

# Slurry Design Considerations for Mechanically Enhanced Cement Systems

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## Abstract

Cement designs, notwithstanding ultimate compressive strength, have focused solely on properties during the liquid state. For years measurements such as thickening time, rheologies, fluid loss, etc. have helped the industry determine the competency of the slurry to help ensure a “successful” cement job. More recently, an increased effort to design cement systems past the fluid state and focus on the hardened cements properties has been observed. This has been aided in increased laboratory techniques and mathematical analysis. It is often found that two modifications can be made to a cement sheath’s mechanical response to defend against failure: 1) manipulation of the cements mechanical properties (i.e. adding elastomers to decrease Young’s modulus) or 2) increasing tolerance to failure (i.e., adding fibrous materials to increase the point of tensile failure).

The new designs being proposed today for their mechanical response are best illustrated by a double-edged sword. On one edge, the designer accounts for the mechanical properties of the cement. Additives are used to adjust the properties to the desired mechanical properties. On the other edge, the added particulate loading can have an adverse effect on the slurry design and placement. The amount of solids added can compromise the solid to liquid ratio such that the cement’s rheologies become high. The increased rheologies can lead to increased pressures such that the material cannot be placed or significantly reduced pump rates are required for placement. In addition, the specific gravity of these mechanical property modifiers can be drastically different than other material within the design. The variance in specific gravities can lead to non-homogeneous slurries if proper care is not taken. Today’s slurries should be designed such that the mechanical properties are improved while maintaining sufficient rheologies for proper placement and a stable slurry once placed within the wellbore. This paper will discuss design techniques and testing for improved slurry designs (rheological and mechanical).

## Introduction

Cement designs are growing in complexity to maintain sheath integrity when exposed to stress loads in a wellbore environment. Designing a cement for survivability by enhancing the set cement properties involves the use of

additives that have secondary effects on the cement’s slurry properties. Some slurry design considerations for mechanically enhanced cement systems are covered in this paper.

## Importance of Mechanically Enhanced Cements

The survivability of the cement sheath is crucial for environmental and economic reasons. The purpose of the cement sheath is to provide support and protect the casing while providing zonal isolation. A damaged cement sheath may do none of these tasks. Loss of zonal isolation can have both environmental and economic consequences. Mobile fluids moving from a hydrocarbon or carbon dioxide-bearing formation to either a freshwater aquifer or the surface has an environmental impact, even more when the wells are located in a heavily populated area. Loss of zonal isolation can also result in an increased economic cost for the operator in many forms including: remedial cementing work, damaged casing, non-optimized production, and in the worst case, well abandonment. For these reasons, a cement sheath with enhanced mechanical properties designed to survive in the wellbore environment is necessary. The need for enhanced cements is further propelled as well complexity continuously increases.

## Dependence on Well Functionality

The planned functionality of the well drives the cement properties needed to provide long-term zonal isolation. Depending on well operations, the cement will be exposed to two types of loads that stress the cement. Temperature changes in wellbore fluids result in thermally induced stresses while pressure changes in the formation and wellbore directly stress the cement. The chance for a particular cement to lose its integrity is a function of the amount of stress seen due to both loading conditions. As the induced stresses from well operation increase, the chances of the cement failure increase. Wells of particular interest include:

- High-pressure (HP) and/or high-temperature (HT) wells
- Deepwater wells
- Gas storage wells
- Steam injection wells
- Producing wells converted to injecting wells

- Wells located in weak unconsolidated formations

### Placement Considerations

Mechanical properties of the cement sheath become a moot point if the cement is not placed properly, resulting in contamination or channeling. Therefore the following “best practices” should always be followed when practical while placing the cement slurry.

- Condition the drilling fluid to free-up low mobility drilling fluid and excess filter cake.
- Use pipe movement, rotation or reciprocation, to break up gelled mud. Use mechanical aids when possible.
- Centralize pipe to provide adequate flow on all sides of the pipe. Centralized pipe will also help prevent stress risers on the set cement sheath.
- Pump at the highest displacement rates possible to provide the energy necessary to remove wellbore fluids. The rate is subject to the formation fracture pressure and fluid rheologies. Mechanically enhanced cements typically impact fluid rheologies negatively.
- Pump spacers and/or flushes that have sufficient volumes to prevent the cement and drilling fluids from mixing while aiding in the removal of filter cake.
- Follow fluid density hierarchy to prevent fluid intermixing.

The cement displacement best practices become of critical concern when a mechanically enhanced slurry is being pumped. Experience has shown that mechanically enhanced cement slurries with high solid content can have much higher rheological properties, making them harder to mix and lowering the maximum pump rate during displacement.

It is also known that pipe centralization is critical to provide an adequate cement sheath thickness to minimize the stress levels the cement sheath experiences at its most narrow point.

### Characteristics of Mechanically Enhanced Cement

Important cement parameters include 1) the cement sheath’s capability to deform with stress causing no permanent damage (elasticity), 2) its resistance to shrinking and consequent loss of pre-compression (leading to debonding or tensile failure), and 3) its tolerance to failure.

The elasticity of cement is defined as the slope of the stress-strain curve as shown in Fig. 1. Stress is a force applied over an area. Strain is a change in dimension relative to its original shape. Therefore elasticity is a measure of how much force (stress) a cement sheath will experience at a given deformation (strain). In most wellbore geometries and loading conditions a lower modulus results in lower stresses.

Most set cement sheaths will experience a change in stress naturally resulting from volume changes the cement undergoes during the hydration process. It is well known that the volume

of the product of the cement hydration reaction is not always equal to the volume of the reactants themselves. Ideally, the change in volume would occur entirely while the cement is in a liquid form, allowing the cement sheath to maintain a constant geometry. Unfortunately, the hydration reaction continues during and after the cement changes from a liquid to a solid. Any changes in volume that occur after the cement has formed into a rigid structure result in a change in geometry and thus a change in the stress state the cement sheath experiences. Although this phenomenon is not fully understood and can be hard to measure, this stress change cannot be ignored. “Shrinking” cement can result in micro-annuli or cracking.

The simplest ways to quantify a cement’s capability to resist failure are determined from uniaxial tests in compression and tension. These tests are performed by deforming the cement, and thus stressing the cement, until failure is observed. The ultimate stresses reported before failure represents the cement’s capability to resist failure. An example of the compressive strength test is observed in Fig. 1 with reported strength values corresponding to the peak of the stress-strain curve.

Attempts to increase the cements survivability come at a cost. While mechanical enhancing admixtures can be added to a variety of cement systems, care should be taken that the slurry properties are not adversely affected. Most admixtures have secondary effects that should be taken into consideration for proper slurry design so that when the cement sets solid, the admixtures can provide the desired enhancement.

### Common Methods to Mechanically Enhance Cement Systems

Cement systems that provide favorable properties can be classified into the following:

- Cement with admixtures that lower the modulus
- Cement that includes a gas phase
- Cement with admixtures and gas phase
- Cements that exhibit great resistance to failure
- Other

### Slurry Requirements

Cement placement should be of utmost concern to assure a competent cement job. The cement should be designed with an adequate pumping time such that it can be placed downhole even in the event of a downtime due to pumping problems. The fluid loss of the cement should be controlled to prevent early dehydration of the slurry causing an artificial premature hardening. The rheology of the cement should be high enough to suspend any particulates that have a tendency to settle or float when the slurry is motionless. The rheology and cement placement flow should be managed such that friction pressure development during placement does not cause the slurry to exceed the breakdown pressures of the surrounding formations causing loss of fluid returns to the surface and causing the cement not to reach the critical area of placement. Finally, every best practice needs to be followed to help ensure that the

cement is placed across critical zones with no channeling or excess contamination.

### **Additives to Modify Mechanical Properties**

There are several ways to modify a cement's mechanical properties.<sup>1</sup> For example, reducing the amount of water in a cement slurry will increase the set cement strength; however, reducing the water alone changes (undesirably) the density of the cement slurry. Therefore, several additives are used to alter the cements set properties while keeping density constant. Such additives include: elastomers, fibers, foam bubbles, and expansion aids. Most of the additives used today do an excellent job at the primary purpose, but expose a 2<sup>nd</sup> order effect that may or may not be desirable, as described in Table 1 and in the following sections.

### **Slurry Considerations with Elastomers**

Elastomers are commonly added to cement slurries to modify the mechanical properties of the set cement; however, their addition to the slurry may impact greatly the slurry design, testing, and placement. The density of a cement slurry is typically defined and cannot be adjusted significantly ( $\pm 0.2$  lb/gal) based on the formation fracture pressure and/or the density hierarchy needed for proper displacement of the preceding mud and spacer.

Many of the elastomers have specific gravities around 1.0 and compete directly with water as a lightweight additive. Thus, the water/solids ratio is greatly impacted as the amount of water (typically reported as %bwoc) is reduced and the solids are increased. Elastomer concentration ranges may be from 5–30%. Though this may assist with water-extended slurry designs (11.5–13.5 lb/gal) by reducing the amount of water, it greatly impacts heavyweight designs where the slurry is already water limited. The reduction in water negatively impacts the capability to mix (mix rate) on the surface limiting the pump rate, which ultimately hinders displacement best practices. In addition, the pump rate can be limited by the higher rheologies of water-starved systems that cause increased frictional pressures.

Given that a slurry requires elastomers to enhance the mechanical properties, the water content may be increased by increasing the concentration of a heavyweight agent. This may even be done in systems that typically do not require heavyweight additives. For example, a 15.8-lb/gal slurry may not typically require heavyweight additives such as barite; however, the addition of barite increases the bulk specific gravity of the solids, requiring additional water to achieve the target density of 15.8 lb/gal. Addition of barite can also be used with heavyweight slurries to increase water content. Unfortunately, a miscible slurry is not the only criterion; slurry stability and rheology should be confirmed for proper placement and zonal isolation.

Slurry stability is a concern with lightweight and heavyweight slurries. Lightweight slurries are problematic because they have high concentrations of water and thus are unable to support the heavier solids (cement s.g. = 3.18). In contrast, heavyweight slurries are more viscous, which

reduces their tendency to settle. However, the addition of elastomers with specific gravity near or below water compounds the problem. No longer is the industry just concerned with settling, but now material may have a tendency to float to the top of a cement column. The specific gravity range of particles within the system may vary by a factor of 10. The stability of the slurry is most commonly controlled by adjusting (increasing) the rheology of the slurry. Once again, the rheology should be carefully monitored such that it may be precisely placed without adverse effects within the wellbore.

Rheology measurements of conventional cements are well understood and documented within the oilfield industry.<sup>2</sup> Coutte viscometers (bob and sleeve configuration) are commonly used within the industry. The instrument is capable of accurately determining the rheological properties (Newtonian, Bingham Plastic, Herschel-Bulkley, etc.) of common fluids. In addition, the instruments are rugged for the harsh conditions and environments in which they are utilized. Elastomers not only affect the rheology of the cement slurry, but also affect how the rheology is measured.

The standard configuration of most oilfield viscometers is such that the ratio of the sleeve to bob is greater than 0.9. The gap of the viscometer should be three times greater than that of the largest particle, or inaccurate measurements can occur. This is the case with most elastomers, and the standard bob and sleeve configuration should not be used because the bob may bind and inaccurate measurements are extremely common. Alternative testing options available are a larger gap within the coutte configuration, or using a viscometer for complex fluids (such as those that contain elastomers). Viscometer bobs with smaller diameters exist that allow for the gap to be sufficient for larger particles. Extreme care should be given during the calculations to account for the larger gap and associated errors. Alternative adapters for the standard viscometer instrument exist that incorporate larger gaps and volumes that also allow for homogeneous mixing of the fluid while testing.<sup>3,4</sup> These adapters were designed for rheological measurements of complex fluids, and the direct measurement of the yield point of the fluid. The yield point plays a critical role in the frictional pressure of the fluid during the dynamic state and stability during the static state. Once the miscibility, rheology, and stability criteria are met, standard oilfield testing may proceed.

In laboratory testing the elastomers are dry-blended and mixed according to standard API mixing procedures.<sup>2</sup> The slurries with elastomers are tested as normal for thickening time, static gel strength, fluid loss, free water, and compressive strength.

### **Elastomer Effects on Mechanical Properties**

Cement and water alone produce a stiff composite whose properties are a function of the temperature and pressure under which it was cured and the water to cement ratio. An easy way to decrease the stiffness, or modulus, of the cement matrix is to add an elastomeric phase. Elastomers can come in a variety of sizes and shapes that embed themselves into the

cement matrix. The result is a bulk material with a lower modulus compared to that of just the binding cement matrix.

The addition of elastomers does not simply decrease the modulus of the cement composite. A reduction in the cement's compressive strength is also experienced. Loads applied to the bulk material will be experienced by both the elastomer phase and binding cement matrix, the failure will be driven by the cement matrix. Initially as a load is applied to the bulk material both the elastomer phase and binding cement matrix will deform together. But at a critical load, the cement matrix will start fracturing while the elastomers are still willing to deform. Since the area of which the load is applied on the cement is decreased by the addition of elastomers, the ultimate compressive strength of the bulk material will decrease. However, higher compressive strengths can occur because the addition of elastomers typically results in higher cement to water ratios. In addition, a decrease in compressive strength is not of concern when the accompanying decrease in the cement's modulus results in lower stress levels applied on the cement sheath at a given loading condition.

### **Slurry Considerations with Fibers**

Fibers are commonly added to cement slurry designs to increase the tensile strength of the set cement. Like elastomers, fibers impact the design, testing, and placement of the slurry. Fibers do not negatively impact the water/solids ratio compared to elastomers. This is mainly due to the specific gravity of fibers, which is significantly greater than that of water; in addition, fibers are used at much lower concentrations (up to 3%). The primary concern with fibers is the miscibility of the resulting system. If the fibers are in high concentration (>5%), the fibers have a tendency to agglomerate and create "hair-balls" within the system. This is problematic in that it creates an inhomogeneous system and renders the fibers useless as one big mass.

Fibers help increase the rheology of the system, as well as introduce measurement problems. For rheology measurement, the same best practices used for elastomers are also used for fibers. A device with sufficient gap and volume to measure a homogeneous fluid without introducing error must be used. As with elastomers, it is necessary to measure the rheology of the entire system (fibers included) because the fibers will impact rheologies within the wellbore.

In laboratory testing fibers may be dry-blended with other solid material for rheology, settling, free water, fluid loss, and compressive strength. On the other hand, it is best to remove the fibers for thickening time and static gel strength. The paddles and detection system for HTHP consistometers and static gel-strength detectors are sensitive; thus, binding of the fibers between the paddles and container surfaces may create false/inaccurate readings. The fibers are chemically inert and will not impact thickening time or the gel strength development of the slurry (Figure 2).

### **Fiber Effects on Mechanical Properties**

The challenge for cement to provide an annular seal is not always measurable by the ultimate compressive strength

alone. In some instances a pressure increase inside a pipe or a temperature increase causing the casing to expand faster than the cement results in a high tensile stress in the cement sheath at the casing-cement interface.

The relationship between the tensile strength and compressive strength of cement can be established.<sup>5</sup> As a rule-of-thumb it is commonly assumed that the tensile strength of oil well cement is around 10% of the compressive strength. But these trends can be affected with addition of enhancing materials, such as fibers, to the cement matrix.

Fibers, even at a low concentration, can increase a cement composite's resistance to tensile failure. Cracks that form in the cement sheath due to tensile stresses are bridged by the fibers. The effectiveness of the fibers to resist tensile or compressive failures depends on the fiber size, shape, concentration, stiffness, pull-out strength, and tensile strength.<sup>6</sup> A fiber with higher modulus and tensile strength compared with the cement matrix will stop a forming crack from opening, thus reducing the chances for crack propagation. The length of the fiber should be long enough to bond with the cement, helping prevent the fiber from pulling out of the cement matrix at lower stress levels.

### **Alternative Solutions**

Elastomers and fibers are not the only two options for adjusting the mechanical properties of a set cement. For years, service companies have introduced gases as a second-phase within cement slurries. This gas phase is capable of significantly modifying the resulting set cement. Like elastomers and fibers, foam cement testing requires modifications and careful attention within the lab.

Foam stability is critical for placement and creating a homogeneous downhole slurry. The base slurry greatly influences foam stability. The base slurry typically does not contain dispersants. Slurry stability is checked by curing a sample of 2-in. diameter and 4 in. tall, at BHST and atmospheric pressure. This method may also be followed, using a static gel-strength detector for elevated pressure. The cured sample is sliced into three smaller samples marked top, middle, and bottom. The densities of the three samples are measured, and should not vary greater than 0.5 lb/gal or 5% of the desired density.

Once a miscible and stable slurry is achieved, rheologies of the base slurry and foamed slurry are taken. The base slurry is taken at three temperatures (typically 80, 135, and 180°F) and atmospheric pressure. The rheologies of the foamed slurries are measured at room temperature and pressure. Foam rheologies may be measured with an alternative adapter that minimizes phase separation and maintains homogeneous slurry. Rheologies at elevated temperature are not possible, since temperature will affect the bubble size of the gas phase foam. Foam slurries will have a higher rheology than that of the base system.

The base slurry (without gas phase) is used for testing of fluid loss, thickening time, and static gel strength. The gas phase is inert and will not chemically alter the thickening time

form the base design. For fluid loss and static gel strength, the gas phase will only enhance the properties of the base slurry. Foam slurries have shown to have much lower fluid loss than their base design. Likewise, the gas phase can minimize gas migration because the compressed gas can adjust to minimize volume changes. Volume changes during the loss of hydrostatic pressure can result in gas channeling through the cement.

If required, equipment has been adapted for testing of thickening time, static gel strength, fluid loss, and compressive strength for gas-phase slurries.

### **Foamed Effects on Mechanical Properties**

Foamed bubbles in the cement matrix add a compressible gas filled bubble that influences the cement composite mechanical response. The size and spacing of the bubbles dictate the set cements mechanical properties.<sup>7</sup> In general, a larger foam quality will result in a lower cement modulus. However, a foam quality too great can cause the gas bubbles to coalesce, resulting in a drastic decrease in compressive strength. Therefore, an optimum foam quality can be found such that the modulus results in a stress lower than the compressive strength for a given wellbore geometry and loading condition.

### **Conclusions**

As hydrocarbon production increases from harsh environments and extreme conditions, it is necessary to design cement slurries such that cement sheath integrity is maintained. The mechanical properties of the cements may be adjusted through the use of elastomers, fibers, or a gaseous phase. These additives enhance the mechanical properties of the cement. These additives result in a secondary effect on the cement properties while in the slurry state. Though some of the secondary effects are positive in nature, many are negative and should be accounted for accordingly. These secondary effects may be:

- Miscibility
- Settling
- Rheology
- Density control
- Other

A new emphasis on slurry designs and new additions to lab best practices has allowed for these slurries to be placed properly, resulting in long-term zonal isolation.

### **Acknowledgments**

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### **Nomenclature**

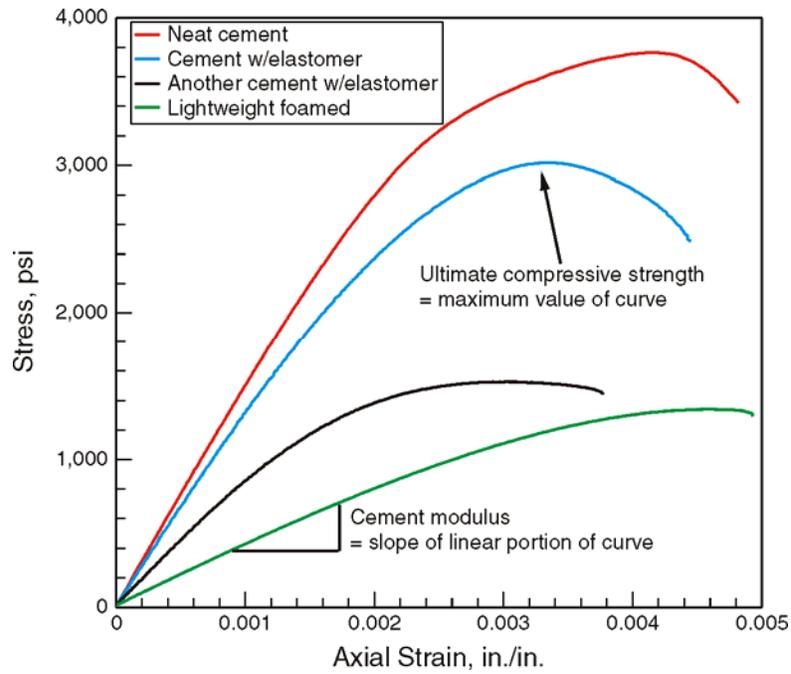
- bwoc* = by weight of cement  
*BHST* = bottom hole static temperature  
*lb/gal* = pounds per gallon  
*HPHT* = high pressure/high temperature

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**Table 1—Effects of Mechanical Enhancing Additive**

Additive Type	1 <sup>st</sup> Order Effect	2 <sup>nd</sup> Order Effect
Elastomer	<ul style="list-style-type: none"> <li>Decreased Modulus</li> </ul>	<ul style="list-style-type: none"> <li>Reduces water/solid ratio</li> <li>Increase rheology</li> </ul>
Fibers	<ul style="list-style-type: none"> <li>Increased Tensile Strength</li> </ul>	<ul style="list-style-type: none"> <li>Miscibility</li> <li>Rheology measurements</li> </ul>
Foam	<ul style="list-style-type: none"> <li>Decreases Modulus</li> </ul>	<ul style="list-style-type: none"> <li>Most locations limited to atmospheric pressure</li> <li>Increased rheology</li> </ul>



**Fig. 1—Example of stress versus strain curves for various cement systems.**

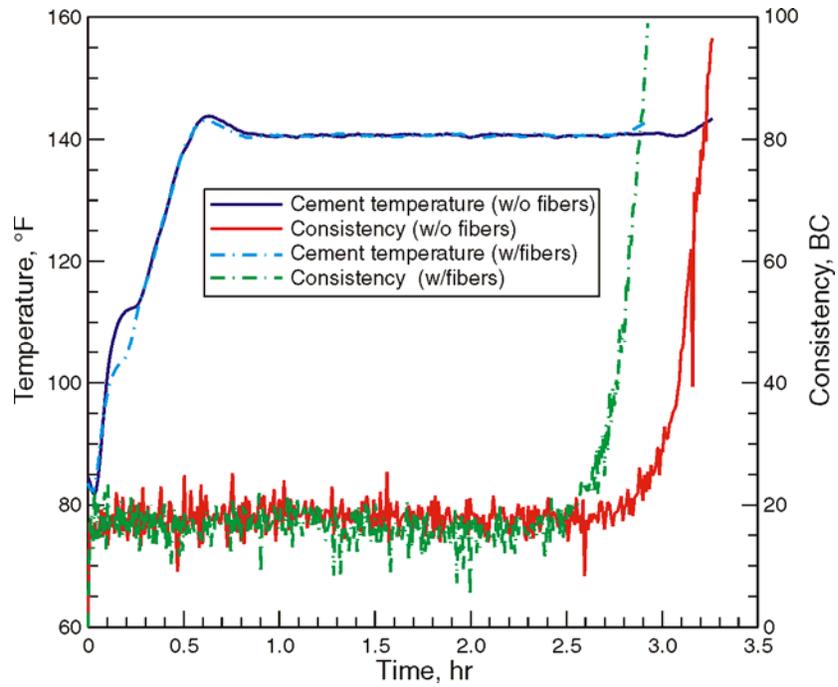


Fig. 2—Thickening time curves for slurries with and without fibers.