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The impact of cement slurry aging creep on the construction process of oil wells

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ABSTRACT

In the present work, a finite element based methodology was developed to assess the deformations and stresses during the construction of a vertical oil well drilled into Brazilian Halite. The impact of each construction stage is addressed focusing on the investigation of the early age creep of the cement slurry and its effects on the well integrity. The cement slurry was considered as an aging viscoelastic material and a parametric case study was addressed using the solidification theory. The rock salt constitutive model accounted for the primary and secondary creep through a combination of a power law and the double mechanism law. It was observed that if the cement slurry time-dependent behavior is neglected, the development of deviatoric stresses in cement slurry and hazard phenomena may be overlooked.

1. Introduction

The scientific community is unison on the importance of the cement on the integrity and good functionality of a well. Its main role is to grant sealing to liquids or gases and support the casing. Efforts in research have been engaged to preclude cement sheath integrity loss**.** A myriad of papers about well cement includes testing well cement formulations (Heathman and Vargo, 2006; Martins et al., 1997; Philippacopoulos and Berndt, 2001; Ravi et al., 2006; Zhang et al., 2010) and in-field studies (Cooke et al., 1984, 1983). Analytical solutions for well integrity are presented in Atkinson and Eftaxiopoulos (1996) and De Simone et al. (2017).

In the numerical analysis framework, the literature presents nonlinear studies that seek the truthful simulation of real events from drilling to production with the Finite Element Method. The main goal of these simulations is to estimate the stress and displacement fields over the life span of the oil well, from the intact rock formation before drilling to well abandonment. Bosma et al. (1999) carried out the first study in permeable rocks with this objective, and since then, others have presented studies using similar methodologies (Gray et al., 2009; Ravi et al., 2002; Ravi and Bosma, 2005; Schreppers, 2015). When drilling into a salt formation, other prominent factors rather than the pore pressure must be taken into account, such as the salt creep motion. Following the same scheme presented in Bosma et al. (1999), other authors have also analyzed the stress history at different well construction stages in wells drilled into salt rock (Poiate et al., 2006; Wang and Samuel, 2016).

Gray et al. (2009) focused on the different construction and production stages and on the modeling assumptions at each stage using the commercial finite-element program ABAQUS. The authors assumed that the cement slurry goes from the fluid to the solid state with an initial hydrostatic stress state inherited from the liquid slurry followed by a reduction of volume in time – shrinkage. The referenced works either follow similar assumptions or do not address the subject.

Pfeifle et al. (2001) carried out bench-scale studies on salt rock to evaluate the integrity of the casing shoe, and compared the results with numerical simulations. To the authors' knowledge, this is the first attempt in the Oil and Gas context to simulate the curing time through an elastic constitutive model with time-increasing Young's modulus for the cement slurry. Other works (Brandão and Roehl, 2016; Mackay and Fontoura, 2014) have also considered the evolution of elastic properties and presented a step-by-step scheme, similar to Gray et al. (2009), but for a salt formation.

So far, it seems that the hydration period of the cement slurry in numerical formulations has been limited to the elasticity framework. Li et al. (2016) presented a state-of-the-art survey of Static Gel Strength (SGS) theory to explain the drop of hydrostatic pressure on cement after

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pumping stage is completed. They identified discrepancies between the hydrostatic stress state achieved by the classic gas-migration theory and the experimental results. The analytical theory explains the drop of stresses through the changes in volume of the cement paste and the transmission of shear stresses between the paste, the casing and the rock formation. Nevertheless, it disregards the microstructural molecular rearrangements in the cement paste and this may end up causing the divergence between analytical and experimental results (Li et al., 2016).

The theory of viscoelasticity has been used to explain macroscopically the molecular rearrangements as a function of time under applied forces or displacement. The decrease of volumetric stresses in the cement sheath is identified in the literature (Cooke et al., 1983; Martins et al., 1997; Sabins et al., 1982) and attributed to the loss of fluids, autogenous shrinkage, slurry compressibility and contact between slurry, casing and formation. Nevertheless, when the cement starts to stiffen, the microstructural molecular rearrangement produced by the aging creep of the cement slurry may contribute to the drop of the volumetric stresses along with the raise of the deviatoric stresses.

This work focuses on the application of a numerical formulation to understand the deformations and stresses developed throughout the construction of a vertical oil well drilled into salt rock (Brazilian Halite). It is aimed to understand the impact of considering the cement an aging viscoelastic material. To this end, a parametric case study with cement slurry modeled using the solidification theory (Bažant, 1977) is presented. Furthermore, this study is carried out at the early age stage of an oil well construction, thus the rock salt model accounts for the primary and secondary creep. A combination between a Power Law (Lomenick and Bradshaw, 1969) and the Double Mechanism Law (Dusseault et al., 1987) is proposed. The Brazilian field case study provided support for the conclusions drawn in this work, showing the drop of the volumetric stresses and the raise of the deviatoric ones in the cement sheath.

2. Constitutive models

In the scenario of interest, a generic oil well is drilled into the salt rock formation, the steel casing is centered and positioned, and the cement slurry is pumped into the annulus between the rock formation and the casing. Therefore, three materials must be considered to model the well construction: the steel, the cement slurry and the salt formation. This section presents a review of the physical behavior, the constitutive behavior and the chosen constitutive laws for the cement paste. It also provides a review of the most common rock salt constitutive models. The steel casing is considered a perfect elastoplastic material and no further discussions are provided.

2.1. The cement slurry system

The cement slurry hydration is a complicated multi-scale mechanism that goes through multi-physics processes. The American Petroleum Institute (API) categorizes cement pastes for Oil and Gas from A to J. Each category has different compound weights of C_3A, C_4AF, C_2S and C_3S and additions (silica powder in cement J, for instance) to reach the desirable properties and suit the design requirements. When in contact with water, the cement paste solidifies and hardens in time. Each compound/addition contributes differently to the mechanical response of the paste. Amongst them, the C_3S is the most important constituent of the cement clinker. The hydration of the C_3S results in the formation of CH (calcium hydroxide) and C-S-H (calcium silicate hydrate), which is responsible for the mechanical properties of the cement paste in its hardened state.

Not only is the mechanical response of the cement slurry a function of the chemical reactions of its constituents, but it also depends on the external loading history. Despite not being fully consensual, the mechanism under cement creep phenomenon appears to be linked to the micro-sliding between C-S-H layers or adjacent particles which macroscopically result in the creep phenomenon (Tamtsia and Beaudoin, 2000). In the 2D and 3D space, two distinct mechanisms for the volumetric and deviatoric behavior represent the response of the materials. Differently from steel or polymers, where the volumetric properties are approximately constant (Huang et al., 1963), volumetric creep (compressibility) of cement paste may be as pronounced as the deviatoric component. Bernard et al. (2003) studied calcium-leached cement paste to isolate the creep phenomenon of C-S-H since this is the constituent responsible for creep in cement pastes. They state that cement paste shows a contractile volumetric behavior to external hydrostatic loads and relate it with deviatoric micro-stresses arising from the cement paste heterogeneities. Micro-deviatoric stresses inflict shear upon C-S-H layers until the microstructure results homogeneous. This explanation is also accepted by Grasley and Lange (2007a).

Moreover, the cement paste suffers chemical shrinkage and loss of water over hardening. Researchers have identified various types of shrinkage (Hewlett, 2003); however, in the Oil and Gas environment, the cement paste is claimed to be affected only by chemical shrinkage (Ravi et al., 2006). Chemical shrinkage results from the difference in volume between the reagents and the final product. Part of the chemical shrinkage unfolds as bulk deformation of cement paste – autogenous shrinkage. Although several mechanisms occur, the variation of capillarity pressure, which leads to pore collapse, is the most relevant to the autogenous shrinkage (Backe et al., 1998; Hua et al., 1995). The microscopic explanation for this behavior is found in the development of capillary pressure that is due to the growth of hydration products that inflict a water-air meniscus in the water capillarity. This event causes a drop of relative humidity and a decrease of pore size, which induces a capillary depression, hence the shrinkage - Kelvin's and Laplace's law (Holt, 2001; Hua et al., 1995; Lura, 2003). Li et al. (2010) showed that pores with 5–50 nm is one of the main factors influencing the autogenous shrinkage. The higher the volumetric percentage is, an increased capillary effect will occur, leading to a larger autogenous shrinkage.

Based on the aforementioned physics, the chronology of the hydration related events is presented:

- The early period [0–5 h] – It is constituted by two stages, the pre-induction and the induction phases. When the cement slurry gets in touch with water, the pre-induction period takes place, mainly corresponding to the reaction between C_3A, gypsum ($CaSO_4 \cdot 2H_2O$) and water. After the pre-induction period, little hydration and chemical shrinkage (Zhang et al., 2010) take place. This period is known as induction or dormant period.
- The middle period [24 h] – The major components of clinker, the C_3S, react with water to form CH and C-S-H. The C-S-H has a foil type of morphology but when drying changes to the form of long fibers that grow into the pore space and form bridges between the cement particles – capillaries – culminating in a greater macroscopic stiffness. The chemical shrinkage rate increases since chemical shrinkage is a function of the degree of hydration. In this period, autogenous shrinkage and chemical shrinkage are of similar magnitude.
- The late period [days] – The hydration products form a dense layer around the original particles that acts as a barrier for the hydration, slowing down the rate of reaction. Thus, the hydration process becomes controlled. The cement paste stiffening rate tends to stabilize and the hydration products fill the capillaries. The autogenous shrinkage stabilizes and the chemical shrinkage proceeds due to the continuation of the hydration process.

2.1.1. Constitutive aging viscoelastic effect on the cement slurry

Assuming the principle of superposition, the viscoelastic response can be calculated through hereditary integrals (Equation (1)), where J represents the compliance, t, the time variable and t' the time when the load is applied. The first part of the equation is related with the elastic strain $\varepsilon^{el}(t)$ and the second part with the viscous response $\varepsilon^{v}(t)$.