

Pressure Reduction in Hydrating Cement Slurries

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1 Abstract

Many oil and gas wells leak and some of the many causes are associated with changes in the cement slurry as it hydrates. The underlying physical mechanisms relate back to evolving rheological parameters of the slurry. This paper gives an overview of both simple and complex models that are under development to predict these phenomena.

2 Context of the research

Fresh cement pastes are fine multi-phase colloidal suspensions that change on the micro-scale due to chemical reactions. On the macro-scale they are commonly modelled as Herschel-Bulkley fluids, i.e. shear-thinning yield stress fluids. Many questions arise concerning the mechanisms for gas invasion and propagation.

One simple theory that has been proposed for gas invasion is as follows. Hydration leads to shrinkage, so that the slurry settles downwards in the well. This downwards settlement is resisted by the yield stress of the fluid, hence reducing the static pressure in the cement column and allowing the formation (gas) pressure to exceed that in the annulus, leading to invasion. To apply and explore this level of model requires macroscopic estimates of the evolution with time of both shrinkage and yield stress (due to hydration).

At a more detailed level, a second theory is as follows. As the solid phase increases in volume fraction through hydration, the cement suspension attains a percolation threshold

where particles begin to join mechanically in a non-hydrodynamic way. As the solid fraction increases further, chemico-mechanical contacts between grains develop, with the remaining liquid slurry occupying inter-granular space in the developing porous media. In this case, can the solid phase become self-supporting, reducing the ability of the liquid phase to resist invasion from the gas within the formation?

To explore these concepts requires a suitably complex level of model, which we outline. We aim for a continuum level description, that clearly must bridge between models for non-Newtonian suspensions and porous media flow, capturing the mechanics of the transition between these. Equally, a pragmatic level of description of the (extremely complex) cement hydration chemistry must be included as this is responsible for changes in phase and transition from slurry to porous solid. Practically, we are in the induction period of the hydration reaction. Here we combine a simplified reaction model with a Herschel-Bulkley extended suspension balance model (SBM) for the (liquid) slurry, switching to a porous media flow at percolation. We present the model outline and our preliminary analysis.

As it is described above cement undergoes various chemical processes during hydration. We need a macroscopic framework for modeling the evolution of solid and liquid phase constituents during hydration, as they will then contribute to the evolution of stresses via constitutive relations.

Thermo-mechanical ageing of concrete/cement during hydration has been the focus of many studies aiming for making a macroscopic model for hydration process.

These studies assumed cement is hydrated and a solid skeleton has been formed and based their model on the framework developed by Coussy [4] for a porous media saturated with pore water. These studies [5–8, 12, 13] applied this framework for capturing the concrete/cement evolution and chemical reactions were responsible for dissipation in the system. This model initially neglected the porosity change e.g Ulm and Coussy [12, 13] and later it was improved by Gawin et al. [5, 6], Pesavento et al. [8] and Lecampion [7] by including implicitly and explicitly the effect of this change on the thermal stresses. The explicit change was brought by applying the linear evolution of the porosity with the hydration degree [3, 11].

Another early work in seeking thermo-mechanical aging of the cement is by van Breugel [14]. This study aimed for developing an in house software to predict the quality of cement (i.e morphology and structure) as a function of temperature and thermal stresses and is based on empirical relations obtained by earlier experiments.

However, all of the discussed models assumed that the solid skeleton of cement is formed and a porous matrix is developed. They simplified the chemical reactions and used bulk kinetics expressions to describe the porosity evolution of cement by relating it to the degree of hydration.

This framework is clearly unable to capture chemico-mechanical evolution of cement during transition from slurry to a porous matrix. As it is mentioned earlier the early gas migration is due to either cement becoming self-supporting or static pressure reduction due to phase change at transition stage. To investigate these causes it is required to evaluate the porosity of the slurry up until porous matrix is built i.e. deceleration period then calculate the stress and pressure in the system. It requires us to model the chemical reactions and use transport equations as a tool for finding solid volume fraction at each stage.

There are also a large number of papers in the scientific and engineering literature that

have mathematically modeled transport and reaction in the cement. A mathematical model for induction period is developed and applied in [1, 9] using clock reaction model. Including only the major component of cement, tricalcium silicate, the length of the induction period has been studied by using an advection-diffusion model in [10]. Later the authors have added more major ingredients of cement including gypsum and another chemical retarder [2] and solved a system of ODE advection-diffusion equation in order to evaluate thickening time in presence of retarder.

In order to obtain the solid volume fraction at early stages of cement hydration, we developed a similar model to those discussed above. The outcome of our model is kinetics of cement from beginning up until porous matrix is formed in presence of gypsum and a sulphate retarder. It should be mentioned that, the chemical retarders including sulphate phase are known for adding another phase to the hydration which is called artificial induction. The values of rate of concentration of solid and liquid phase, then are fed into a continuum model similar to that proposed by Brouwers [3]. From this preliminary analysis the constituent phases of the cement including chemical shrinkage can be obtained. To complete our continuum model, we are going to marry this chemical part to a closure model for a yield stress suspension.

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