Characterizing early-state physical properties, mechanical behavior of cement designs

By Dan Mueller and Ramy Eid, BJ Services Company

PRESSURE EVENTS THAT occur after surface casing cementation, such as casing integrity testing, formation integrity testing, impose stress on the recently set cement sheath. Should pressure testing take place during the early stages of cement curing, the tangential stress imposed by the pressure event can exceed the tensile strength of the cement, inducing cement sheath failure.

In most wellbore pressure scenarios, cement fails in tension. The proportionality between the compressive strength and the tensile strength of set cement is generally assumed to be an 8:1 to 10:1 ratio. During typical pressure testing events, the cement will have a compressive strength ranging from 500 psi to upwards of 2,000 psi. Accordingly, the tensile strength of the cement would be in the range of 50 to 200 psi at the time of casing pressure testing. However, accurate prediction of the degree of pressure-induced cement sheath stress requires more than a general correlation to derive cement tensile strength.

This paper characterizes the early-state physical properties and mechanical behavior of accelerated API Class A, G, H and ASTM Type I cement designs during the 12 hours following placement. The results provides guidance as to when pressure testing of the casing/formation can take place without inducing damage to the set cement sheath.

INTRODUCTION

Typical surface casing cement designs incorporate economical volume extended slurries mixed at 11.5 to 13.5 lbm/gal followed by a "tail" cement mixed at 14.8 to 16.5 lbm/gal that is placed in the lower section of the casing-wellbore annulus. Accelerators, such as calcium chloride, are often used to reduce the slurry thickening time and enhance early compressive strength development, thereby minimizing waiting-on-cement (WOC) time.

Once the cement is in place, maintaining annular isolation will depend on the mechanical behavior of the cement and formation and the stress conditions, but the early state physical properties and mechanical parameters of cement employed in surface casing applications have not been reported on.

SLURRY DESIGNS AND TEST METHODS

A group of 4 commonly used "tail" cements employed in surface casing applications were evaluated:

- ASTM Type I + 2% CaCl2 mixed at 15.2 lbm/gal;
- API Class A + 2% CaCl2 mixed at 15.6 lbm/gal;
- API Class G + 2% CaCl2 mixed at 15.8 lbm/gal;
- API Class H + 2% CaCl2 mixed at 16.2 lbm/gal.

The samples were cured at 100ºF bottomhole static temperature (BHST) and ambient pressure. Unconfined compressive strengths (UCS) and direct tensile strengths were measured at 4-, 6-, 8-, 10- and 12-hour intervals. Young's Modulus, Poisson's Ratio and confined compressive strengths were measured at 4- and 12-hour intervals. The ultrasonic compressive strength testing was conducted for 120 hours at 300 psi curing pressure.

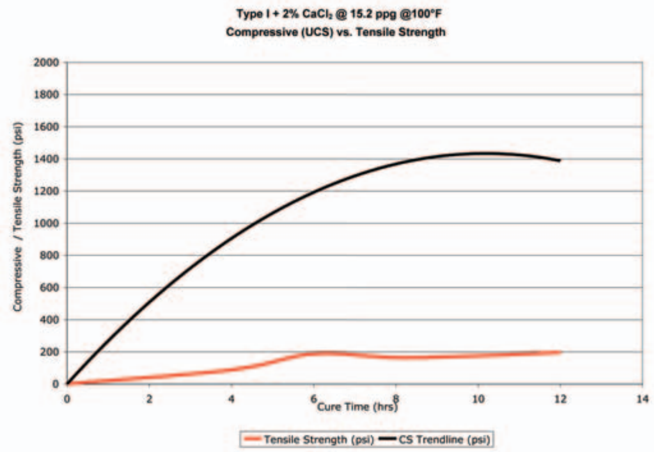

Figure 1

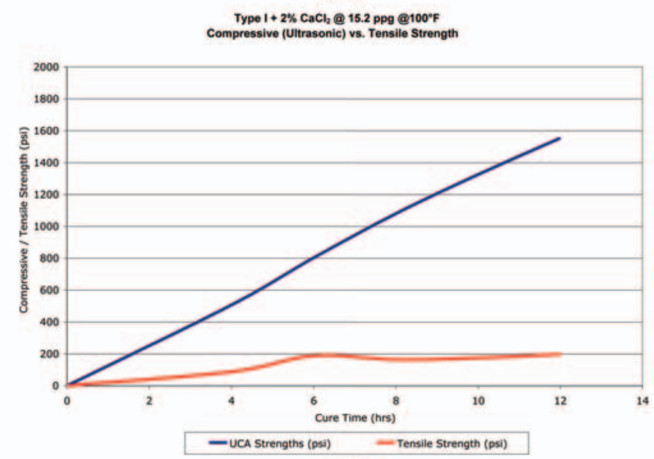

Figure 2

Unconfined compressive strength and ultrasonic strength testing was performed using the techniques defined in API RP10B, "Recommended Practice for Testing Well Cements," 22nd Edition, 1997. Ultrasonic compressive strength was determined by an Ultrasonic Cement Analyzer (UCA). The tensile strengths of the samples were determined by the briquette mold method described in ASTM C 190-85, "Tensile Strength of Hydraulic Cement Mortars," using a Gilson Model HM-138 Cement Strength Tester. Young's Modulus, Poisson's Ratio and confined compressive strength were statically determined by means of compression testing using a load frame.

DISCUSSION

In lab testing of the 4 cement designs, the early compressive strength development of the Type I, Class A and Class G systems demonstrated non-linear behavior from what would be considered a normal strength development response. For instance, the 3 cube average of the 8-hour strength for the Type I + 2% CaCl2 (1,261 psi) was actually less than the 3 cube average determined at 6 hours (1,539 psi). The Class A + 2% CaCl2 system exhibited similar behavior. The Class G + 2% CaCl2 system produced 1,665 psi compressive strength in 10 hours, with the 12-hour value being reduced to 1,557 psi.

API cement testing has shown the coefficient of variation for the 8 hour, 100ºF compressive strength specification test to be among the highest of all the various API cement specification tests. Dating to 1988, the average compressive strength reported using the method defined in API Specification 10A was 673 psi with a standard deviation of 170 psi and a coefficient of variation of 25%. The 2004 API Subcommittee 10 Cooperative Testing Program results produced an average 8 hour compressive strength of 785 psi, a standard deviation of 229 psi and a coefficient of variation of 29%. Actions to improve the test method for compressive strength determination contained in API Specification 10A (ISO 10426-1) are ongoing. It should be noted that methods for destructive compressive strength testing for well cements were adopted from ASTM codes and are not meant to reflect the actual conditions found within a wellbore. Under confining stress found in a wellbore, the compressive strength of well cement is generally much higher.

Given the intrinsic variability of the values of unconfined compressive strength during early set time, the authors choose to use a linear regression curve-fit for the raw compressive strength values. Figures 1, 3, and 5 represent the curve-fit of unconfined compressive strength compared with the tensile strength values over the test period. Figures 2, 4 and 6 represent the actual ultrasonic compressive strengths vs tensile strengths over the test period. (For additional related figures, please go online to www.iadc.org/drilling_contractor.htm.)

TEST RESULTS

ASTM Type I + 2% CaCl2 system observations (Figure 1 & 2):

- *Tensile strength gain was rapid between 4 and 6 hours. Afterwards, the tensile strength remained essentially flat;*
- *This system produced the lowest tensile strengths of the systems tested;*
- *Ratio of tensile strength to compressive strength averaged 0.13;*
- *Ratio of tensile strength to ultrasonic compressive strength averaged 0.16;*
- *Young's Modulus increased from 173,000 psi at 4 hours to 607,000 psi at 12 hours; and*
- *Poisson's ratio increased from 0.25 at 4 hours to 0.28 at 12 hours.*

API Class A + 2% CaCl2 system observations (Figures 3 & 4):

- *Tensile strength gain was rapid between 4 and 6 hours. From 6 to 12 hours the tensile strength remained essentially flat;*
- *This system produced comparable compressive strengths to the ASTM Type I system and higher tensile strengths than the ASTM Type 1 system;*
- *Ratio of tensile strength to compressive strength averaged 0.14;*
- *Ratio of tensile strength to ultrasonic compressive strength averaged 0.18;*
- *Young's Modulus increased from 251,000 psi at 4 hours to 401,000 psi at 12 hours; and*
- *Poisson's ratio decreased from 0.33 at 4 hours to 0.26 at 12 hours.*

API Class G + 2% CaCl2 system observations (Figures 5 & 6):

- *Tensile strength gain was linear through the first 6 hours, plateaued through 8 hours, then increased again through 12 hours. The tensile strength development was more proportional to ultrasonic compressive strength gain than the ASTM Type I and API Class A systems. However, comparing the 10 and 12 hour values of ultrasonic compressive strength and tensile strength shows the ultrasonic compressive strength increasing 18% in 2 hours vs a 9.7% increase in tensile strength over the same period;*

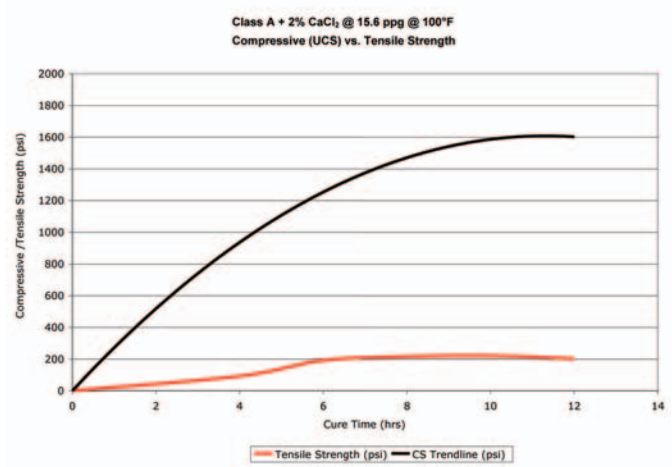

Figure 3

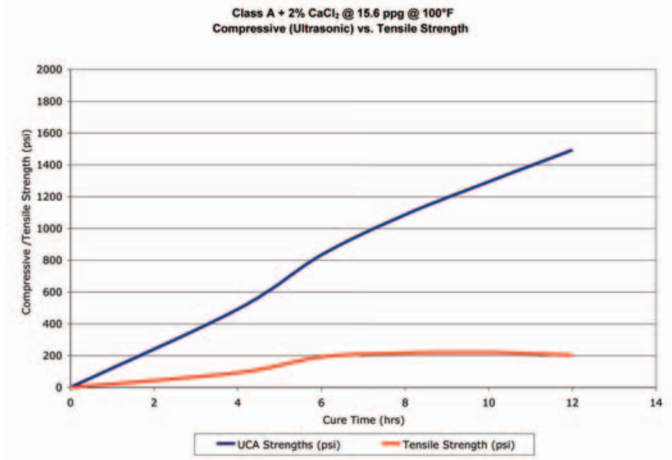

Figure 4

- *This system had higher compressive and tensile strengths than the ASTM Type 1 and API Class A system but lower than the API Class H system;*
- *Ratio of tensile strength to compressive strength averaged 0.17;*
- *Ratio of tensile strength to ultrasonic compressive strength averaged 0.20;*
- *Young's Modulus increased from 235,000 psi at 4 hours to 441,000 psi at 12 hours; and*
- *Poisson's ratio remained essentially unchanged vs time with a 0.27 value at 4 hours and a 0.26 at 12 hours.*

API Class H + 2% CaCl2 system observations (figures online):

- *Tensile strength gain was linear through the first 6 hours, decreased somewhat through 8 hours, then increased through 12 hours. As with the API Class G system, the tensile strength development was more proportional to ultrasonic compressive strength gain than the ASTM Type I and API Class A systems. However, comparing the 10 and 12 hour values of ultrasonic compressive strength and tensile strength does show the ultrasonic compressive strength increasing 19% in the 2 hours vs a 5.3% increase in tensile strength over the same period;*
- *This system produced the highest compressive and tensile strengths of any of the systems tested;*
- *Ratio of tensile strength to compressive strength averaged approximately 0.13;*
- *Ratio of tensile strength to ultrasonic compressive strength averaged 0.17;*
- *Young's Modulus increased from 240,000 psi at 4 hours to 510,000 psi at 12 hours; and*

• *Poisson's ratio remained essentially unchanged vs time with a 0.28 value at 4 hours and a 0.29 value at 12 hours.*

The most significant finding, illustrated in Figures 1-6, is the lack of correlation between the rate of compressive strength development and the rate of tensile strength development during the early set history of the samples. From a strength development standpoint, these 2 parameters are proceeding at different rates.

WELLBORE STRESS MODELING

Once the mechanical parameters of the cement designs were established, the results were used to predict the coupled behavior of casing/cement/formation as a response to a pressure change. Under the test conditions, the radial stress is compressive in nature while tangential stress produces a tensile load.

The applied pressure used for modeling purposes was 80% of internal yield for a K-55 grade of casing. Casing weights typical of those used in 13 ⅜-in. and 10 ¾-in. surface casing applications were chosen. In none of the modeling scenarios did the compressional or tensional stress imposed by the pressurization event exceed the compressive or tensile strength of the cement sample. The compressive strength of the Type I system in all tests was well above the compressional stress induced by the pressurization event. This was also the case with the Class A, Class G and Class H designs.

CONCLUSIONS

• The Young's Modulus of the tested designs increases as a function of curing time.

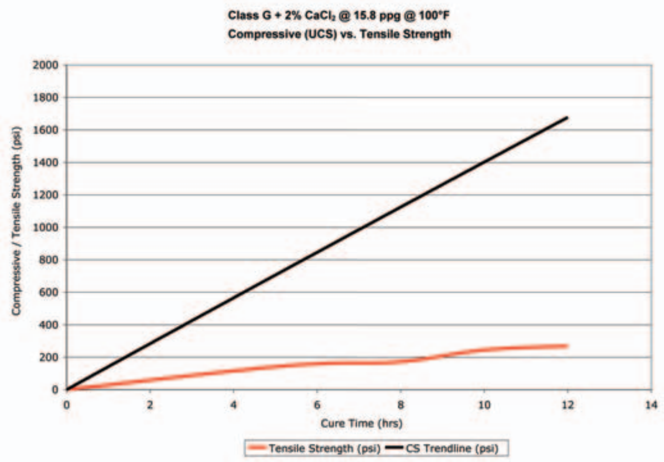

Figure 5

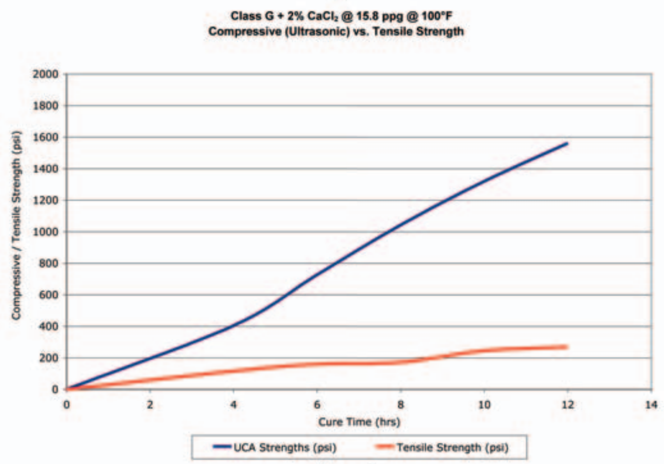

Figure 6

• The Poisson's Ratio of the tested designs, once established, varied little over time.

• During the early set period, compressive strength development and tensile strength development proceed at different rates. Test results indicate these 2 strength parameters are not coupled and develop independently.

• The ASTM Type I and Class A designs reached a plateau in tensile strength after 6 hours curing time. The Class G and H systems exhibited a different mode of tensile strength development; gaining tensile strength through 6 hours, followed by a latent period, followed by a 2nd phase of strength development.

• Under simulated pressure events, all the tested designs have on average twice the required unconfined compressive strength to withstand the anticipated compressional stress.

• Under simulated pressure events the Class A, Class G and Class H designs have, on average, twice the required tensile strength required to withstand the anticipated tensional stress after 12 hours of curing. In 1 test case however, the tensile strength of the Type I design is only 10% higher than the predicted tensional stress.

• The modeling of wellbore pressure events demonstrates the importance of cement tensile strength, not compressive strength, as the key parameter in the maintenance of zonal isolation.

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