

Effects of Long-Term Exposure to Ultrahigh Temperature on the Mechanical Parameters of Cement

Long-term cement-sheath mechanical durability is critical to maintaining zonal isolation for the life of a well. Wells subjected to cyclic steam stimulation (CSS) undergo extreme temperature changes that cause substantial stresses on the cement sheath. Analysis models that are useful in predicting the failure potential of a cement sheath require input of cement mechanical parameters. The full-length paper presents a test methodology for measuring the mechanical parameters of five cement formulations after exposure to 645°F.

Introduction

The Cold Lake development in eastern Alberta, Canada, has been in operation since the mid-1980s. It is the largest in-situ heavy-oil recovery operation in Canada and one of the largest thermal heavy-oil operations in the world. Production of the heavy oil is by CSS, in which steam is injected into the reservoir above fracture pressure and a mixture of bitumen, gas, and water is produced from the same wells.

Historically within the oil and gas industry, the only concern with cement formulations at ultrahigh temperatures was chemical stability. The loss of compressive strength in Portland cement and increase in permeability at temperatures greater than 235°F was discussed in the literature as early as 1935. This phenomenon, commonly referred to as strength retrogression, is the result of morphological changes

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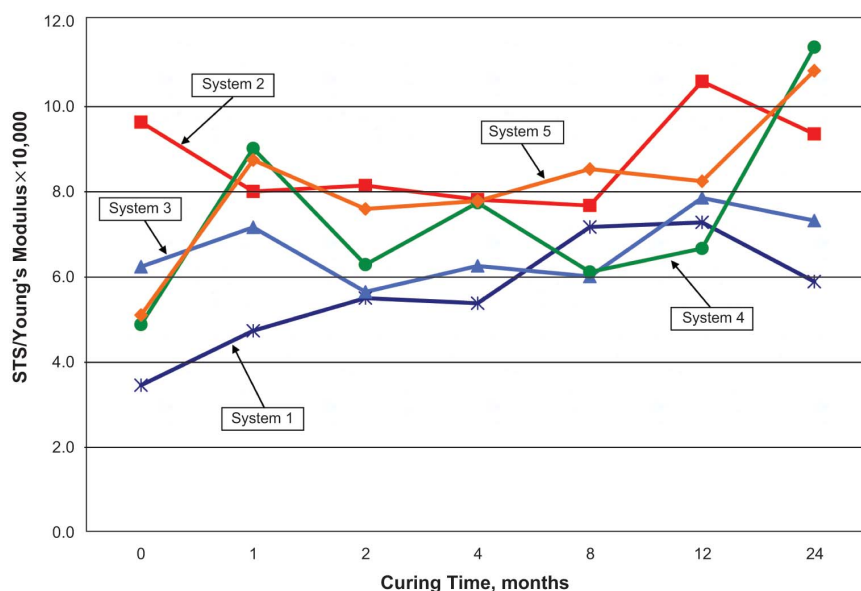


Fig. 1—Ratio of STS to Young's modulus for specimens cured at 645°F.

in the crystalline structure of cement when it is exposed to elevated temperatures. Preventing strength retrogression by addition of finely ground crystalline silica at a 35 to 40% concentration by weight of cement (BWOC) was discovered nearly 50 years ago and has been the industry standard ever since. All cement formulations used throughout the Cold Lake project have contained the recognized silica concentration.

Cement-sheath failure resulting from wellbore stresses received little attention before 1992. While there are distinctive differences in the mathematical models that have been developed, they all agree that sheath failure is a function of the stress states imposed on the wellbore and the mechanical parameters of the cement sheath and the surrounding rock. The stress states imposed on the wellbore by large temperature increases, such as those encountered during steam injection, have been recognized as sufficient to cause tensile cement-sheath failure.

The key mechanical cement parameters responsible for whether or not sheath failure will occur are Young's modulus, Poisson's ratio, and tensile strength. No measurements of these parameters ever had been performed on cement samples that had undergone long-term exposure to the ultrahigh temperatures encountered during CSS at Cold Lake.

Systems Evaluated

Conventional System. System 1 was a Class G cement containing 40% BWOC silica flour, 4.3% BWOC gypsum, a fluid-loss-control additive, and calcium chloride (CaCl_2) accelerator mixed at 15.4 lbm/gal. This was the system used in Cold Lake at the time the study began. It was tested to provide baseline data and evaluate its acceptability for withstanding the CSS stresses.

Thixotropic Cement System. System 2 was an economical low-density thixo-

For a limited time, the full-length paper is available free to SPE members at www.spe.org/jpt. The paper has not been peer reviewed.

tropic cement system. The 14.5-lbm/gal system was a blend composed of 92% Class A and 8% gypsum with 40% by weight of blend silica flour. A fluid-loss-control additive and CaCl_2 accelerator also were included in the system. This system was under consideration to replace System 1 at the time the study was undertaken.

Foamed-Cement System. System 3 was foamed cement with an 11.65-lbm/gal density. The base slurry was composed of Class G cement containing 40% BWOC silica flour and mixed at 15.8 lbm/gal. A surfactant package was added to produce a stable foamed-cement slurry that contained 26% gas by volume.

High-Strength Low-Density System. System 4 was a low-density specialty system containing hollow ceramic microspheres. The 11.65-lbm/gal system was designed with a maximized solid-volume-fraction technique. The final design had a silica content greater than 40% BWOC. A fluid-loss-control additive and CaCl_2 accelerator were included in the system.

Flexible and Expanding Low-Density System. System 5 was a low-density specialty system containing solid flexible particles and a magnesium oxide based expanding agent. The 12.5-lbm/gal system was designed with a maximized solid-volume-fraction technique similar to System 4. The flexible particles were added at a concentration of approximately 50% by volume of blend to lower the Young's modulus. It was known that the flexible particles used in this system were subject to thermal alteration at temperatures greater than 350°F.

Test Methodology

Sample Preparation. Specimens to be used for triaxial compression testing required a 2-in.-long, 1-in.-diameter cylinder. Specimens to be used for the splitting-tensile-strength (STS) method (also known as the Brazilian compression testing method) for indirect tensile strength required a 0.75-in.-thick, 1.5-in.-diameter disk.

The nonfoamed-cement slurries were prepared according to American Petroleum Inst. (API) *RP 10B11*, and the foamed-cement system was prepared according to API *RP 10B-412*. The slurries were poured into cylindrical molds. The molds for the nonfoamed-cement specimens were placed in a pressurized

curing chamber to eliminate volumetric air entrainment and allowed to cure for 48 hours at 80°F. The foamed-cement samples were allowed to cure for 48 hours at 80°F in a water bath at atmospheric pressure.

High-Temperature Curing. The specimens were placed inside pressure curing vessels. Approximately 100 g of 20/40-mesh silica sand was poured into the vessels to maintain silica saturation during curing. The vessels then were filled with water to cover the cement specimens completely.

Each curing vessel contained three specimens for triaxial compression testing and three specimens for Brazilian compression testing, allowing repeat testing to be performed as required. A separate curing vessel was prepared for each cement formulation tested and for each curing time period. Extra specimens were prepared and placed in extra vessels in case any of the original specimens were compromised during curing and handling.

The sealed curing vessels were placed in a preheated 645°F oven and were maintained at that temperature for the duration of the curing. On the basis of steam tables, the pressure inside of the curing vessels was 2,133 psi. Curing vessels were removed from the oven at 1-, 2-, 4-, 8-, 12-, and 24-month time periods. After allowing the vessels to cool to ambient temperature, they were opened and the specimens removed. After removal from the pressure vessels, all specimens were stored in fresh water until they were ready to undergo mechanical testing. Additional sets of specimens for each cement system were cured at room temperature. These specimens underwent mechanical parameter testing at the same curing periods as the specimens placed in the oven.

Results

Effective Compressive Strength (ECS). The evolution of ECS over time was as expected. System 1, the standard-density silica-stabilized Class G system, showed a steady increase in strength throughout the first year as the secondary crystalline phases continued to form in the cement matrix. A slight decrease was seen over the second year; however, the strength in excess of 8,000 psi was still quite high. Systems 2 and 3 had behavior similar to System 1, although the magnitude of the strength was significantly lower because

of the lower densities. The specialty cement blends, Systems 4 and 5, showed a marked decrease in strength after the first month exposed to 645°F; however, the strength stabilized at approximately 2,000 psi for the remainder of the 2-year period. All five of the systems maintained a level of ECS that would withstand the compressive stresses encountered in a CSS well.

Young's Modulus. The Young's modulus trends were similar to the ECS trends. Systems 4 and 5 had very low Young's modulus ranges, between 3×10^5 and 4×10^5 psi, indicating a high degree of flexibility. The standard System 1 started with a Young's modulus greater than 1×10^6 , which steadily increased over the 2-year test period to a value of nearly 1.8×10^6 psi. Systems 2 and 3 showed an increase in Young's modulus over the first 4 months and thereafter stabilized in the range between 8×10^5 and 1×10^6 psi, approximately half the value of System 1.

Poisson's Ratio. Analysis of the Poisson's ratio trends is very difficult for all five cement systems. No clear trends in Poisson's ratio can be defined, and no relative comparison of the various systems can be made.

STS. The evolution of the STS parameter over the 2-year curing period provided a good indication of which systems would be able to handle relatively higher tensile stresses without failure. As with the ECS, System 1 had the highest STS. The STS for System 2 was significantly higher than the STS for System 3, the foamed cement, in spite of the fact that the ECS for both systems was similar. Systems 4 and 5 exhibited the lowest STS of the group, with values in the 200- to 300-psi range.

Ratio of STS to Young's Modulus. Cements with a low Young's modulus and a high tensile strength can be thought of as being the most resistant to failure under tensile stresses. The low Young's modulus provides a greater capacity for strain at a given stress level, while the high tensile strength allows a greater stress tensor before material failure. Thus, the ratio of STS to Young's modulus (**Fig. 1**) can be useful for providing an indication of the effectiveness of one cement system to resist failure as compared with another. Two of the sys-

tems, System 2, the thixotropic blend, and System 5, the specialty blend with flexible particles, consistently had the highest STS/Young's modulus ratios of the five systems studied.

Strain vs. Stress. Strain-vs.-stress plots indicate axial strain-hardening behavior for the room-temperature specimens for all five systems. This ductile behavior is evidenced by a continued increase in stress after reaching the initial yield of the specimens. System 1 data for the specimens cured at 645°F showed a classic brittle behavior with a marked drop in stress after the initial yield was reached. Specimens cured at 645°F for Systems 2, 4, and 5 behaved in a plastic manner after reaching their initial yield, with a continued increase in axial stress vs. axial strain. The System 3 specimen cured for one month at 645°F showed a ductile behavior, but the specimens from the subsequent curing periods had a brittle response.

Anomalous Positive Radial Strain. All of the radial-strain curves for Systems 4 and 5 cured at 645°F moved into the

positive region of the graph instead of remaining negative as one would expect. This unusual behavior indicates a radial contraction under application of a triaxial compressive load. This anomaly is not evident from looking at the Poisson's ratio data because the early-time strain in the region where Poisson's ratio was determined was, in fact, slightly negative.

While there is no clear explanation for this behavior, one hypothesis is that both of these systems contained a large volume of large-diameter non-cementitious particles that caused the specimens to act in a heterogeneous manner. If those particles began to collapse under triaxial compression, the resulting volumetric reduction of the specimen could manifest itself in the form of radial contraction.

It is interesting that the same behavior was not seen for System 3 foamed cement because it could be expected that the bubble spaces would collapse under triaxial compression in a manner similar to the particles in Systems 4 and 5. This could be explained by the assumption that water from the curing vessel filled the bubble spaces

by means of diffusion during specimen curing. During triaxial loading, the water would be incompressible and volumetric reduction would occur only as the water slowly drained through the low-permeability cement matrix. The fact that the magnitude of radial strain for the foamed-cement system is very small supports this hypothesis.

Conclusions

1. None of the five systems studied indicated a catastrophic degradation of mechanical parameters after a 2-year exposure to 645°F.

2. In terms of ability to withstand wellbore stresses, simple cement blends, such as the low-density thixotropic System 2, may have mechanical parameters (i.e., low Young's modulus and high STS) that are as good as, or better than, the parameters of specialized flexible blends such as System 5.

3. The conventional cement system and the foamed-cement system had a brittle behavior after curing at 645°F, while the other systems continued to exhibit plastic behavior after long-term exposure to this temperature. **JPT**