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Water absorption and shrinkage behaviour of early-age cement in wellbore annulus

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ABSTRACT

Controlling cement shrinkage in a wellbore is important in maintaining its integrity. Although numerous laboratory experiments on the water absorption and shrinkage behaviour of oil well cement have been reported in the past, such behaviour in the wellbore annulus with consideration of pore water migration from the surrounding formation has seldom been examined. In this study, using a cement shrinkage model calibrated against available experimental data, a coupled hydromechanical finite element analysis of a cement-formation model is conducted to simulate the water migration, absorption and shrinkage behaviour of early-age cement placed in the annulus of a wellbore. The objectives of this study are (i) to identify the threshold permeability value of the formation above which there is no longer a bottleneck for pore water to flow into the cement and (ii) to estimate a reasonable range of cement bulk shrinkage volume in wellbore annulus geometry. Results show that the threshold permeability of the formation would be around 0.1 mD for three different types of cement examined in this study: Class G cement, rapid setting (RS) cement and Schlumberger optimized particle size distribution (OPSD) technology cement. The bulk shrinkage volume varies from 0.01% to 2.4% depending on cement type and formation permeability (1 mD to 0.1 μD). The proposed methodology facilitates the simulation of water migration/absorption and shrinkage behaviour of well cement in different formations.

1. Introduction

Cementing operations in oil and gas wells are often performed under an assumption that cement shrinkage is negligible in terms of well-formation interaction. However, if the hardening cement slurry is surrounded by low permeability formation, large bulk volume shrinkage can occur because the cement cannot absorb sufficient water from the formation to compensate for its hydration process. Although there are several reported studies on cement shrinkage behaviour in the laboratory, the measured bulk shrinkage volumes may not be representative under the wellbore conditions. It is hypothesised in this study that a proper evaluation of cement shrinkage volume is crucial for assessing the wellbore and formation integrity prior to oil/gas production.

Various bulk shrinkage values of typical oil well cements are reported in the literature. As shown by a summary given in Table 1, a wide range of bulk shrinkage volume between 0.1% and 7.15% of the original volume is reported. It is generally known that cement bulk shrinkage behaviour is affected by many different factors, such as temperature and pressure and employed test methods (Reddy et al., 2009). High curing temperature changes the cement hydration chemistry in such a way that hydration temperature has two peaks, resulting in the S-shaped shrinkage curve (Lyomov et al., 1997). For Class G cement, Goboncan and Dillenbeck 2003 showed in their laboratory-scale high-pressure and high-temperature cement shrinkage tests that the bulk shrinkage volume was 0.1% at 100 h after cement mixing under the curing condition of 20 MPa and 150 °C. The bulk shrinkage volume of Class G cement decreases with decreasing water-to-cement ratio as well as with increasing amount of calcium carbonate and polyvinyl alcohol (PVA) (Justnes et al., 1995). Also, shrinkage volume reduces by decreasing cement contents (Backe et al., 1999) and by adding bonding agents (Parcevaux and Sault, 1984). Shrinkage test results on Class H cement also show that the bulk shrinkage volume decreases with decreasing amount of available water for cement hydration which is achieved by increasing the temperature and pressure as well as using water-consuming additives such as sodium chloride, silica flour, bentonite, or sodium silicate (Chenevert and Shrestha, 1991). For instance, the bulk shrinkage volume of Class H cement cured under 8.3 MPa and 38 °C typically reaches its asymptotic value of 3.8% in 70 h (Chenevert and Shrestha, 1987).

Despite the uncertainty in the magnitude of cement shrinkage

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Table 1
Bulk shrinkage volume values of oil/gas well cements measured in the laboratory.

	Cement type	Water-to-cement ratio	Additives	Temperature (°C)	Pressure (MPa)	Drainage	Test duration (h)	Shrinkage volume (%)
Backe et al. (1999)	Class G	0.44	Retarder	90	0.0025	Open	20	3.92
Chenevert and Shrestha (1991)	Class H	N/A	Retarder	37.8, 65.6, 93.3	8.27, 24.1, 35.9	Closed	70	4.3, 3.8, 3.4
Goboncan and Dillenbeck (2003)	Class G	N/A	Fluid loss control, dispersant	149	19.3	Open	110	0.1
Justnes et al. (1995)	Class G	0.3, 0.4, 0.5	None	20	Ambient pressure	Closed	48	2.2, 1.5, 1.1
Lyomov et al. (1997)	N/A	N/A	Retarder	25, 60,	0.6–1.6	Open	24	3.7, 3.5
Parcevaux and Sault (1984)	Class G	0.44	Dispersant, retarder	20	0.5, 4.0, 10.0	Closed	48	7.15, 6.30, 4.30
Reddy et al. (2009)	N/A	N/A	Defoamer	26.7	0, 6.89, 13.8, 20.7	Closed	70	1.3, 3.1, 3.6, 3.8

volume in actual wellbore annuli, the effect of cement shrinkage volume on wellbore integrity has been examined in the past by numerical simulations of the problem. For example, Ravi et al. (2002) showed that, the smaller the cement shrinkage volume is, the less the risk of cement failure such as fracture, plastic deformation and debonding becomes. Oyarhossein and Dusseault (2015) reported that the combination of stiff formation and cement shrinkage volume would increase the risk of loss of zonal isolation because stiff formation could not follow cement shrinkage to prevent debonding at the interface. However, they stated that cement data under the downhole conditions would be necessary to improve their numerical model. Gray et al. (2007) built a 3D model that incorporated the non-linear mechanical behaviour of cement and formation and showed that cement shrinkage could lead to debonding between casing-cement interface because of plastic straining of the formation reaching their maximum values in the direction of the minimum horizontal stress. In the abovementioned studies, uniform shrinkage volume is specified over the entire cement elements and it is noted that the values used for cement shrinkage volume are different (i.e., 0% and 4% (Ravi et al., 2002), 0.5% (Oyarhossein and Dusseault, 2015), and 5% (Gray et al., 2007)). Saint-Marc et al. (2008) incorporated a volumetric strain term arising from cement shrinkage, which was correlated with change in the degree of cement hydration, in the isotropic elastic constitutive equation to model cement shrinkage behaviour. However, pore fluid flow was not coupled with the constitutive equation.

Cement shrinkage behaviour is characterized by the development of capillary suction pressure in the pores of cement material as water is consumed by hydrating cement particles. Hua et al. (1995) show in their tests on early-age cement paste that cement shrinkage after the initial set (i.e. the thickening time) can be estimated by calculating the capillary suction development during the cement hardening process and by using it as confining pressure on an elastic porous body with time-varying stiffness. Lura et al. (2003) incorporate the degree of water saturation as a coefficient to calculate the confining stress caused by the capillary suction pressure and incorporate the stiffness of the cement particles in addition to the bulk stiffness of the cement skeleton, to accurately predict the linear shrinkage volume of early-age cement paste. By conducting a thermo-hydro-mechanical coupled simulation on early-age cement shrinkage, Zhen and Xiong (2013) find that the contribution from thermal strain is pronounced during the first 5 h of the shrinkage since the initial set but becomes negligible after 24 h. The capillary suction pressure concept for estimating cement shrinkage volume is also found effective for post early-age cement (Coussy et al., 2004). Rougelot et al. (2009) show that the capillary suction pressure concept is valid for hardened cement and argue the influence of cement particle stiffness and cement bulk stiffness in estimating cement shrinkage volume.

Considering the abovementioned findings on the physics of cement shrinkage, it is more realistic to carry out a hydro-mechanical coupled simulation on a porous cement material by utilizing the capillary suction pressure concept rather than specifying uniform shrinkage over the entire cement. By doing so, the bulk shrinkage behaviour of early-age cement and the associated wellbore behaviour can be evaluated for more realistic scenarios. An earlier attempt of such simulation was made by Thiercelin et al. (1998) who introduced a fluid sink term in the hydro-mechanical coupled simulation as it can be directly related to the water consumption of a porous material during hydration. Bois et al. (2011) and Bois et al. (2012) also simulated the behaviour of annular cement as a porous material and modelled cement shrinkage volume by changing the pore pressure in their simulations. It is noted that capillary suction pressure (p_g-p_l) reduces to pore liquid pressure (p_l) when the cement pore space is fully saturated ($p_g = 0$) and cavitation is unlikely to occur due to high liquid pressure (e.g. offshore cementing).

This study extends the work of Thiercelin et al. (1998) by conducting a coupled hydro-mechanical finite element analysis to simulate the water migration, absorption and volume shrinkage behaviour of early-age cement in a wellbore configuration. The primary objectives of this study are (i) to determine the threshold permeability value of the formation below which the cement cannot absorb adequate water from the formation to compensate for the water consumption by the hydration reaction and (ii) to estimate a reasonable range of cement shrinkage volume in downhole conditions. The wellbore is modelled to be placed in the overburden of the Nankai Trough in Japan (Yamamoto et al., 2014), where the cement is surrounded by the low permeability clay formation on the outer boundary and by impermeable casing on the inner boundary. The mechanical and hydrological parameters of hardening cement paste are calibrated by utilizing laboratory test data on three different types of cement: Class G cement, rapid setting (RS) cement and optimized particle size distribution (OPSD) technology cement from Schlumberger.

2. Mechanism of cement shrinkage

The bulk shrinkage of cement can occur by three different mechanisms: (i) capillary depression effect, (ii) surface tension effect, and (iii) disjoining pressure effect (Hua et al., 1995). One or more of these mechanisms are dominant over the others depending on the relative humidity of the cement. For example, the capillary depression effect is the dominant mechanism at high relative humidity (i.e. over 80%) whereas the other two mechanisms are activated at lower relative humidity levels (i.e. below 45%) (Rougelot et al., 2009; Lura et al., 2003; Hua et al., 1995). The relative humidity of early-age cement paste is known not to decease below 75% even though it is left in contact with the air (Lura et al., 2003). Therefore, in the wellbore condition where the cement is surrounded by water-saturated formation, the primary mechanism of cement bulk shrinkage volume is the depression of capillary suction pressure (i.e. pore pressure). Such phenomena can be simulated by the coupled hydro-mechanical equations for porous materials; the hydraulic part of the equations is derived from the conservation of fluid mass in a porous media, whereas the mechanical part