



Procedures to Optimize Cement Systems for Specific Well Conditions

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Abstract

Sustained casing pressure (SCP) is a challenge faced by the oil and gas industry during the life cycle of a well. From the cementing point of view, SCP could be caused by (1) inadequate drilling fluid displacement and/or (2) the failure of cement sheath to withstand well operational loads. Primary cement jobs should be designed and deployed so that the cement slurry is placed in the entire annulus and the cement sheath properties are fit for purpose to withstand downhole chemicals and the anticipated stresses from well operations.

This paper outlines the challenges during drilling fluid removal and cement slurry placement. After the cement slurry is placed in the annulus, a hydration reaction transforms the cement slurry to a solid cement sheath. The shrinkage and expansion characteristics and mechanical properties of the cement system play a crucial role in how well the cement sheath withstands subsequent well operations.

The hydration volume change and the mechanical properties of a cement sheath under downhole conditions were measured in laboratory tests. These tests show that cement slurry formulations can be optimized to meet the property requirements for specific well conditions. Properties of different cement systems are compared and their applicability to well conditions is discussed.

The work reviewed in this paper should help in the design of cement systems to suit well parameters and to withstand well operations during the life of the well. This should address nonproductive time by reducing remedial and intervention costs.

Introduction

The main purpose of a primary cementing job is to provide effective zonal isolation for the life of the well so that oil and gas can be produced safely and economically. To achieve this objective, the drilling fluid should be removed from both the wide and narrow segments of the annular cross section, and the entire annulus should be filled with a competent cement system.

In recent years, the number of wells worldwide, with annular pressure has increased significantly. In the late 1990s, in the Gulf of Mexico alone there were more than

11,498 casing strings in 8,122 wells with pressure on the annulus side.¹

From a cementing perspective, a path for fluid migration could be created (1) if drilling fluid is not effectively displaced, (2) if cement slurry is not placed in the entire annulus, and/or (3) if the cement sheath fails during well operations. Many publications have addressed the subject of drilling fluid displacement and cement slurry placement.²⁻⁶ The current discussion focuses on contributors to cement sheath failure during well operations.

The cement system should meet both the short-term and long-term requirements imposed by the operational regime of the well. Typical short- and long-term properties required from the cement system are listed in **Table 1**.

Traditionally, the industry has concentrated on the short-term properties that are applicable during the cement slurry stage. This is necessary for effective cement slurry mixing and placement. It has been common practice to assume that high compressive strengths are adequate indications of long-term performance. However, the long-term integrity of a cement system depends on its shrinkage and expansion characteristics, mechanical properties such as Young's Modulus, tensile strength, and resistance to factors present in the downhole environment, such as temperature and chemicals.

After the cement slurry is placed in the annulus, if there is no immediate migration of formation fluid to the surface, it is likely that short-term properties, such as density, rate-of-strength development, and fluid loss of the cement slurry were designed satisfactorily. Experience has shown, however, that after operations such as completions, pressure testing, hydraulic stimulation, and production, the cement sheath can lose its ability to provide zonal isolation. The loss of zonal isolation could create a path for formation fluids to enter a casing annulus, which could pressurize the well. Remedial cementing jobs can then be required (if feasible) before the well can continue normal hydrocarbon production.

Failure of the cement sheath is most often attributed to stresses induced by pressure and temperature changes resulting from operations during the well's

economic life. Examples of wells in which the cement sheath may be subjected to significant stress levels are:

- High-pressure and/or high-temperature (HP, HT, and HPHT) wells;
- Deepwater wells;
- Gas-storage wells;
- Wells penetrating weak, unconsolidated formations;
- Steam-injection wells.

In most cases, the effect of well operations on the integrity of the cement sheath is not taken into account when selecting the cement slurry. Only recently has the subject received the deserved industry attention.

In 1990, Goodwin et al.⁷ conducted an experimental study to evaluate the performance of different cement systems subjected to various pressure and temperature changes. The study demonstrated that stiff cement sheaths or cement sheaths that possess a high Young's modulus are more susceptible to damage caused by pressure and/or temperature change. This work also pointed out the importance of the Young's modulus of a sealant. In 1996, Benge et al.⁸ recognized the unique elastic or resilient behavior of foamed cement system and successfully implemented them in the Gulf of Mexico, particularly in HPHT applications.

The experimental work was then followed by mathematical studies of the effect of stresses on a cement sheath. Bosma et al.⁹ simulated the mechanical responses of a cement sheath based on finite element analysis (FEA). Thiercelin et al.¹⁰ applied analytical procedures to study the effect of cement sheath mechanical properties, assuming fully-bonded or non-bonded sheath interfaces. Bosma et al. modeled debonding, cracking, and plastic deformation for cement sheath failure modes and simulated the effect of cement sheath shrinkage and expansion. Several other contributions have appeared since those studies were published.¹¹⁻¹⁴

Some major consequences of damage to the cement sheath, such as annulus pressure or damage to the casing, could force well shutdown or result in high remedial costs. Other consequences of damage to the cement sheath, such as loss of hydrocarbon production, production of unwanted fluids (e.g. water), and wellhead movement, could negatively affect the normal operations of oil and gas assets. Therefore, the long-term integrity of the cement sheath should be considered during the early stages of well construction and designed for uninterrupted, safe, and economic production of hydrocarbons.

Cement Slurry Hydration

A cement slurry undergoes a hydration reaction in the presence of water. The main constituents of Portland cement are C_3S , C_2S , C_3A , and C_4AF . When Portland cement reacts with water, the main products that contribute to the long term mechanical properties are CSH gel and calcium hydroxide. The reaction can be

represented as:



The volume of the products formed is less than the volume occupied by the reactants. A phenomenon referred to as hydration volume shrinkage. The total volume shrinkage can also be classified as bulk (external shrinkage) and contraction of pores (internal shrinkage). Drying shrinkage, as used in the construction industry, refers to the shrinkage observed when the cement sheath is cured in the absence of water, after curing in the presence of water for a certain number of days. This does not apply directly to oilwell cementing, but the findings and results can increase overall understanding of cement slurry behavior.

If the capillary pores in the cement sheath are at water saturation, internal shrinkage may not be a concern. However, external shrinkage can still be a concern, leading to a micro-annulus if not addressed. The risk of pores not being at water saturation increases when the cement sheath is curing in an environment devoid of surrounding water. If internal shrinkage is not offset, it could lead to tensile cracks.

Different methods of measuring volume shrinkage are discussed elsewhere.¹⁵⁻¹⁶ Shrinkage during the early hydration phase contributes to external or bulk shrinkage. During this phase, if the cement system is able to compensate for the external or bulk shrinkage, a microannulus can be avoided. The dimensional changes caused by external or bulk shrinkage can be offset by a physical occurrence, such as cement system expansion. Beyond the stage when the cement sheath matrix becomes rigid, bulk shrinkage may no longer be a problem, but internal shrinkage becomes increasingly important. In oilwell cementing, the pores can be below water saturation if the environment in which the cement system is curing is devoid of water (tie back cementing and cementing across low to ultra-low permeable zones).

In the concrete industry, total volume shrinkage is commonly measured with a conical flask and pipette.¹⁵⁻¹⁶ Water uptake is assumed to represent the total shrinkage in the cement system during hydration. This method might serve for measurement at ambient conditions, but measurements at downhole temperatures and pressures require the use of an alternate device discussed later in this paper. A flask-pipette setup (**Fig. 1**) was used to measure the water uptake for different slurries.

The flask was filled with a known volume of slurry and excess water. A pipette was inserted into the flask, as shown, to measure the change in water level. Precautions were taken to minimize evaporation losses. Precautions were also taken to remove any trapped air by subjecting the slurry to vacuum for 30 minutes after stirring in an atmospheric consistometer for 30 minutes. All slurries were formulated with appropriate additives to prevent free water.

If the slurry took water at any time, it was interpreted as shrinkage, and the volume of water added was

assigned a negative sign. If the slurry expanded, the level in the pipette increased, and the volume of water was assigned a positive sign.

The result of such a measurement for Slurry 1 is shown in **Fig. 2**. Slurry 1 is a 16-lb/gal system with cement, water, and enough silicalite to prevent free water and settling. The water-to-cement ratio by weight in Slurry 1 is 0.4 ($w/c = 0.4$). The flask-pipette test indicates that Slurry 1 had an uptake of approximately 3.85% by volume of the cement slurry. This value agrees with that for a similar system tested elsewhere.¹⁵⁻¹⁶ This uptake is the amount of water that the cement system would retrieve from the surrounding environment, if available, during cement slurry hydration.

To perform tests at elevated pressures and temperatures, a UCA ultrasonic cement analyzer was used to measure the water uptake during hydration. In oilwell cementing, a UCA analyzer is commonly used to monitor the compressive strength of the cement slurry as it cures under temperature and pressure. Here, the UCA analyzer was connected to a constant supply of water, a pressure controller, and a pump. Decrease in pressure during cement slurry hydration was offset by pumping water to maintain a constant pressure. The amount of water required to maintain a constant pressure was monitored using a volumetric flow rate measuring device.

The water uptake in the UCA analyzer for Slurry 1 at 80°F is shown in **Fig. 3** along with the flask-pipette data. There is agreement between the UCA analyzer and flask-pipette data, implying the UCA analyzer method can be extended to measure water uptake during cement slurry hydration at downhole conditions.

Fig. 4 compares the water uptake for Slurry 1 with that of Slurry 2. Slurry 2 is a 13-lb/gal system with cement, water, and enough bentonite to prevent free water and settling. The water-to-cement ratio by weight in Slurry 2 is 0.55 ($w/c=0.55$). The flask-pipette test shows that Slurry 2 had an uptake of approximately 2.8% by volume of the slurry in the flask. This value is lower than the 3.8% water uptake for Slurry 1. Slurry 2 is of lower density and contains lower per unit volume of cement than Slurry 1, leading to the lower shrinkage value.

Fig. 5 compares the water uptake of Slurries 1, 2, and 3. Slurry 3 is a 16.4-lb/gal system with polymers to improve the elasticity of the cement sheath. The water to cement ratio of Slurry 3 is similar to Slurry 1. Mechanical properties for Slurry 3 are discussed later in this paper. **Fig. 5** shows that the water uptake is positive during the first 10 hours, implying Slurry 3 expands during this period. After ten hours, the water uptake is 2.1%, much less than Slurry 1 with similar density.

Slurry 3 should have zero to minimal external shrinkage from expansion during the first ten hours. The slurry takes water during subsequent hydration, presumably to maintain water saturation of the pores. However, this value is much lower than Slurry 1 and should be of help in reducing total shrinkage.

Slurry 4 is a 9.85-lb/gal system with cement, water,

surfactants, and gas (foam system). **Fig. 6** compares the water uptake of Slurries 1, 2, 3, and 4. The water uptake for Slurry 4 is positive (the system expands for the first ten hours). The water uptake at 48 hours is 1.2%. Similar to Slurry 3, Slurry 4 should also help in reducing total shrinkage.

Companion tests were also performed by placing each cement slurry in a balloon and measuring the change in volume of the balloon under water.^{15,16} The challenge in this method was finding a balloon material that (1) could withstand higher temperatures, and (2) was impermeable to water.

Fig. 7 shows change in balloon volume with time as the cement slurries hydrated. The figure shows that the change in volume of Slurry 2 is 1.3% and 1% for Slurry 1. The difference between the total shrinkage (flask-pipette test) and external shrinkage (balloon test) gives possible indication of the contraction of pores in the absence of surrounding water. In **Fig. 7** the values from flask-pipette test are plotted along with the results from the corresponding balloon tests. The difference between the total and external shrinkage for Slurry 2 is 1.5% (2.8-1.3) and, for Slurry 1 it is 2.8% (3.8-1). This possibly suggests that Slurry 1 is more prone to contraction of pores than Slurry 2.

The difference between the total and external shrinkage for Slurry 3 is 1.1%. When Slurry 3 is compared to Slurry 1 of similar density and water to cement ratio, the implication is that an elastic cement system could reduce the damage from shrinkage.

Fig. 8 shows the effect of an expansion additive in the balloon test. The expansion additive starts to undergo chemical reaction at about 8 hours and begins to compensate for shrinkage. **Fig. 6** showed that Slurry 3 with elastic polymers and Slurry 4 with foam are able to compensate for shrinkage during the early period of cement slurry hydration. Hence a combination of the foam and/or elastic polymers and expansion additives could help to minimize the effect of hydration volume shrinkage on cement sheath integrity.

Cement Sheath Mechanical Properties

Oilwell cementing typically uses compressive strength as the only measure for cement sheath characterization. However, as with any solid material, other properties, such as Young's modulus, Poisson's ratio, and plasticity parameters should help in determining the effect of stresses on the cement sheath during the life of the well.

Measurement of cement sheath mechanical properties is in its infancy, particularly with regard to oilwell cementing. The force-displacement tests summarized here were performed in a tri-axial cell. Both the axial and radial displacements were measured using strain gauges under confined and unconfined conditions. Parameters such as Young's modulus, Poisson's ratio, and plasticity parameters were calculated from this data.

The load-displacement data for Slurry 1 is shown in **Fig. 9**. The cement sheath has high compressive strength but the axial strain to a given load is very low. The area under the stress-strain curve, a measure of the

energy a material can absorb before failing, is small when compared to **Fig. 10** for Slurry 3. For oilwell cementing, the area under the elastic regime of the stress-strain curve is important because a cement sheath in the elastic regime could recover when the load is removed. If a cement sheath is loaded to its full capacity in the elastic regime, the sheath will recover for only a few cycles. On the other hand, if the cement sheath is loaded to less than its full capacity, it can withstand more cycles.¹²

The Young's modulus of Slurry 1 is 1.75×10^6 psi. This is much higher than the Young's modulus of Slurry 3. The load-displacement curve for Slurry 3 is shown in **Fig. 10**. The Young's modulus of Slurry 3 is 0.61×10^6 psi. Slurries 1 and 3 have a similar density and water-to-cement ratio. However, Slurry 3 contains polymers to improve its elasticity, which is reflected in its lower Young's modulus when compared to Slurry 1, which contains cement and water. The area under the stress-strain curve for Slurry 3 is much higher than Slurry 1, in both the elastic and the ductile regime.

Pictures of cylinders on which the load-displacement tests were conducted are shown in **Figs. 11** and **12**. **Fig. 11** is for Slurry 1 and clearly shows that the cement sheath is brittle and shattered when it failed. Brittleness is also evident from the load-displacement curve shown in **Fig. 9**. As can be seen in **Fig. 12**, Slurry 3 does not show any brittle behavior. The cement sheath exhibits ductile behavior when it is taken beyond its elastic range.

Summary

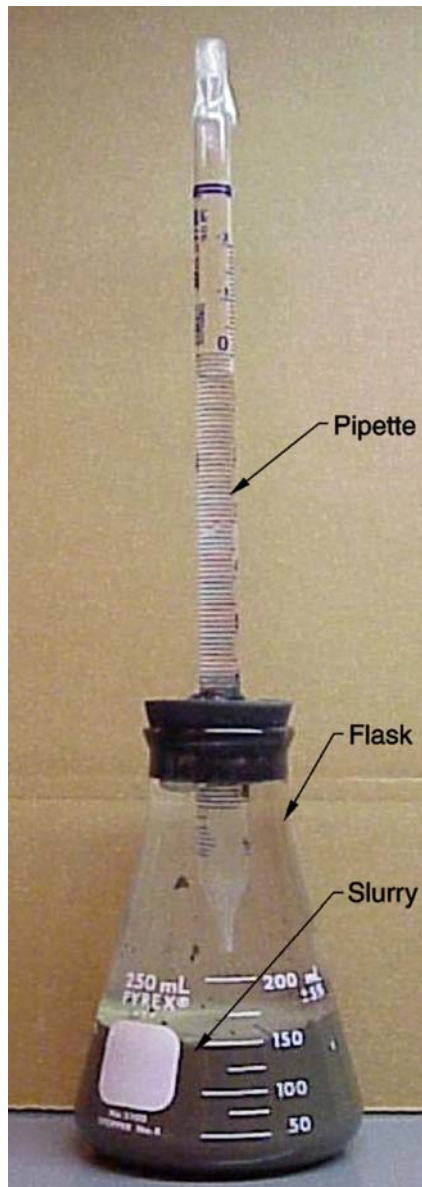
- Cement slurry formulation can be modified to optimize the hydration volume shrinkage and cement sheath mechanical properties.
- A combination of foam and/or elastic polymers and expansion additive can help reduce the effect of total shrinkage on cement sheath integrity.
- Elastic polymers modify the Young's modulus of the cement sheath. In the example shown, the Young's modulus of a 16-lb/gal system was decreased by a factor of 3.
- The cement sheath properties discussed should be considered for long-term integrity of the well, and compressive strength is not a sufficient parameter for determining the durability.
- Tests discussed in this paper quantify cement sheath hydration volume reduction.

References

1. Bourgoyne, A. Jr. et al.: "A review of sustained casing pressure occurring on the OCS," Contract No. 14-35-001-30749, U.S. Department of the Interior, Washington, D.C.
2. Al Khayyat, B. et al.: "Successes in production-liner cementing in oil-based mud: a case study," paper SPE 57560 presented at 1999 SPE/IADC Middle East Drilling Technology Conference, Abu Dhabi, UAE.
3. Biezen, E., van der Werff, N., and Ravi, K.: "Experimental and numerical study of drilling fluid from a horizontal wellbore," paper SPE 62887 presented at the 2000 Annual Technical Conference and Exhibition, Dallas, USA.
4. Ravi, K., Covington, R.L., Beirute, R.M.: "Improve primary cementing by continuous monitoring of circulatable hole", paper SPE 26574, presented at the 1993 Annual Technical Conference and Exhibition, Houston, USA.
5. Griffith, J.E., Ravi, K.: "Monitoring circulatable hole with real-time correction: case histories," paper SPE 29470, presented at the 1995 Production Operators Symposium, Oklahoma City, USA.
6. Smith, T.R., Ravi, K.: "Investigation of drilling fluid properties to maximize cement displacement efficiency," paper SPE 22775 presented at the 1991 Annual Technical Conference and Exhibition, Dallas, USA.
7. Goodwin, K.J. and Crook, R.J.: "Cement sheath stress failure," paper SPE 20453 presented at the 1990 Annual Technical Conference and Exhibition, New Orleans, USA, 23-26 September.
8. Benge, O.G. et al.: "Foamed cement job successful in deep HTHP offshore well," *Oil & Gas J.* (March 1996) 58.
9. Bosma, M. et al.: "Design approach to sealant selection for the life of the well," paper SPE 56536 presented at the 1999 Annual Technical Conference and Exhibition, Houston, USA, 3-6 October.
10. Thiercelin, M.J. et al.: "Cement design based on cement mechanical response," *SPE Drilling & Completion* (December 1998) 266-273.
11. Mueller, D. et al.: "Characterizing Casing-Cement-Formation Interaction Under Stress Conditions; Impact on Long-Term Zonal Isolation," paper SPE 90450 presented at the 2004 Annual Technical Conference and Exhibition, Houston, TX, 26-29 September.
12. Ravi, K. et al.: "A Comparative Study of Mechanical Properties of Density-Reduced Cement Compositions", paper SPE 90068 presented at the 2004 Annual Technical Conference and Exhibition, Houston, TX, 26-29 September.
13. Sassen, A. et al.: "Foam Cement Engineering and Implementation for Cement Sheath Integrity at High Temperature and High Pressure", paper SPE 87194 presented at the 2004 IADC/SPE Drilling Conference, Dallas, TX, 2-4 March.
14. Ravi, K., et al.: "Optimizing the Cement Sheath Design in HPHT Shearwater Field", paper SPE 79905 presented at the 2003 IADC/SPE Drilling Conference, Amsterdam, The Netherlands, 19-21 February.
15. Justnes, H. et al.: "Chemical shrinkage of cement pastes with plasticizing admixtures," *Nordic Concrete Research* (2000), No. 24, 39-44.
16. Justnes, H. et al.: "Chemical shrinkage of oil well cement slurries," *Advances in Cement Research* (1995) 7, No.26, 85-90.

Table 1—Short-Term and Long-Term Properties Recommended of Cement System

Short-Term: Cement Slurry	Long-Term: Cement Sheath
Environmentally friendly	Thermally and chemically stable under downhole conditions of pressure and temperature
Mixable at surface	Resist shrinkage
Stable	Optimum mechanical properties to withstand stresses from various downhole operations and provide zonal isolation for the life of the well
Optimum thickening time and density	
Optimum strength development and fluid loss	
100% placement in the annulus	
Resist fluid influx	
Resist shrinkage during hydration	

**Fig. 1—Flask-pipette setup.**

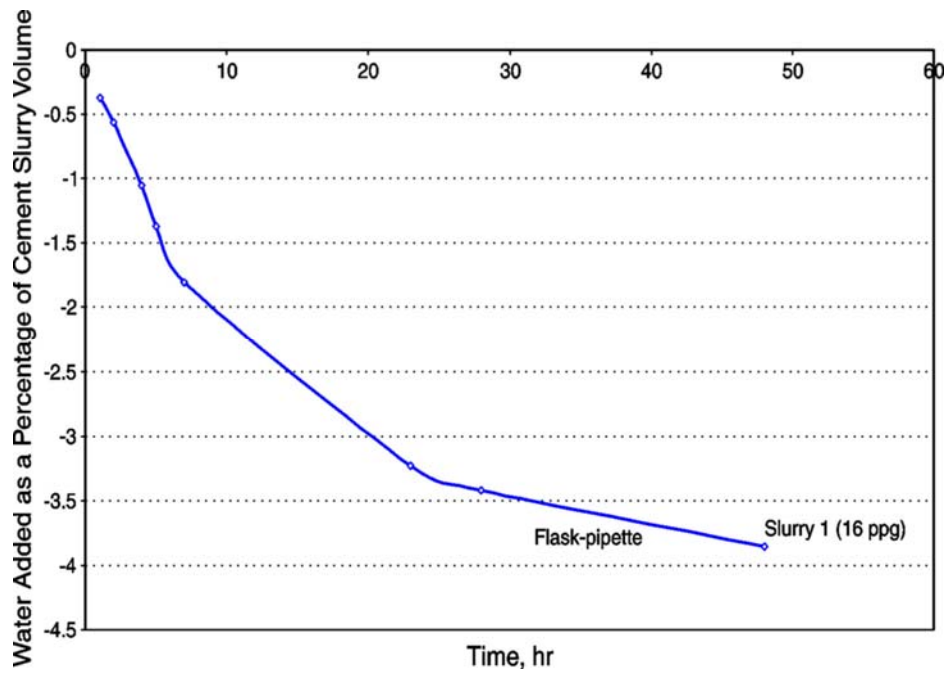


Fig. 2—Flask-pipette test for Slurry 1.

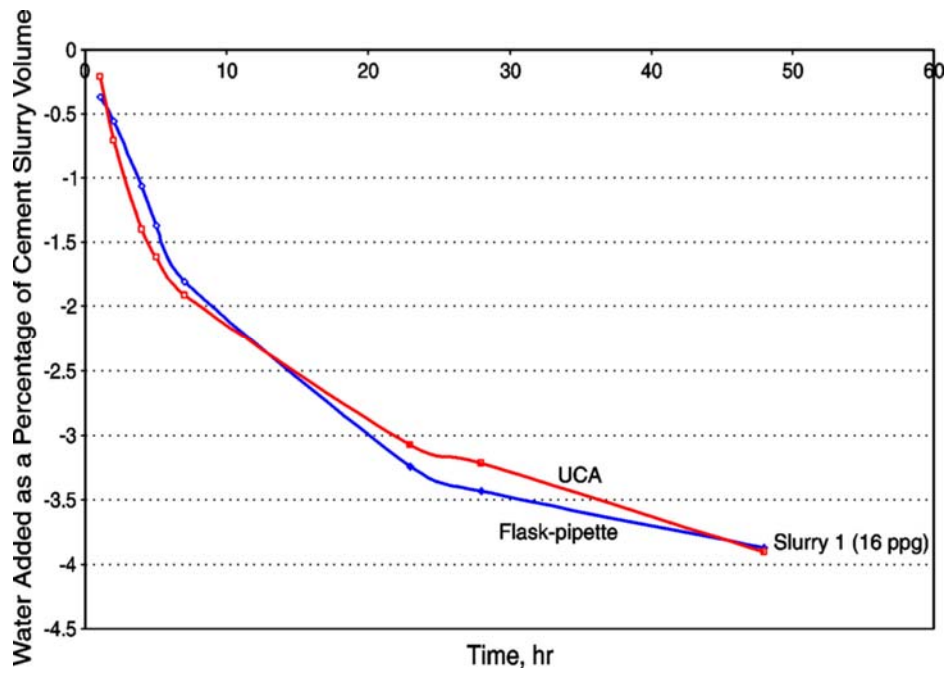


Fig. 3—A comparison of water uptake for Slurry 1 in UCA and flask-pipette.

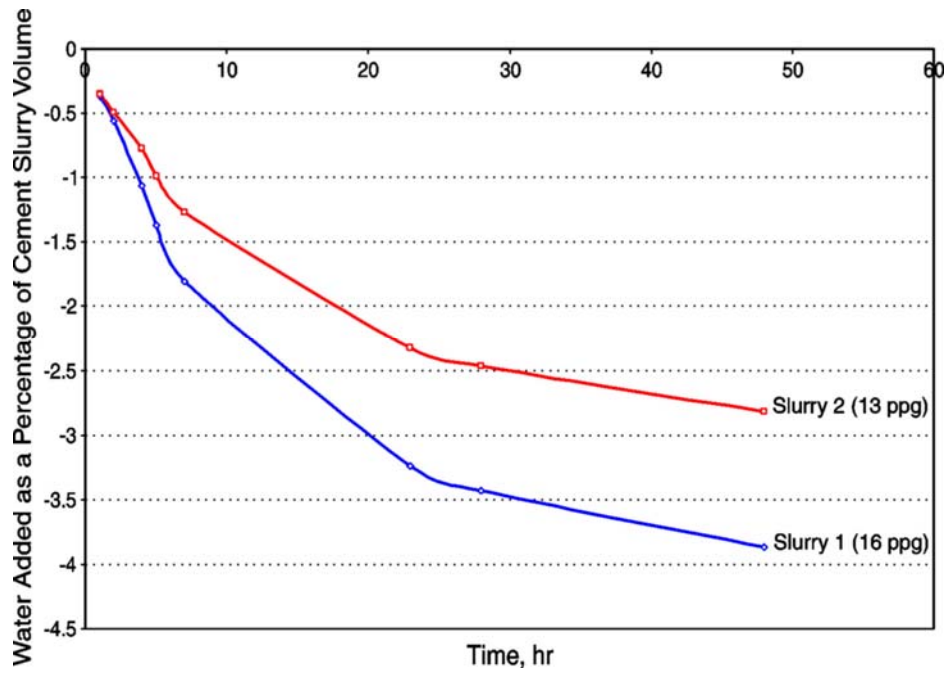


Fig. 4—A comparison of water uptake for Slurries 1 and 2 in flask-pipette.

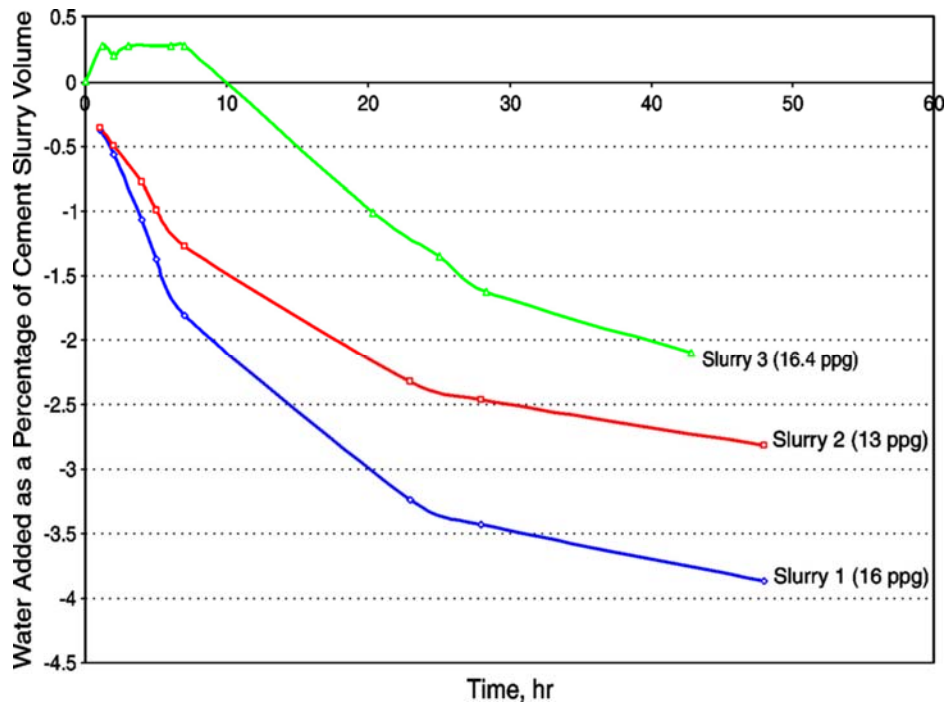


Fig. 5—A comparison of water uptake for Slurries 1, 2, and 3 in flask-pipette.

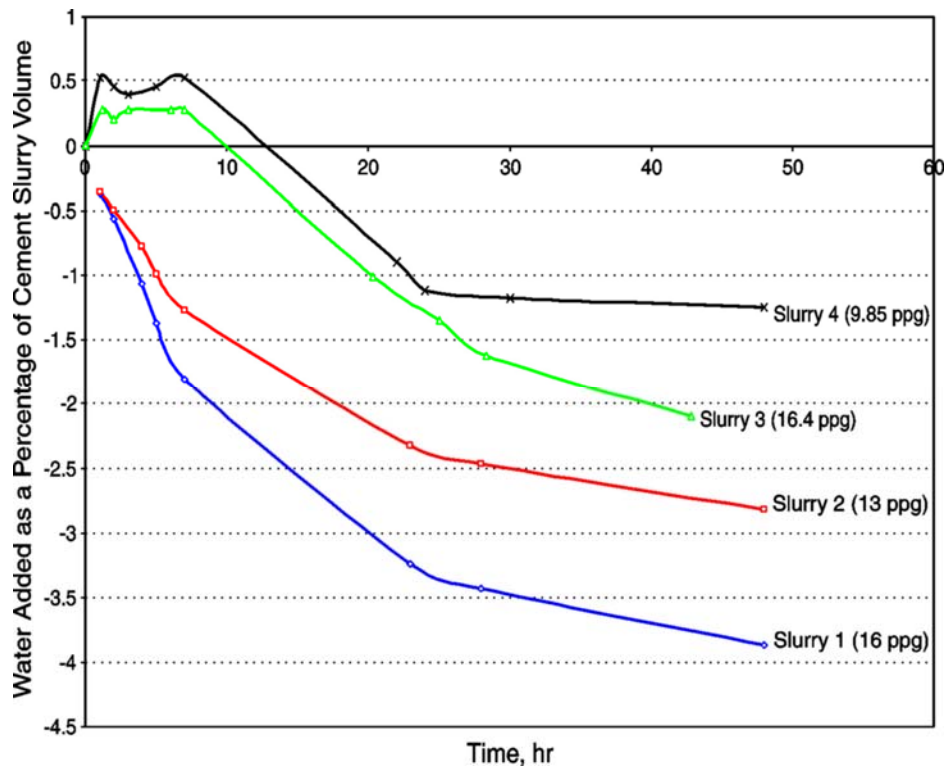


Fig. 6—A comparison of water uptake for Slurries 1, 2, 3, and 4 in flask-pipette.

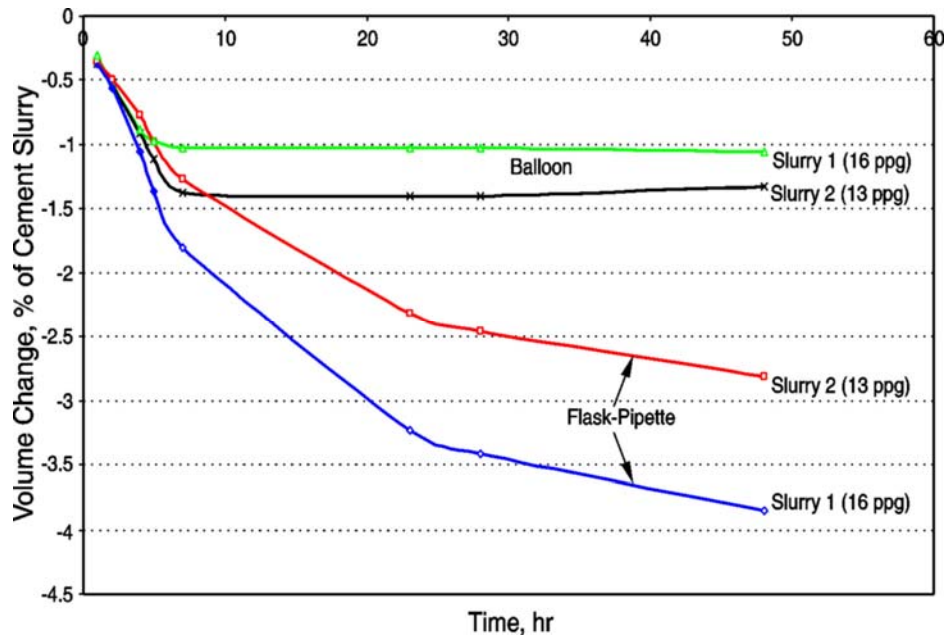


Fig. 7—Balloon and flask-pipette tests for Slurries 1 and 2.

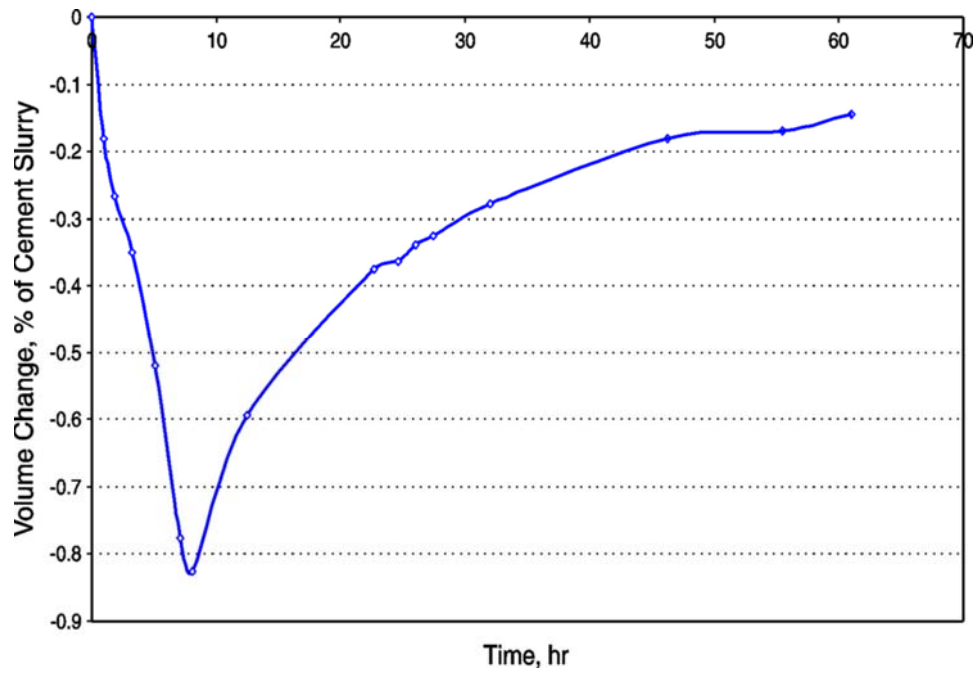


Fig. 8—Balloon test for Slurry 5.

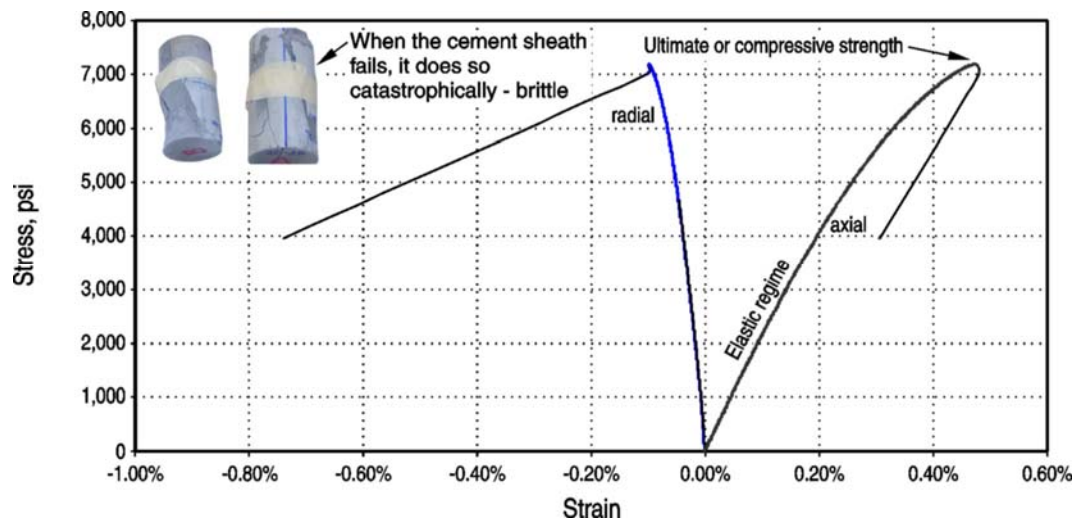


Fig. 9—Load-displacement test for Slurry 1.

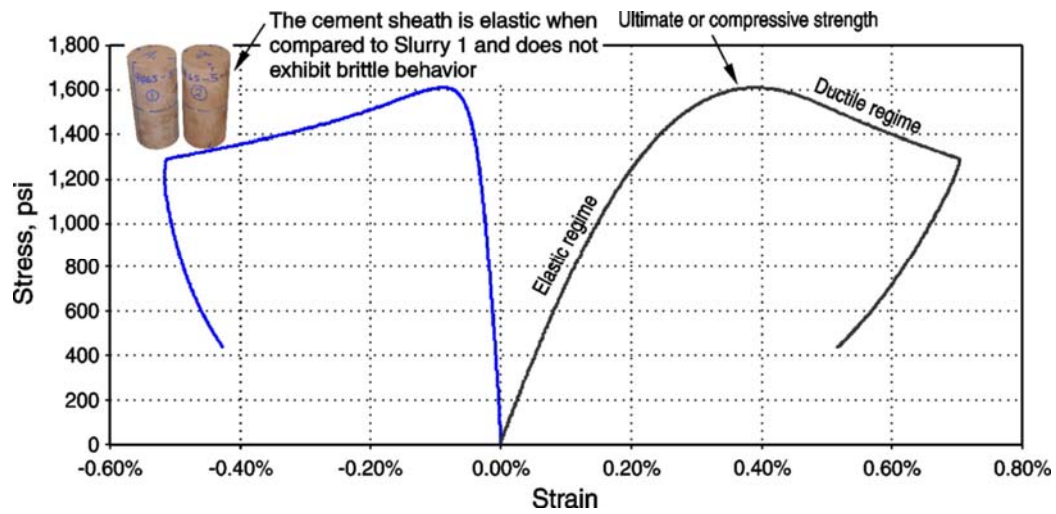


Fig. 10—Load-displacement test for Slurry 3.



Fig. 11—Cylinder after load-displacement test for Slurry 1.



Fig. 12—Cylinder after load-displacement test for Slurry 3.