Abstract

The prediction of the performance of cement-based materials requires a holistic model integrating the progressive hydration of the material, the coupling between water consumption and strains, and the history of the applied loadings. This is particularly important when modelling the behavior of the cement sheath in oil wells which is subjected, from its earliest age and during its lifetime, to a wide range of mechanical and thermal loadings that could have a detrimental effect on its future mechanical properties.

The aim of the present thesis is to provide a complete modelling framework for the hydro-mechanical behavior of an oil well cement paste from its earliest age to its hardened state. The manuscript is divided in two parts.

Part I: hydration kinetics

The evolution of the most significant physical properties of cement-based materials is controlled by the advancement of the hydration reactions. Two different modelling approaches are presented:

- A theoretical framework for the modelling of cement hydration is developed as an extension of classical nucleation and growth models. The proposed multi-component model explicitly considers anhydrous cement and water as independent phases participating in the reaction. We also introduce a growth rate that encompasses linear as well as parabolic diffusion growth in a single continuous mathematical form. The formulation naturally introduces some of the most relevant parameters of cement paste mixtures, such as the cement powder composition, mass densities of the different phases, water to cement ratio, chemical shrinkage and hydrates properties. The different rate-controlling mechanisms can be identified and interpreted on the basis of the proposed physical model.
- A general hydration kinetics law based on the theory of solid phase transformations is proposed. This formulation is compared with the evolution laws found in the literature and helps providing a physical explanation that could shed light on the understanding of cement hydration kinetics.

In both cases, the kinetic models are calibrated over a series of experimental results in order to properly evaluate the quality of the predictions.

Part II: mechanical constitutive law

The mechanical behavior of cement paste is described in the framework of reactive porous media. The cement paste is modelled as a multi-phase porous material with an elastic-viscous-plastic constitutive law, with mechanical parameters depending on the hydration degree. Furthermore, the cement paste chemical shrinkage and pore water consumption during hydration are accounted for in the determination of the macroscopic strains. The evolution of the poroelastic parameters of the cement paste during hydration is calculated by means of a micromechanical upscaling model. An asymmetric yield surface with compressive and tensile caps is adopted for the elastoplastic regime, with hardening mechanisms considering both the cumulated plastic deformations and the hydration degree. The viscous behaviour is based on the notions of solidification theory. A water retention curve is introduced to account for the potential desaturation of the material during hydration.

The model parameters for a class G cement paste are evaluated by simulating the results of mechanical loading experiments in a device specially designed for testing the thermo-mechanical behavior of cement paste from the early stages of hydration. The results show that the proposed model predicts with good accuracy the response of a hydrating cement paste when subjected to various loading paths from its early age. The importance of the loading history is outlined, as well as the need for the accurate determination of the effective stresses throughout the life of the material.

Keywords: cement, hydration kinetics, poromechanics, oil well, cement sheath