S. Department of Energy (DOE) program, seeks to improve HPHT well economics by improving drilling and completion technology. As part of the Deep Trek effort, CSI Technologies is attempting to improve the economics of deep-well completions with the development of a supercement capable of providing long-term, HPHT sealing integrity. The material may also be applicable in less extreme environments that still require high stress resistance, or where annular gas pressure is a known problem. With tensile and compressive strength, permeability, expansive properties, and pipe and formation bonding sufficient for long-term durability, the potential for mechanical failures at temperatures exceeding 350°F and at pressures over 15,000psi will be minimized.

Three years—Three phases

Last year, the CSI laboratory team began working on the first phase of the three-phase, 3-year Deep Trek project. Phase I began with laboratory analysis of various Portland and non-Portland materials, and admixtures in conventional and unconventional tests. Identification of compositions that provide the mechanical properties required for withstanding extreme downhole temperatures and pressures resulted. In Phase II, the team's work is continuing with scale-up testing and well trials to determine performance on a field scale. Scale-up activities include manufacturing, mixing, placement mechanics and performance in a test well. Demonstrations of the cement's performance in three to six field applications in hot deep wells and technology transfer activities will complete Phase III.

An industry advisory committee, comprised of representatives from 12 companies, has assisted in the technical development of the supercement material and continues to provide a combined expertise for project execution. Membership is voluntary and includes Anadarko, BHP Billiton, BP, ChevronTexaco, ConocoPhillips, the DOE, Dominion, McMoran, PDO, 3M, Shell and Unocal.

In Phase II, committee members will assist in monitoring and evaluating performance of the candidate supercement material(s) in actual wells. Additionally, committee members contribute data to a deep hot well database used for test design, specification development and as a technical exchange medium.

Phase I—Project objectives

Phase I, conducted from October 2003 through December 2004, concentrated on identifying state-of-the-art sealant systems, especially those applicable to HPHT environments. A baseline series of Portland cement designs commonly used in HPHT environments was identified and tested to determine currently-available performance. Various candidate systems, designed and screened at low and high temperatures, narrowed the field to a manageable number.

Finally, unconventional tests were utilized to gain insight into the sealing capability of the candidate systems. This work is in preparation of Phase II scale-up and field trial work.

General project execution

During Phase I, 169 different slurry compositions were evaluated in more than 1,100 laboratory tests. Low-temperature screening tests were abandoned for some slurries, because they were engineered for reactions at higher temperatures and would not attain strength at lower temperatures. The "base" series of testing consisted of compressive strength, compressive Young's Modulus and tensile strength utilizing the splitting tensile method (Figure 1).

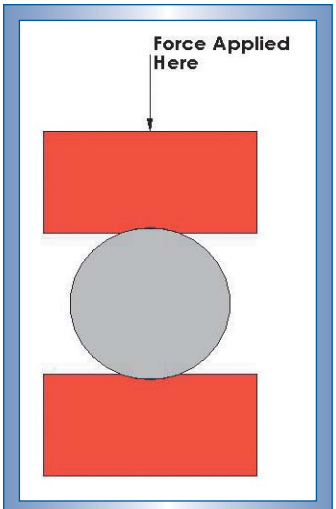

Figure 1. Splitting tensile test method (ASTM D3967-95A). Diametrically-applied force induces tensile stress in a plane normal to the load application.

Tests not routinely conducted in today's industry include flexural strength, shearbond, anelastic strain and annular seal (Figure 2). These unconventional analyses helped gain insight into the interactions between a material's mechanical properties and wellbore sealing capability. Anelastic strain is a measure of permanent deformation in cement as a result of repeated low-stress load application. This permanent deformation represents cumulative damage, leading to eventual failure at loads well below ultimate stress levels (Figure 3).

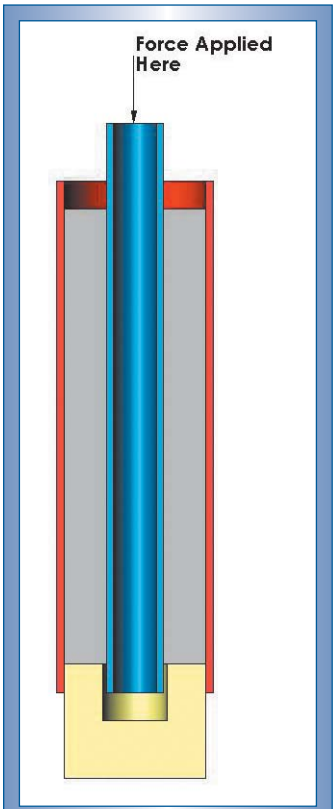

Figure 2. Measurement of the shear bond between the inner pipe and cement.

No combinations of mechanical properties, and specifically no single mechanical property, are sufficient to predict the ability of a cementing material to produce an effective and long-term annular seal in a wellbore environment. The precise nature of the interaction of the various mechanical properties of cementitious materials, in context of well failure, is yet unknown. Some correlation work has been done, but it represents a preliminary evaluation of cement properties required to form a competent annular seal in a wellbore environment.

Significant efforts were expended developing monolith production, test protocols and equipment modifications for the project. Specialized devices were designed and built to measure deformation during loading for compressive Young's Modulus, as well as for flexural test beams. The Splitting Tensile Test (ASTM D3967-95A) was chosen for tensile strength testing because of the simpler test requirements, sample productions and test procedures. A controlled-rate press was modified to allow for cycle-testing determining anelastic strain properties.

Annular seal test

The annular seal test is considered the best available predictor of a material's sealing performance in a well environment. Cement is placed in a geometrically representative test fixture with loading applied from internal pipe pressure. A cross section of the test fixture is shown in Figure 4.

The red outer tube represents the formation or outer pipe and can be varied to simulate formation of various strengths. The gray material is the cement sheath, and the blue pipe represents the wellbore tubing or casing. The yellow end piece conducts gas flow to the cement sheath. In practice, the cement is cured in the fixture. Low-pressure gas (10psi) is connected to the open end of the yellow end piece, and a source of high-pressure water is connected to the inner diameter of the blue tubing.

Water pressure is applied in successive pressure cycles in increments of 1,000psi and then released, starting at 1,000psi. When a maximum pressure of 10,000psi is reached, four more cycles of 10,000psi are applied. This sequence represents one full cycle; after which, the cycle is repeated starting at 1,000psi. The flow of gas remains at zero while the annular seal is intact. When the cement fails, a flow path opens through the cement and the gas flow rate is measured. In practice, the material mechanical properties and the interactions between the properties determine when the annular seal is compromised. Materials engineered for sealing performance at high temperatures may not set at low temperatures or may exhibit mechanical properties different from those obtained at higher temperatures. As Phase II progresses, the annular seal test is being redesigned to evaluate material properties at elevated temperatures.

Energy analysis

Cement sheaths subject to loads imposed by well conditions and intervention activities are subject to failure at some point. In the well, a strong formation and heavy pipe essentially "back up" the cement, resulting in more energy absorption before cement failure. Laboratory studies conducted in the

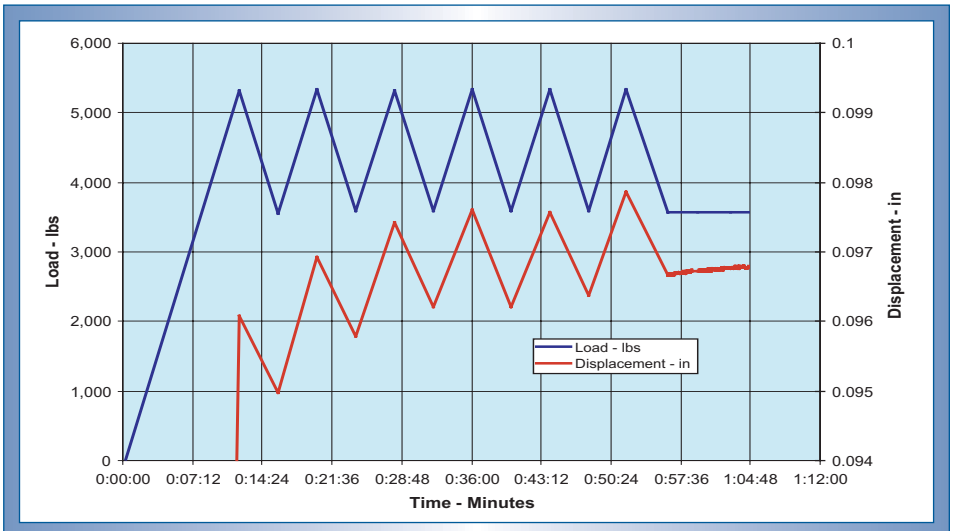

Figure 3. Measure of permanent damage (measured in permanent strain) in cement sample as a result of low-stress loading.

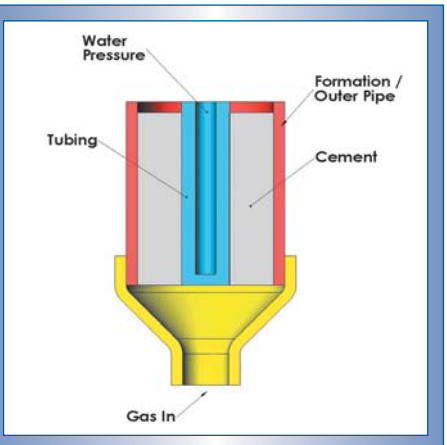

Figure 4. Measures annular seal integrity in a geometrically-representative model. Failure is related to a complex interaction of cement mechanical properties and indicated by measured gas flow.

annular seal model indicate that cement failure is related to the amount of energy imposed on the cement sheath during the life of the well. Mechanical properties of cement strength are important, but there are other cement and non-cement variables that affect long-term integrity of the cement sheath. These variables include:

- cement properties
  - cement tensile strength
  - cement Young's Modulus
  - anelastic strain
  - radius of cement sheath
- well properties
  - size and wall thickness of casings
  - hole size
  - formation Young's Modulus
- loading data
  - anticipated intervention and production loading profile

The correlation involves a dimensionless energy application factor, representing the energy applied to the cement sheath in a well; and an energy resistance factor, representing the ability of the pipe/cement/formation system to resist the applied energy. The correlation derived to date is useful but not comprehensive in terms of mechanical properties. Additional tests, using different mechanical properties and load rates, are planned.

Test compositions

Compositions tested throughout the project include:

- baseline Portland cement recipes;
- ceramicrete and its derivatives;
- reduced water systems (highly dispersed);
- high-concentration reactive and nonreactive fibers;
- Portland cement with unconventional additives; and
- non-Portland cements.

Throughout this project, material selection and chemistry efforts are based on the theory that improvement in the crystalline structure results in reducing porosity and permeability, thereby strengthening the mechanical structure of the cement and improving annular sealing performance. As shown in the table on the next page, low values are desirable for anelastic strain and annular seal test results; high values are desirable for the remainder of the reported tests.

Portland cements are comprised of a highly heterogeneous matrix in which large particles of various materials are present in a cementitious binder. These cements are relatively brittle, exhibit significant compressive strengths and relatively low tensile strengths, and bond reasonably well to steel. Heat can degrade the cement during time, and the matrix is usually porous and permeable because of the excess water required to mix and pump the material.

In Portland systems, not much can be done about the mechanically inefficient matrix structure, but decreasing the amount of water present in the slurry can reduce shrinkage and improve strength, permeability and porosity. The following strategies were utilized to affect performance improvements.

Reduced water—Reducing the amount of water present in the slurry improved strength and reduced porosity. This is straightforward cement chemistry where strength is generally proportional to the cement-to-water ratio for a given cement composition. The slurries tested with reduced water were highly dispersed to improve mixability. In common cements, highly-dispersed slurries can cause difficulties because of settling. The slurries investigated were not tested specifically for settling, but appeared to produce reasonable suspension properties for the solids due to water content reduction.

Fibers—Fibers are known to improve tensile strength, or more specifically, the toughness of cement. However, they can actually create problems by bonding mechanically to the matrix and providing fracture points when the cement is stressed. Reactive fibers, such as ceramics and silicates, were used to provide

mechanical and chemical bonding properties to the matrix. Various compositions and fiber lengths were investigated. Results incorporating ceramic fibers are encouraging, and fibers are applicable to a wide range of Portland and non-Portland systems.

Unconventional additives—These include additives commonly used in cements, but in higher concentrations than typical, as well as new additives not utilized in the industry. Studies focused on molybdenum and high concentrations of magnesium oxide, both of which cause significant expansion in the cement matrix. If expansion occurs at the right time during the hydration process, it can result in a denser matrix, higher strength and lower permeability product.

Timing is critical during the hydration process; if expansion occurs too early or too late, it can lead to matrix disintegration. When cured under confined conditions, where dimensional expansion is restricted, the expansion is theoretically directed inward to the matrix, thereby reducing porosity and permeability. In practice, this method has led to high shear bonds, although both compressive and tensile strengths of cored samples have been modest. Annular seal tests are planned to determine the ultimate potential of the material.

Non-Portland systems—Initial research focused on ceramicrete and other acid-base systems, but produced insufficient results for inclusion in Phase II. Other systems included a calcium-aluminum-silicate mix and a high-temperature resin.

A range of calcium aluminum silicate, calcium aluminum phosphate and magnesium aluminum phosphate systems were screened for strength development at 350°F. Although results were unexceptional, work in this area was incomplete at the end of Phase 1. Testing with a CAS system varying slurry density and component ratios is continuing during Phase II, and initial results are encouraging.

Preliminary test results of candidate systems. Blue—Best properties (or nearly best). Red—Worst values in systems studied. Low values—Desirable for anelastic strain and annular seal tests. High values—Desirable for remainder of tests.

System	Formula	Compressive Strength psi	Tensile Strength psi	Anelastic Strain in/in/min	Shear Bond psi	Annular Seal Ml/min flow
Baseline	77	5,650	730	44%	471	1.0
Baseline	99	4,790	710	100%	256	2.4
MgO	128	3,190	280	In Proc	1,850+	In Proc
Moly	132	4,280	1,080	25%	310	2.3
Moly	133	6,680	1,370	18%	570	3+
Resin	120	In Proc	2,210	In Proc	In Proc	In Proc
Resin	121	In Proc	3,200	In Proc	In Proc	On Proc
Fiber	130	3,710	1,020	52%	299	0
Fiber	131	3,020	1,150	54%	186	0.6
Fiber	136	4,510	1,310	31%	1,021	In Proc
Ca Al Silicate	169	1,920	220	In Proc	In Proc	In Proc

The high-temperature resin produced high tensile strengths, which were as much as 10 times higher than those of conventional Portland cements. Typically, resins soften with temperature, making them of dubious value in high-temperature wells. The resin under consideration has been formulated to retain properties at elevated temperatures, thereby qualifying the material as a candidate for this project. The high elasticity exhibited by the material may be useful in attaining long-term sealing integrity; other property testing is incomplete.

A full-scale mixing test yielded the following difficulties with handling the resin on a large scale in an oilfield cementing environment:

- vapors pose possible health risks;
- surface mixing consists of mixing the liquid resin with a liquid activator in precise relative quantities;
- air and water entrainment causes a persistent entrainment issue in the mixing tub, which can cause problems if density measurements are required during mixing;
- resin chemistry is a highly exothermic reaction, creating high temperatures that can damage mixing equipment and pose a health risk to personnel;
- resin can be weighted or lightened for placement efficiencies. The limits of weighting and the impact on material performance are unknown;
- resin does not mix with water, which may generate advantages or disadvantages. Issues include displacement mechanics, mixing requirements, and sweep efficiency for mud and spacer removal; and
- mixing on a field scale will require the development of specialized equipment with sealed containers, precise rate control and dedicated pumps. The heat-activated nature of the material may make it difficult to place the material in the HPHT well environment. Cleanup procedures and disposal of cleanup materials must be addressed.

Conclusions

The first year of this Deep Trek-related project has generated new insights and theories into the mechanisms by which cement mechanical properties translate to annular sealing performance in oil and gas wells. Test protocol and analysis methods have been developed to better understand cement performance, and a suite of materials has been identified for evaluation in scale-up field trials. Ultimate improvements in HPHT well economics will result with the successful development of an HPHT supercement. ✧