AADE-17-NTCE-089

Evaluation of Testing Environments and Additives on Cement Tensile Strength using HPHT Tensiometer

Li Li, Cresencio Perez, and Rolando Lew, Baker Hughes

Abstract

The current mechanical properties of cement are usually measured under ambient temperature and pressure, which does not represent the actual downhole conditions. In order to test the mechanical properties *in situ*, an HPHT tensiometer has been developed in-house to conduct tensile strength testing at downhole temperatures and pressures. The *in-situ* tensile strength results are compared with results tested at ambient conditions. Temperature and pressure effect on the *in-situ* tensile strength were investigated. Different types of mechanical enhancers, including polymeric and fiber additives, were also investigated. No direct correlations in the tensile strength results are found between the *in-situ* and ambient testing. The difference between the tensile strength tested *in situ* and at ambient conditions varies depending on the types of mechanical enhancers. This result demonstrates that testing environment significantly affects the measured mechanical properties of cement, and conventional measurement does not accurately reflect the downhole conditions. The *in-situ* testing results provide a more accurate understanding of the mechanical properties of set cement and offer better judgments of cement designs with challenging downhole environments.

Introduction

Zonal isolation and long-term cement integrity is the foremost function of primary cementing. Understanding the mechanical performance of cement sheath at downhole environment is crucial for successful cementing operations. It is believed that the majority of cement mechanical failures are due to tension rather than compression, which has led to increased focus on cement tensile strength.

There are two laboratory testing standards which are widely accepted in the oil and gas industry to measure tensile strength for set cement: the indirect splitting method, and the direct uniaxial or dog bone test. Laboratory data have shown that the splitting tensile strength (STS) is approximately twice the value of uniaxial tensile strength (UTS). Heinold et al. [1] has established the correlation between the two tensile strength values where UTS is a function of STS and cylinder volume. Although the cement sample is cured under temperature and pressure to simulate the downhole conditions, it must be cooled down, de-pressurized and removed from the molds before proceeding to the testing at ambient conditions. These extra steps may cause induced stress and micro-fracture patterns on the cement surface, which has been observed and reported in previous publications [2]. The unconfined test environment does not represent the actual (confined) downhole conditions of temperature and pressure.

New testing equipment has been developed over the years to achieve *in situ* mechanical analysis for cement. A mechanical properties analyzer (MPRO) has been developed from the conventional ultrasonic cement analyzer (UCA) to continuously measure the mechanical properties of cement from liquid to solid state under pressure and temperature [3]. The compressive strength is derived from compressive wave velocity and direct measurements. Other properties such as the dynamic Young's modulus, bulk modulus and Poisson's ratio are calculated from compressive and shear wave velocities. The dynamic values are always higher than the static values with direct measurements. Therefore, it is important to measure the mechanical properties of cement *in situ*, where the cement samples are cured and tested at simulated downhole conditions.

HTHP Tensiometer

The HPHT tensiometer (**Figure 1**) has been developed to test the direct tensile strength of set cement *in situ* at downhole conditions [4]. The HTHP tensiometer is an automated testing device that cures cement and measures its tensile strength at simulated downhole conditions. The device consists of a pressure vessel, a precision hydraulic pump, an electronic load cell, two linear displacement variable transducers (LVDT), and control panel. Cement samples are cured inside the pressure vessel under temperature and pressure for the desired period. The temperature limit is 500 °F and the pressure limit is 4000 psi. Inside the pressure vessel, the sample holder (**Figure 2**) fits a maximum of three molds with a dog bone shape. The mold (**Figure 3**) is specially designed to serve as the testing cell, which combines with the precision hydraulic pump and electronic load cell, and can apply tensile stress directly to set cement until mechanical failure. Several parameters are recorded during the testing including time, temperature, pressure, applied force, sample deflection, *etc*.

This design avoids the possibility of micro-crack formation during cooling, depressurizing, and removal for further testing. The design also provides the possibilities of curing and testing cement at the same or different conditions, testing cement with same or different slurry designs, and testing at different time intervals.

In this work, a HTHP tensiometer is used to test the direct tensile strength of set cement *in situ* at simulated downhole conditions. Variations in temperature and pressure are investigated to understand their effect on cement tensile strength. The effect of additives on cement mechanical properties is also compared with the traditional uniaxial method at ambient conditions to understand how the testing environment affects downhole cement.

Effect of Temperature and Pressure

The effect of temperature and pressure on cement mechanical properties remains unclear over the years due to the fact that all current available testing devices are unable to perform direct *in-situ* measurement. Although the confined compressive strength can be obtained from triaxial testing, the cement sample has been exposed to atmospheric conditions before testing. Previous studies have shown that the confined compressive strength is usually higher than the unconfined value. The data from our study [5] also prove that the compressive strengths from triaxial tests with 1,000 psi confining pressure are approximately 20% to 40% higher than the unconfined values for various slurry designs.

With the HTHP tensiometer we can investigate the effect of both the temperature and pressure on cement mechanical properties in tension. The slurry is neat class H cement mixed with a liquid defoamer and fresh water at 16.4 ppg. The cement samples are cured for 48 hours before testing. The testing temperatures and pressures are the same as the curing conditions for all tests. The test pressures are varied from 50 to 3000 psi and the test temperatures are kept at 90 and 200 °F. The results (**Figure 4**) show that the *in-situ* tensile strength of set cement reduces at higher temperature and pressure. No significant reduction is observed when the pressure increased from 50 psi to 1,000 psi. The results show 20% and 30% reductions in tensile strength when the curing and testing pressure are 2,000 psi and 3,000 psi, respectively. At 3,000 psi, the tensile strength of the cement reduced from 330 psi at 90 °F to 260 psi at 200 °F. All the data show that increasing the curing and testing pressure and temperature have a negative effect on cement tensile strength.

Effect of Cement Additives

Typically, the compressive strength of set cement reduces when additives are used, regardless of the type and the number. The reduction is attributed to the replacement of the Portland cement with the additives and to the interruption of the interlocking mechanism from the strength-giving, needle-shaped C-S-H phases in the set cement matrix. The effect of cement additives on cement tensile strength is more complicated and depends on the functions of each individual additive as well as the additive-additive interactions in actual slurry designs. [6]

Individual Additive

To investigate the effect of an individual additive on cement tensile strength, several additives are added to the base slurry and tested to verify the difference between the *in-situ* and uniaxial tensile strength. The results are plotted in **Figure 5**. All cement samples were cured at 200 °F and 3,000 psi for 72 hrs in the curing chamber and the HTHP tensiometer. The base slurry is mixed at 16.2 ppg containing class H cement, an anti-settling agent, a liquid defoamer, and fresh water. The loading of individual additive is 35 and 50% bwoc for MF, 0.5 and 1% bwoc for PVA, 1 and 1.5% bwoc for HEC.

Additive MF is a naturally occurring mineral fiber which has been approved to improve the cement elasticity. Both the UTS and *in-situ* TS results show that MF improves the tensile strength of the base cement significantly. The UTS of cement with 35 % and 50 % MF are 79 % and 56 % higher than the value of the base slurry, respectively. On the contrary, the *in-situ* TS results show an increase of 59 % and 83 % in value for the slurry with 35 % and 50 % MF, respectively.

Additive PVA is a synthetic polymer which can enhance gas migration control and bond strength of cement. PVA improves the tensile strength of the cement in both the UTS and *in-situ* TS results. No significant improvement in tensile strength was observed for the additional 0.5 % PVA above the slurry with 1 % PVA. The *in-situ* TS testing shows a significant higher tensile strength value compared to the UTS result.

Additive HEC is a water-soluble polymer which is typically used in cementing to control fluid loss. Both the UTS and *in-situ* TS results show that adding HEC into the slurry leads to approximately 50 % to 60 % increase in tensile strength. The cement with 1 % HEC provides similar or lower tensile strength than with 0.5 % HEC. Additional HEC shows no further improvement or slightly negative effect in tensile strength of the cement.

These findings indicate each additive has an optimum loading, below or above, which may have detrimental effect on the tensile strength. The UTS for certain additives are significantly different from their *in-situ* measurement.

Additive-Additive Interactions

Although studies have shown how an individual additive improves the cement mechanical properties, field cement slurry designs are usually complex and include multiple additives. These additives are mixed in neat cement slurry to achieve desired properties including retardation, fluid loss control, bonding properties, mechanical properties, *etc*. Researchers have observed that certain combinations of additives result in unexpected changes in cement slurry properties, which is known as synergistic and antagonistic effect. [7-8]

To study the effect of additive-additive interactions on cement tensile strength, mixtures of MF, PVA and HEC are added to the base slurry and tested to verify the difference between the *in-situ* and uniaxial tensile strength. The cement samples were cured and tested at the same conditions with the previous testing for individual additives. Slurry 1 - 3 contains only two additives, 35% MF and 1% PVA, 35% MF and 0.5% HEC, 1% PVA and 0.5% HEC, respectively. Slurry 4 contains all three additives, 35% MF, 1% PVA, and 0.5% HEC. The results are plotted in **Figure 6**. The *in-situ* TS are higher than UTS for all slurries especially in slurry 1, 3 and 4 which contains PVA. The result further confirms the dramatic difference between *in-situ* TS and UTS is due to additive PVA. The combination of 1% PVA and 0.5% HEC (slurry 3 and 4) showed reduced performance in tensile strength compared to their individual addition, indicating an antagonistic effect between the two additives.

In actual downhole applications, cement slurry designs may contain a variety of additives to meet all the requirements to achieve zonal isolation. Therefore, the additive-additive interactions can be extremely complicated. **Figure 7** presents the difference between the *in-situ* and uniaxial tensile strength for three field slurry designs. The slurry density is 16.7 ppg and the cement samples are cured at 296°F for 96 hrs at 3,000 psi. The results show that the *in-situ* TS are lower than UTS for slurry 5-7, which is inconsistent with the previous results. This indicates that the cement tensile strength cannot be predicted from the individual additive contribution. The additive-additive interactions occurred during cement setting also play an important role in determining cement mechanical properties. More work is needed to understand the complexity of additive-additive interactions and how it affects the cement at downhole conditions.

In-situ TS vs. UTS

For the UTS testing method, the cement samples are cured under temperature and pressure, cooled down, de-pressurized, removed from the molds and tested under ambient conditions. These extra steps may cause induced stress and micro-fracture patterns on the cement surface, and the unconfined test environment does not represent the actual (confined) downhole conditions of pressure and temperature. On the contrary, the *in-situ* TS testing method cures and pulls apart the sample inside the mold at confined temperature and pressure, eliminating the potential damage of the specimens during removal and transfer. **Figure 8** presents the comparison of both testing using the same slurry design and curing conditions. Majority of the results show that the *in-situ* TS are generally 10 % to 30 % higher than the UTS.

Cement Elasticity

Stress-strain curves represent mechanical properties of various materials. The elasticity of a material is determined by both the Young's modulus and the yield strength, which are the slope and the end of the initial linear portion on the stress-strain curve, respectively. The elasticity of the set cement in compression is defined by Young's modulus and yield strength. These criteria are widely accepted by cementing scientists and engineers.

The Young's modulus and confined compressive strength of set cement were obtained from the stress-strain curve in compression by triaxial testing. Triaxial or confined tests are performed on a GCTS™ hydraulic test frame. Cement cylinder samples are sleeved in thin polyolefin heat-shrink tubing (0.017-inch thick) and mount between two steel platens. The spherical seat of the upper platen contacts an internal pressure-compensated load cell (100,000 pound load capacity). Two LVDT's are positioned parallel to the length of the cement sample (and internal to the pressure vessel) and used to measure the change in sample length. A circumferential displacement gauge is wrapped around the sleeve and used to measure the change in circumference of the sample. All tests are conducted at room temperature with 1,000 psi confining pressure. The results are plotted in **Figure 9**. The confined compressive strength shows a similar trend in value as the Young's modulus. Implementing any additive to the base slurry will lower the confined compressive strength and Young's modulus of the corresponding set cement. 50% MF resulted in the highest reduction (~35%) in Young's modulus.

However, it is believed that most mechanical failures of the cement sheath are in tension rather than in compression. The tensile to compressive strength ratio (TS/CS) is another parameter to predict the elasticity of cement samples due to the limitation of mechanical testing in tension. The higher ratio means the cement can withstand more tangential stress. The TS/CS ratios for all slurry designs are plotted in **Figure 10** using uniaxial tensile vs. unconfined compressive strength (UTS/UCS) as well as the *in-situ* tensile vs. confined compressive strength (*in-situ* TS/CCS). The results show a similar trend regardless of the data collected from unconfined or confined results except for additive PVA. The base cement is brittle and has the lowest TS/CS ratio, ~5%. The slurries with MF have relatively higher TS/CS ratio which can be contributed to the lower compressive strength and higher tensile strength. The only exceptions are the slurries with additive PVA. The *in-situ* TS/CCS is much higher than the UTS/UCS ratio for slurries with PVA which can be predicted from the *in-situ* TS results. The difference in the trend of the

TS/CS ratio based on the measurement also indicates the effect of testing environment on cement mechanical properties.

Conclusions

The HPHT tensiometer has been developed to cure and measure the *in-situ* TS of set cement at simulated downhole conditions. Cement samples are never exposed to non-downhole conditions during the setting or testing. Important features of the HPHT tensiometer include:

- Curing mold is served as the testing cell to pull apart the sample through load cell;
- Slurries in all three molds can be the same or different designs;
- Cement samples can be cured and tested at the same or different temperature and pressure;
- Set cement can be tested at different time intervals.

The following conclusions can be drawn from the results:

1. Temperatures and pressures have a negative effect on cement tensile strength.

2. Testing environment may have different effects on cement tensile strength for some additives.

3. The mechanical properties of cement slurries with simple mixtures of few additives may be predicted from their individual contributions and additive-additive interactions.

4. The mechanical properties of cement slurries in actual field applications are always difficult to predict due to the complexity of the additive-additive interactions in their slurries designs.

5. The elasticity of cement should be determined in both compression and tension. The Young's modulus determines the cement elasticity in compression. The TS/CS ratio can serve as a guide to predict elasticity in tension.

In-situ measurements provide a more accurate simulation of downhole pressure and temperature, better understandings of the effect of additive-additive interactions on cement mechanical properties, and improve engineering judgments about cement designs for various downhole environments.

Acknowledgments

The authors would like to thank Baker Hughes for permission to publish the data.

Nomenclature

API = American Petroleum Institute
bwoc = by weight of cement
CCS = confined compressive strength
CS = compressive strength
HEC = hydroxyethyl cellulose
HF = high-performance fiber
HPHT = high pressure and high temperature
in. = inches
MF = mineral fiber
PVA = polyvinyl alcohol
RP = recommended practices
STS = splitting tensile strength
TS = tensile strength
UCA = ultrasonic cement analyzer
UCS = unconfined compressive strength
UTS = uniaxial tensile strength
YM = Young's modulus

References

1. Heinold, T., Dillenbeck, R.L., Bray, W.S., and Rogers, M.J. 2003. Analysis of Tensile Strength Test Methodologies for Evaluating Oil and Gas Well Cement Systems. Presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, 5-8 October. SPE-84565-MS.
2. Dillenbeck, R.L., Go Boncan, V.C., and Rogers, M.J. 2005. Testing Cement Static Tensile Behavior Under Downhole Conditions. Presented at the SPE Eastern Regional Meeting, Morgantown, West Virginia, 14-16 September. SPE-97967-MS.
3. Reddy, B.R., Santra, A. K., McMechan, D. E., Gray, D. W., Brenneis, C., and Dunn, R. 2007. Cement Mechanical Property Measurements under Wellbore Conditions. SPE Drilling & Completion 22(1): 33-38. SPE-95921-PA.
4. Go Boncan, V.C. Dillenbeck, R.L., Heinold, T., and Rogers, M.J. 2007. Testing Apparatus and Method of Deriving Young's Modulus from Tensile Stress/Strain Relationships. US Patent No. 7,191,663.
5. Li, L., Go Boncan, V.C., Brandl, A., Jordan, A. 2015. Fundamental Investigation of Mechanical Properties of Additives and Class H Cement under Downhole Conditions. Asia Pacific Oil and Gas Conference and Exhibition: Bali, Indonesia, Oct. 20-22. SPE-176175-MS.
6. Heinold, T., Dillenbeck, R.L., and Rogers, M.J. 2002. The Effect of Key Cement Additives on the Mechanical Properties of Normal Density Oil and Gas Well Cement Systems. Presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia, 8-10 October. SPE-77867-MS.
7. Plank, J., Tiemeyer, C., Bülichen, D., & Recalde Lummer, N. 2013. A Review of Synergistic and Antagonistic Effects Between Oilwell-Cement Additives. SPE Drilling & Completion 28(4): 398-404. SPE-164103-PA.
8. Tranquini, V., Soto, J. F., Reveth, V. J., Prato, L. E., & Williams, R. 2007. Proven Synergistic Approach in Well Cementing Across Thief Zones: East Venezuela. Presented at the Latin American & Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina 15-18 April. SPE-107501-MS.

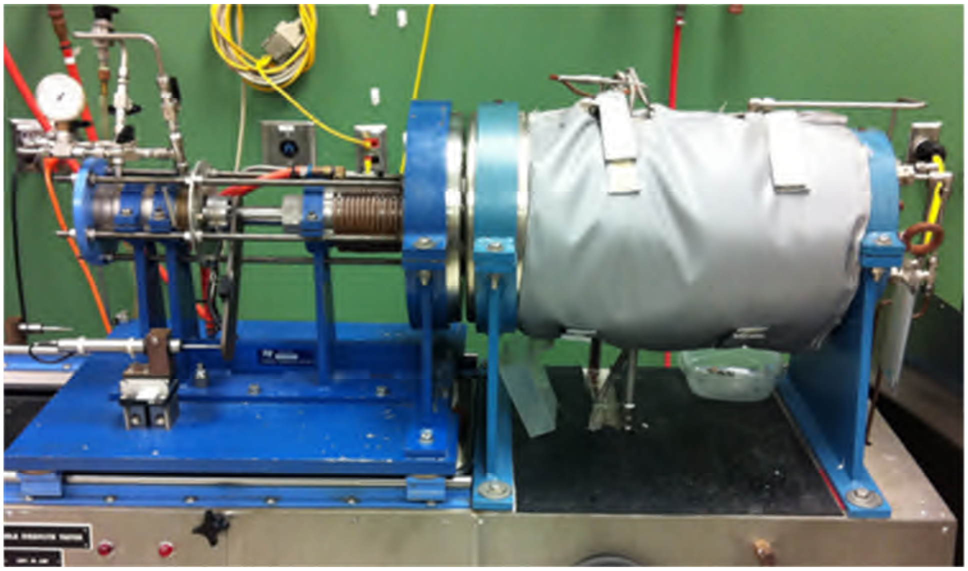

Figure 1. HTHP Tensiometer.

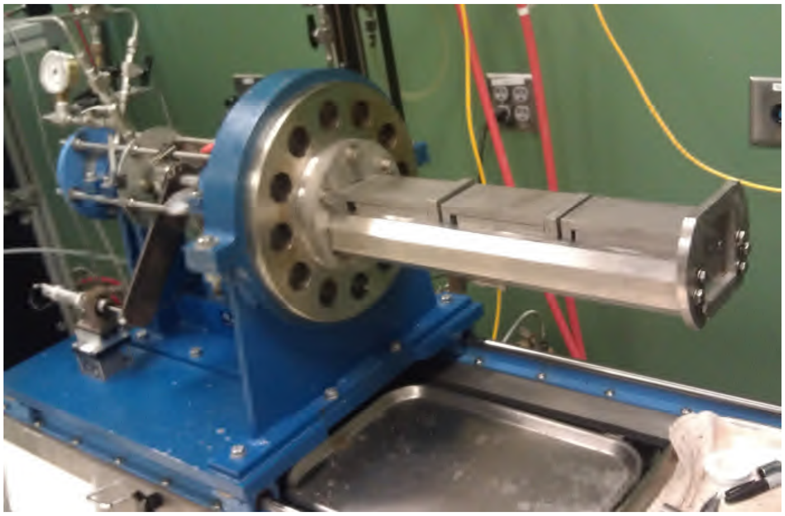

Figure 2. Sample Holder for HTHP Tensiometer.

Figure 3. Mold and Testing Cell for HTHP Tensiometer.

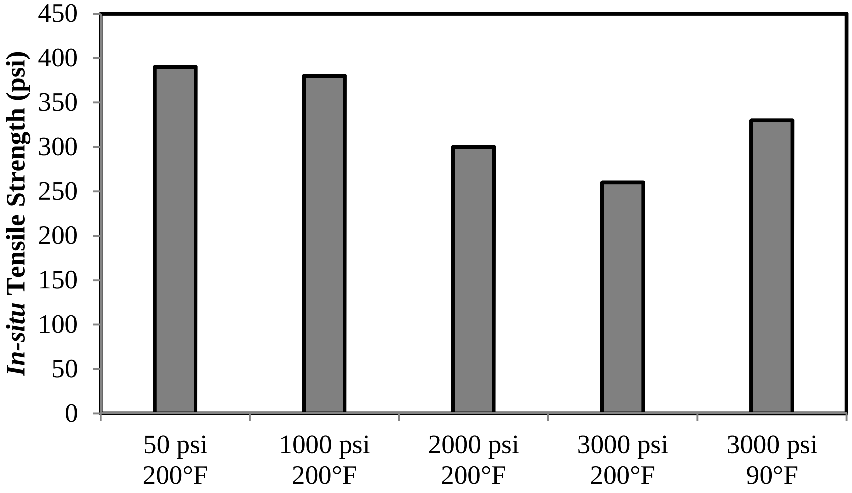

Figure 4. Temperature and Pressure Effect on *In-situ* Tensile Strength of Set Cement.

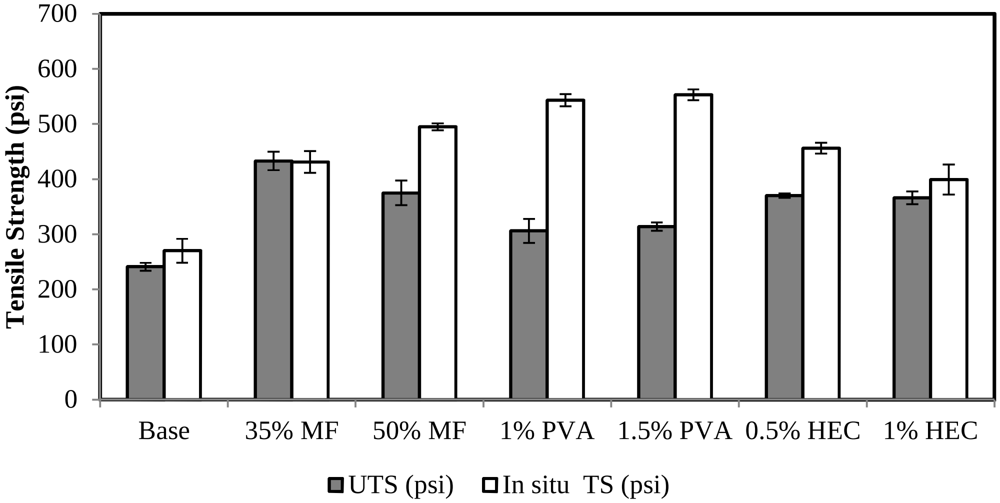

Figure 5. Comparison of Uniaxial and I*n-situ* Tensile Strength for Individual Additive.

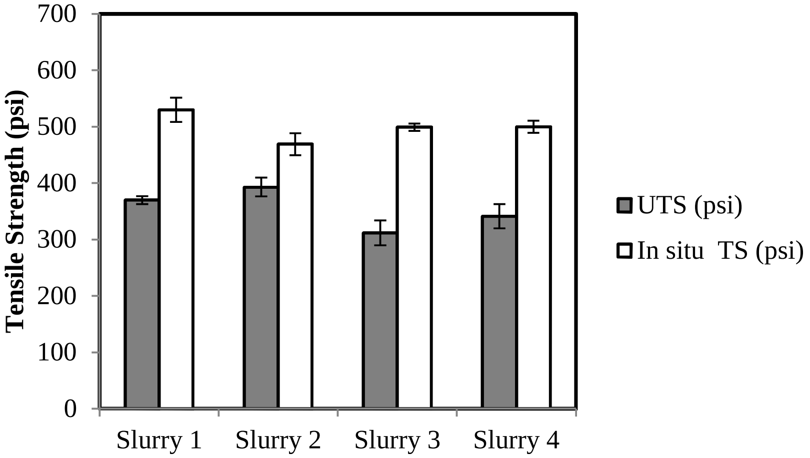

Figure 6. Comparison of Uniaxial and I*n-situ* Tensile Strength for Additive Mixtures.

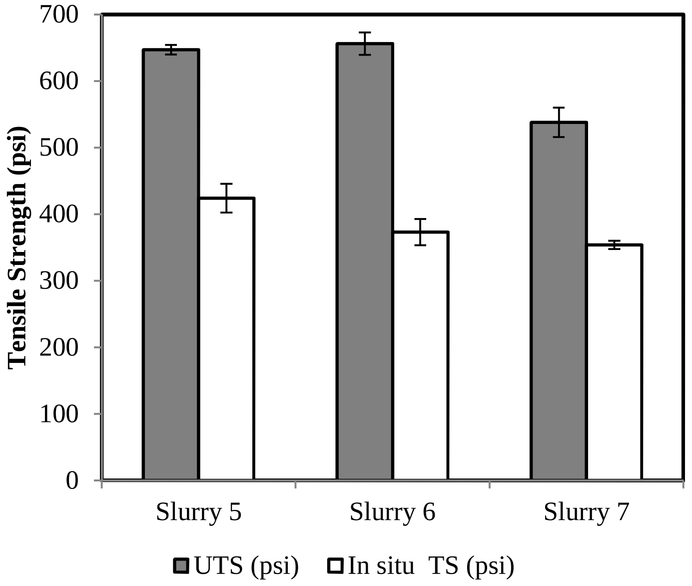

Figure 7. Comparison of Uniaxial and I*n-situ* Tensile Strength for Field Designs.

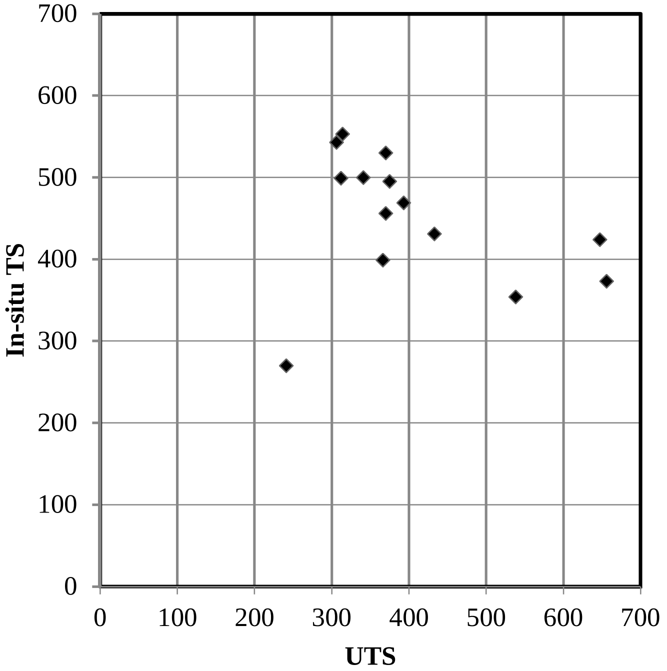

Figure 8. *In-situ* Tensile Strength verse UTS.

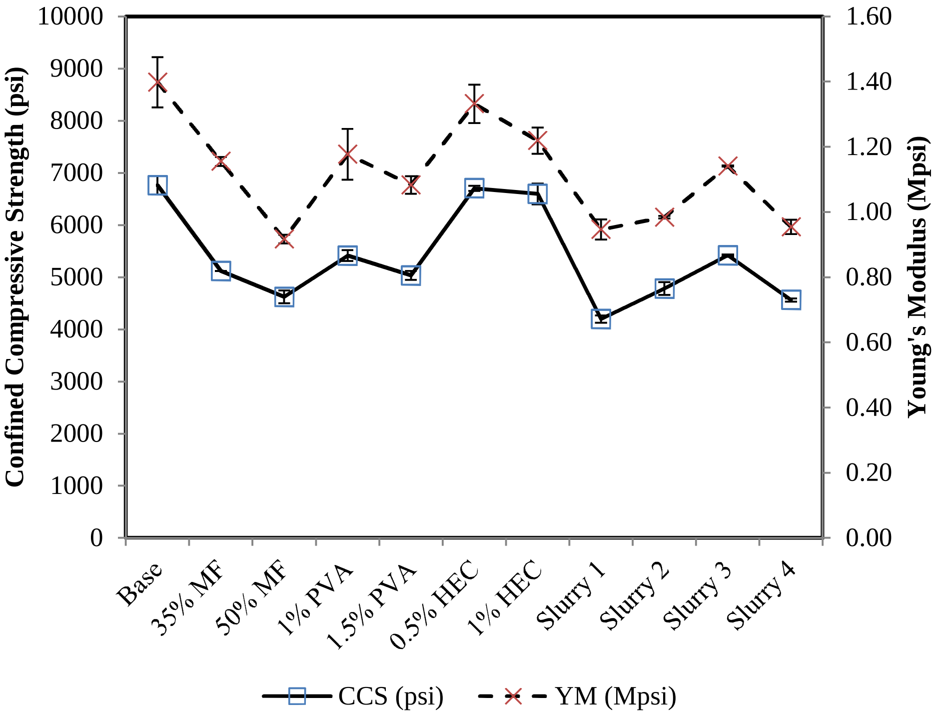

Figure 9. Results of Confined Compressive Strength and Young's Modulus with Standard Deviation.

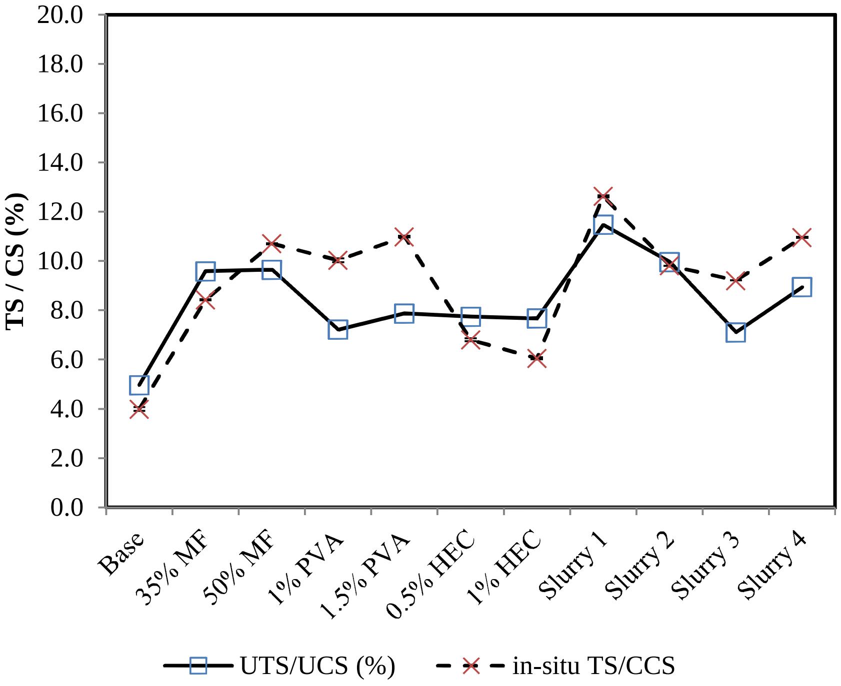

Figure 10. Ratio of *In-situ* Tensile Strength verse Confined Compressive Strength.