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A study of freezing behavior of cementitious materials by poromechanical approach

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ABSTRACT

The freezing behavior of cementitious materials is investigated in this paper through poromechanical approach after the Biot–Coussy theory. The material is taken as a porous medium saturated with water and subject to freezing. The involved thermodynamic laws are recalled to establish the constitutive equations for the phase change, mass transport and heat transfer processes. As a result, the pore pressure arising from freezing is converted to macroscopic effective stress through homogenization scheme. The established model is applied to predict the macroscopic freezing strain of a saturated cement paste and the theoretical prediction is compared to observed experimental results in (Powers and Helmuth, 1953). The results show that the poromechanical model can reasonably capture the freezing behaviors from pore pressure accumulation, pore pressure relaxation as well as the thermal shrinkage associated with the freezing process.

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1. Introduction

Cementitious materials, after hydration reactions, have extremely intricate microstructure, containing C–S–H gels, mineral crystals and pores fully or partially occupied by water. The phase change of confined pore water to ice can build up important pore pressure and cause material deterioration at macroscopic scale. For freezing behavior of cementitious materials, the hydraulic pressure theory (Powers and Helmuth, 1953) was the first systematic modeling dedicated to the mechanical effects of freezing water in pores: it attributed internal pore pressure accumulation to the viscous flow of liquid water driven by around 9% volumetric increase during water freezing. By this theory, the safety air void spacing has been correctly predicted for air-entrainment techniques (Powers, 1949). However, the experiments conducted in (Hodson and Mcintosh, 1960; Beaudoin and MacInnis, 1974) showed clearly that porous materials could also be damaged by freezing liquid without volumetric increase during solidification. A micro-ice-lens model has been developed by Setzer (2001) to take into account the water and heat transport during micro-ice-crystal formation. Also based on thermodynamic equilibria of phase change, Penttala derived material freezing deformation by effective freezing stress arising from crystallization pressure (Penttala, 2006). The crystallization pressure of freezing water in pores was detailed by Scherer (1993, 1999). Coussy and Fen-Chong (2005) proposed a pore model, taking into account both viscous water flow and thermodynamic equilibrium between ice and capillary supercooled water, to describe the pore water cryo-suction and stress relaxation during freezing. This model was later developed into a comprehensive thermoporoelastic model for freezing cementitious materials (Coussy, 2005; Coussy et al., 2008).

However, there is not direct experimental verification for this theory. We here try to address the poromechanical framework to the freezing behavior for cementitious materials with specific and defined porosity presented in (Powers and Brownyard, 1947) and compare the predicted results with the experiment ones presented in (Powers and Helmuth, 1953). This paper follows the same thermoporomechanical approach established so far (Coussy, 2005, 2010; Fabbri et al., 2008; Zuber and Marchand, 2004) and investigates particularly the freezing strain of saturated cementitious materials with and without entrained air. To this aim, this paper starts with the thermodynamic descriptions for phase equilibria and phase change for water confined in pores, mechanical constitutive equations are derived from standard poromechanics, and then the mass conservation for water and heat transfer are expressed in terms of pore water pressure and temperature. Using the established model, the freezing strain measurements on cement paste presented in (Powers and Helmuth, 1953) are simulated and concluding remarks are drawn on the basis of the comparison between the simulated and measured strains.

2. Poromechanical modeling

2.1. Ice-water equilibrium in pores

As a saturated porous material is exposed to freezing, the solidification temperature of pore water depends on the "throat" size

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