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Shrinkage of Oil Well Cement Slurries

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Abstract

Gas leakage into and through the cemented annulus in oil and gas wells is a safety problem. The conditions for gas migration develop when the hydrostatic pressure of the hydrating cement slurry column slowly declines and finally falls below the pore pressure of a gas bearing formation. This pressure decline is mainly caused by chemical shrinkage of the cement. A low shrinkage will reduce the pressure decline and hence the risk of gas migration.

A new and simple method for measurement of total chemical shrinkage at high temperatures has been developed. It has proved to be reliable and sensitive for monitoring the cement hydration process. The equipment was used to show that there is a marked difference in shrinkage behaviour for the tested slurries up to 180° C, probably due to a temperature effect on the cement hydration chemistry. The results confirmed the correlation between total shrinkage and cement content, and thus it follows that using more extender will reduce the likelihood of gas migration.

Introduction

Cement slurries are used in oil and gas wells for cementing the steel casing to the wellbore and thus sealing the rock formations from the well. Gas leakage into and through the cemented annulus is still a problem, in particular where shallow gas sands are penetrated and in deep gas wells, i.e., under high temperature and high pressure (HTHP) conditions. The leakage may manifest itself either as vertical communication between permeable gas reservoirs or migration all the way to the surface. Gas pressure in excess of the cement hydrostatic slurry pressure is the driving force behind gas migration.

Reasons and mechanisms of gas migration are discussed by Levine et al.,[1] Sabins et al.[2], and Cheung and Beirute[3]. Annular gas flow may be initiated when the hydrostatic pressure of the cement slurry declines and falls below the pore pressure of a gas bearing formation due to the combined effect of shrinkage, fluid loss to the porous well bore and gel strength build up. Normally a slurry volume reduction would be compensated for by contraction and downward movement of fluids from above, thus maintaining its hydrostatic head. However, during the setting process the cement slurry develops a gel structure causing it to stick to the wall thus hindering compensation of the shrinkage. The second requirement for gas migration is that the cement must enable gas flow into the cement either by permeability, channels, microannuli or microfractures before the slurry has reached a sufficient strength. Thus, the gas migration phenomenon is thought to be initiated during the transition state, from being fluid to becoming hard, i.e., between initial and final set of the cement.

A low shrinkage is preferable because the resulting hydrostatic pressure decline will be lower than for a slurry with high shrinkage, i.e., pressure equilibrium between gas and slurry column is reached at a later point of time.

The chemical shrinkage may be divided into two parts: external shrinkage and total shrinkage. The external shrinkage expresses the bulk volume change of the slurry leading to a possible microannulus between the cement and the borehole wall. The total chemical shrinkage is the sum of the external chemical shrinkage and the contraction pores of the slurry. The formation of contraction pores contribute to the connectivity between pores in a set cement and hence to its permeability.

Chemical shrinkage of oil well cements have been investigated by several authors. The most extensive tests have been carried out by Chenevert and Shrestha[4], and by Sabins and Sutton[5], but other papers have been presented as well[6-8]. Both total[5-8] and external chemical shrinkage[4-6] were reported with a total shrinkage at 20 or 24 hours varying from 0.6 to 6 vol.%, while most results were in the range of 1.5 – 3 vol.%. Only Sabins and Sutton[5] have performed measurements of external shrinkage under realistic downhole conditions. According to them, most external shrinkage occurs when the slurry still is plastic. Their results showed an average shrinkage of 0.15 vol.% and they calculated the contraction pores to account for 97.5 to 99% of the total shrinkage. Thus, from a gas migration point of view, the formation of contraction pores is by far the largest and most important part of the chemical shrinkage.

Experimental Method

The method we have used exploits the pressure-volume relationship of a gas. The principle is shown in Figure 1, indicating initial conditions in the left hand figure. At a later stage, shown in the right hand figure, the shrinkage process, consuming water, leads to a lower gas pressure. When the initial temperature, pressure and volumes are known, the shrinkage can be calculated on the basis of the continuously declining pressure during the test. The calculation is corrected for gas temperature. Total shrinkage was measured by submerging a permeable paper cup containing around 50 ml of cement slurry in water inside the measuring cell. All samples were weighed before and after each test, and the volume of the hardened sample was found by applying the principle

FIGURE 1: Principle of the shrinkage measurements.
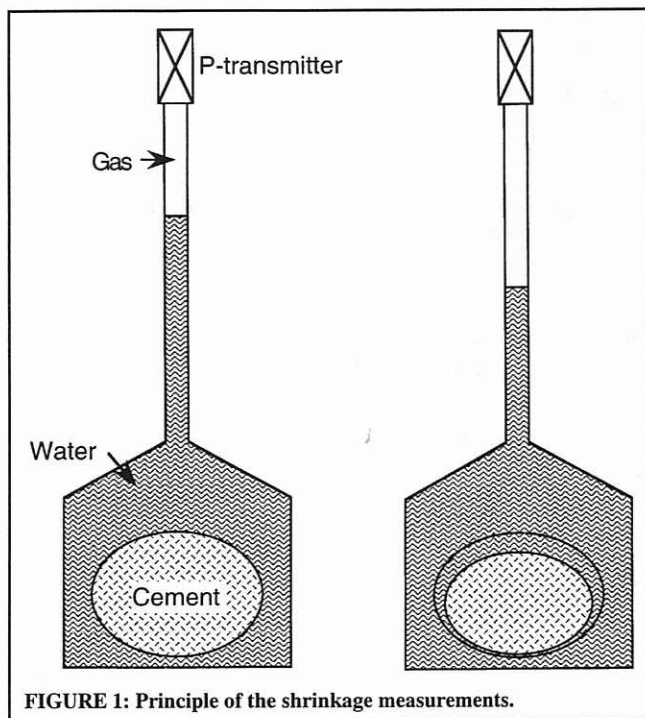
of Archimedes. The applied pressure was in the range of six to 16 bars, and all parameters, including cement temperature evolution, were recorded by a data logger and stored in a personal computer.

The method works well and the results are repeatable, but the method has some drawbacks. It requires precision in the initial values as any inaccuracy will lead to systematic errors, and at pre-
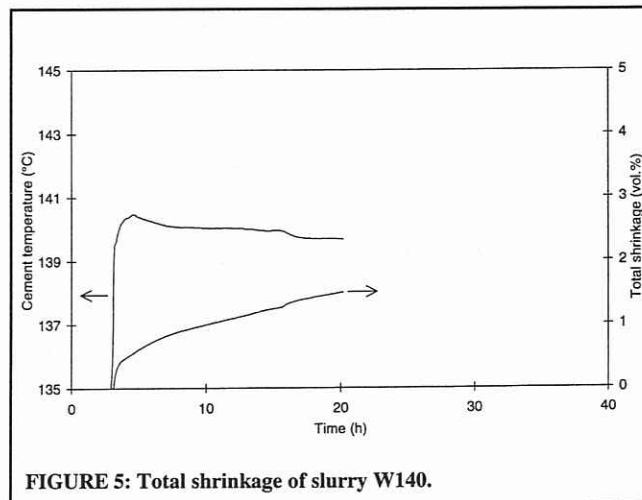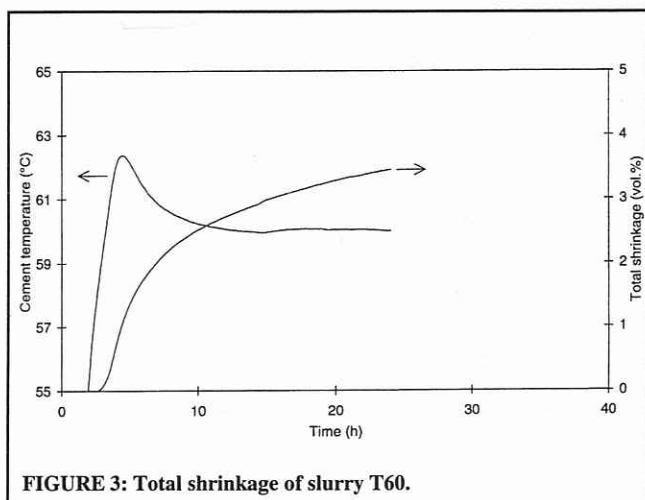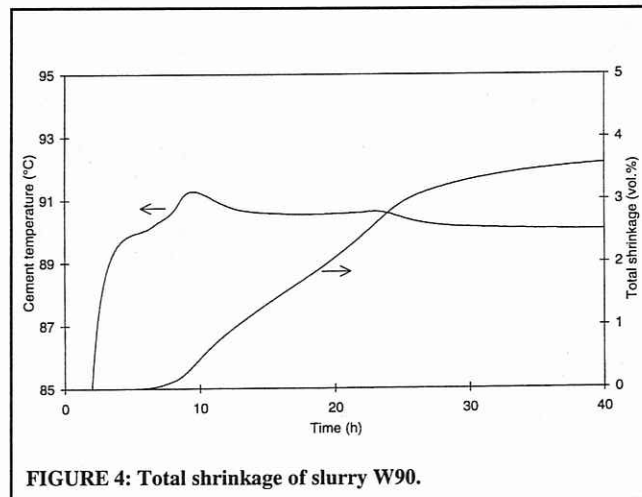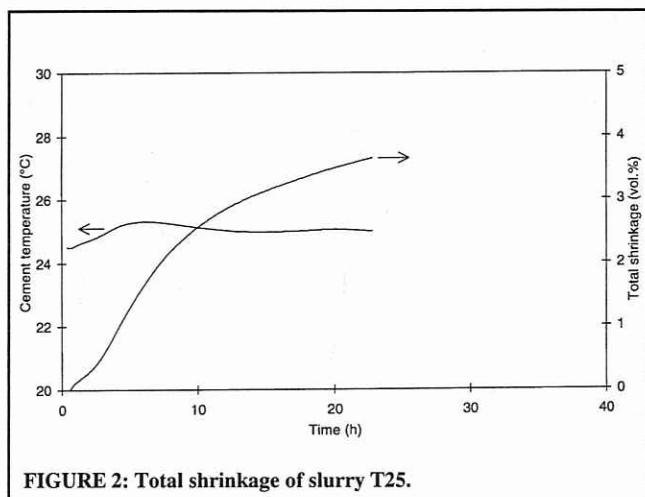
sent the set-up cannot handle downhole pressures. The temperature influence on the measurements is large: both when heating up the cell and when the set temperature is reached. When the cell is heated, the water inside will expand and increase the pressure. The shrinkage calculations are therefore taken from the point when the test temperature or pressure levels off and stabilizes. This has the advantage that it simulates field conditions; any shrinkage occurring before placement of the cement in a well will not be taken into account. However, some initial but minor shrinkage may not be observed. A stable set temperature is important for the same reason. At 180° C, a 1° C temperature fluctuation will lead to an apparent change of 0.3 percentage points in the cement shrinkage. This influence is reduced at lower temperatures.

Results and Discussion

Temperature Influence

The tests were run at several temperatures ranging from 25 to 180° C. A total of 20 slurries were tested. The shrinkage curves for six of the tests are shown in Figures 2 to 7 where the slurries are named T25, T60, W90, W140, and W180. The number represents the test temperature and T stands for a very simple test slurry containing only water, cement and retarder. The W slurries contain all the necessary additives for actual oil well use. The W180 slurry was run twice, both at the stated temperature and at 160° C. The slurry recipes are shown in Table 1.

It is immediately seen that there is a considerable difference in temperature evolution and shrinkage behaviour between the six slurries in Figures 2 to 7, which of course is influenced by the different additives they contain. However, for all slurries the temperature peaks coincide with maximum shrinkage rates. And generally, the higher the cement temperature is above the set temperature,
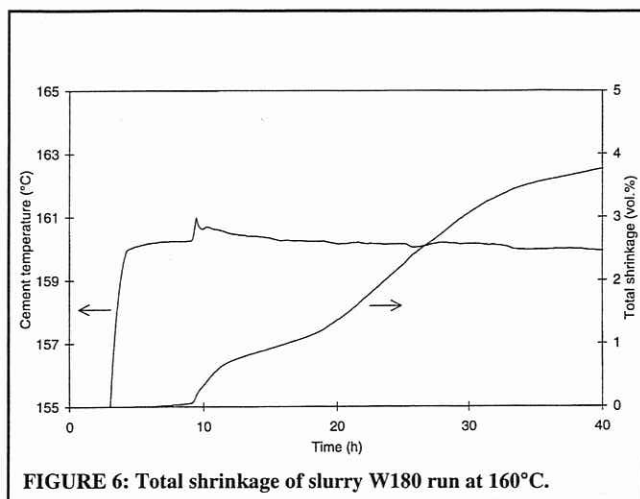

FIGURE 2: Total shrinkage of slurry T25.

FIGURE 3: Total shrinkage of slurry T60.

FIGURE 4: Total shrinkage of slurry W90.

FIGURE 5: Total shrinkage of slurry W140.

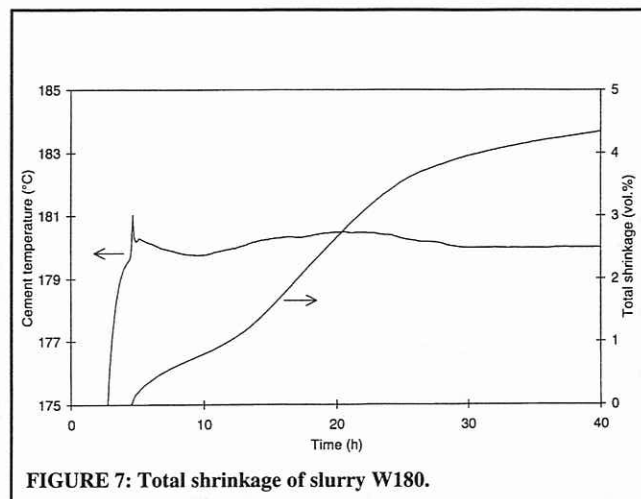**FIGURE 6: Total shrinkage of slurry W180 run at 160°C.**

FIGURE 7: Total shrinkage of slurry W180.

the higher the shrinkage rate is. This correlation is to be expected as the temperature evolution reflects the rate of hydration and hence the shrinkage. Note the two temperature peaks of slurry W90 and W180 (with the exception of Figure 6), the first being at five to ten hours and the secondary peak around 20 – 25 hours.

Both peaks again coincide with the highest shrinkage rates, and the step-wise hydration rate may be influenced by a number of organic admixtures in the slurries.

Some other slurries (not presented here) were tested at 90, 140, and 180° C and they exhibited the same shrinkage and tempera-

TABLE 1: Cement slurry data and recipes.

		T25	T60	W90	W140	W180	A140	B140	C140	D140	E140	F140
Test temperature,° C		25	60	90	140	180	140	140	140	140	140	140
Slurry density, g/cc		1.90	1.90	1.90	2.05	2.15	2.05	2.00	2.06	2.07	1.98	1.88
Cement, vol.%		39.48	40.62	39.84	27.37	27.47	26.63	29.73	33.12	33.22	37.67	39.02
Shrinkage at 20h, vol.%		3.44	3.29	2.08	1.50	2.65*	1.79	1.98	2.58	2.49	2.84	3.11
Additive	**g/cc**											
API class G cement	3.22	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salt water, lhk**	1.03	45.61										
Accelerator, lhk	1.36	2.00										
Fresh water, lhk	1.00		45.09	35.70	51.81	43.59	45.52	39.96	44.28	44.28	44.28	44.28
Retarder, type A, lhk	1.20		0.3									
Retarder, type B, lhk	1.08			1.20								
Anti-gas migration, type A, lhk	1.10			3.50								
Dispersant, type A, lhk	1.18			3.00								
Fluid loss control, type A, lhk	1.07			3.50								
Retarder, type C, %bwoc***	1.42				1.00							
Retarder, type D, %bwoc	1.57					2.00						
Fluid loss control, type B, %bwoc	1.48				0.75	1.00						
Weight material, %bwoc	4.85				30.00	40.00	38.77	13.88	13.88	13.88	13.88	
Anti-strength retrogr., %bwoc	2.65				35.00	35.00	25.97	30.00	30.00			
Anti-gas migration, type B, lhk	1.40				10.00	15.00	13.00	12.00				
Retarder, type E, lhk	1.18						1.25	1.25	1.25	1.25	1.25	1.25
Dispersant, type B, hk	1.21						3.00	3.00	3.00	3.00	3.00	3.00
Fluid loss control, type C, lhk	1.04						5.00	3.00				
Calcite flour, %bwoc	2.72									30.00		

   *   This slurry run at 160° C exhibits a shrinkage of 1.37 vol.% at 20 hours.

  ** Litres per hundred kilos of cement.
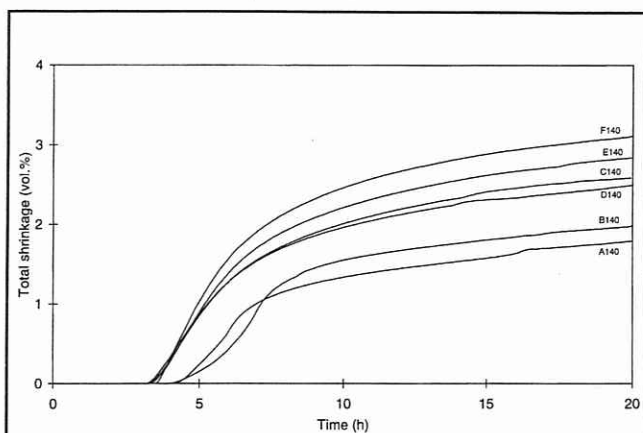
*** Per cent by weight of cement.

FIGURE 8: Shrinkage of the six 140° C slurries.

FIGURE 9: Shrinkage vs. cement content at 20 hours for the six 140° C slurries.

ture behaviour demonstrating that this is a general trend. The behaviour is also confirmed by Lile et al.[9] using permeability, tensile strength, hydrostatic pressure and temperature as indicators. Chenevert and Shrestha[4] tested fresh water slurries at 93, 121, and 177° C and their medium temperature slurry showed the fastest initial shrinkage.

The difference in shrinkage and temperature evolution that we see in the results may also be due to a temperature effect on the cement hydration chemistry. It is well known that curing of cement already at 50 – 70° C leads to an uneven distribution of hydration products with a densified calcium silicate hydrate (CSH) layer around the remaining unhydrated cement grains which eventually will slow down the following hydration rate. It is possible that, at even higher curing temperatures, such a densified layer is formed initially and broken off after some further moderate hydration (rate increasing with increasing temperature), leading to a renewed acceleration period of the cement hydration explaining the step-wise hydration rate shown as the S-shaped shrinkage curves in Figures 4, 6, and 7.

Given that the shrinkage rate reflects the hydration rate, an initial fast shrinkage covering the transition period will limit the time in which gas can enter the cement and thus reducing the likelihood of gas migration. This is the case for slurry W140.

Shrinkage versus Cement Content

Elvebakk[10] used the methods of Lile et al.[9] to study the influence of additives on gas migration. He found that the hazard of gas migration generally increased when the recipe was simplified. The same slurries were also tested for shrinkage. The shrinkage curves of the six slurries A140 through F140 are presented in Figure 8 and the slurry recipes are shown in Table 1. The difference in shrinkage level was found to be correlated with the cement content as shown in Figure 9 where the straight line fitted to the data points is forced through zero, as zero cement content should yield no shrinkage.

This correlation is self-evident and known[4,5], but has not before been linked to the gas migration problem. As long as the strength development of the cement slurry is satisfactory, more use of an extender will reduce the shrinkage and the risk of gas migration. And if the extender particles are small enough, they will fill the space between the cement particles, lowering the cement permeability and thus reducing the likelihood for gas intrusion even further.

Conclusions

A new and simple method for measuring total shrinkage of curing oil well cements at elevated temperatures has been developed. It has proved to be reliable and sensitive for monitoring the cement hydration process. The recorded shrinkage at 20 hours varied between 1.4 and 3.5 vol.% which is in agreement with pub-lished results.
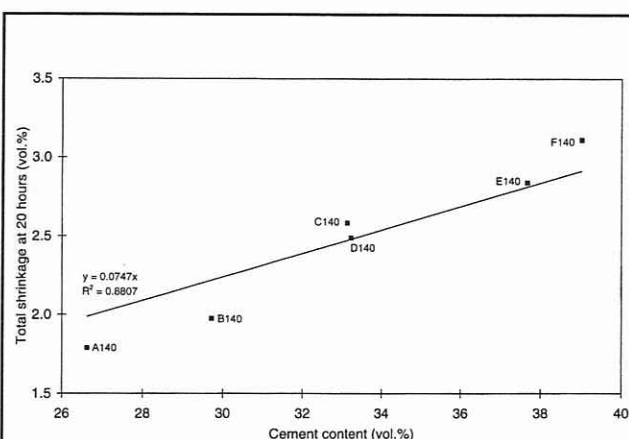
The results show that there is a marked contrast in shrinkage behaviour over the temperature range from ambient and up to 180° C, where the tested slurries at 90, 160, and 180° C exhibited two temperature peaks and S-shaped shrinkage curves. This difference is most likely a temperature effect on the cement hydration chemistry.

It was confirmed that there is a close correlation between total chemical shrinkage and cement content. A low shrinkage and a short transition period (i.e., fast initial shrinkage) should reduce the risk of gas migration.

Acknowledgement

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