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Freezing of partially saturated air-entrained concrete: A multiphase description of the hygro-thermo-mechanical behaviour

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ABSTRACT

Even though air-entrained concrete is usually used for concrete structures located in cold climates that are exposed to wet environments, frost damage is frequently detected during inspections. However, it is often hard to assess the extent and severity of the damage and, thus, there is a need for better tools and aids that can complement already established assessment methods. Several studies have successfully shown that models based on poromechanics and a multiphase approach can be used to describe the freezing behaviour of air-entrained concrete. However, these models are often limited to the scale of the air pore system and, hence, hard to use in applications involving real structures. This study proposes a hygro-thermo-mechanical multiphase model which describes the freezing behaviour of partially saturated air-entrained concrete on the structural scale. The model is implemented in a general FE-code and two numerical examples are presented to validate and show the capabilities of the model. The first concerns a series of experimental tests of air-entrained cement pastes, whereas the second aims to show the capability of the model to account for an initial non-uniform distribution of moisture. While the model predictions underestimate the magnitude of the measured strains, the results still show that the model can capture the general freezing behaviour observed in the experimental tests on the structural scale. Furthermore, the results demonstrate that the model is capable of describing freezing induced deformations caused by non-uniform moisture distributions.

1. Introduction

It is well established that a system of appropriately spaced entrained air pores significantly reduces the susceptibility to frost damage in concrete and other cement-based materials (Powers, 1949; Powers and Helmuth, 1953). This effect is essential for structures located in cold climates and exposed to wet ambient conditions, e.g. hydropower dams, road pavements and bridges. Even though such structures are often cast using air-entrained concrete, frost damage is often found during inspections. However, it can sometimes be hard to assess and determine the extent and severity of these, especially if the damage is located in the internal parts of the structure, and not directly visible on the surface. Hence, there is a need for more refined tools and aids, which can complement other existing assessments methods in the effort of establishing the extent and severity of frost damage.

Mathematical models based on thermodynamics and poromechanics have been used in several studies to describe the freezing behaviour of both air-entrained and non-air-entrained concretes and cement pastes (e.g., Bažant et al., 1988; Coussy, 2005). Koniorczyk (2015) applied this type of models on fully saturated materials without entrained air to describe the behaviour of concrete during freeze-thaw cycles, also accounting for the hysteresis effect between ice formation and melting, see also Koniorczyk et al. (2015). The applications to air-entrained materials have often been limited to the analysis of an elementary cell, see Powers (1949), which consists of a single air pore surrounded by a shell of cement paste containing water saturated capillary pores (e.g., Zuber and Marchand, 2004; Coussy and Monteiro, 2008; Zeng et al., 2011; Fen-Chong et al., 2013). Furthermore, Mayercsik et al. (2016) expanded this concept and instead modelled a small system of air pores surrounded by a porous solid, in which they also considered the gradual ice filling of the air pores during freezing. Although these modelling approaches adequately describe the freezing behaviour of air-entrained concrete and cement pastes, they are limited to the scale of the air pore system. In order to use this type of models in structural applications, it is essential to account for the effect of the air pore system on the struc-

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tural scale. However, such models are scarce in the literature. One example, though, is the model derived by Rahman et al. (2016), but they did not explicitly account for the pore size distribution of the air pore system nor the gradual filling of it with ice during freezing. Instead they assumed that the air pore system could accommodate all expelled water from the freezing sites without affecting the spacing of the air pores.

The purpose of this study is to establish a hygro-thermo-mechanical multiphase model that describes the freezing behaviour of air-entrained concretes and cement pastes, which can be used for applications on the structural scale. It utilizes the size distribution of the air pore system to account for a varying spacing factor between the air pores as these are gradually filled with ice during the freezing process. Gel and capillary pores are lumped together and referred to as capillary pores throughout this study and categorized as pores having a radius < 10 μm, whereas all larger pores are considered as air pores (Jennings et al., 2015). The model is limited to cases where all capillary pores are fully saturated with liquid water prior to freezing, i.e. capillary saturation, whereas the air pore system can be unsaturated or partially saturated with water. This limitation can be justified by the findings of Fagerlund (1977) that there exists a certain critical degree of saturation that must be reached before frost damage occurs in a certain concrete mixture. For air-entrained concretes, this value is often found to be higher than the degree of capillary saturation, which means that the air pore system at least must be partially saturated with water.

2. Effect of air pores during freezing

During freezing of concrete and other cement-based materials, ice forms progressively in the porous network, starting from the largest water-filled pores. As the temperature continues to decrease, smaller pores are successively occupied by ice crystals. This propagation of ice in the porous network can be shown theoretically by using the principles of thermodynamics as done by for example Scherer (1993, 1999), but has also been observed in low temperature calorimetry studies of ice formation in concrete (e.g., Sellevold and Bager, 1980; Zuber et al., 2000).

According to Powers hydraulic pressure theory (Powers, 1945), an increased pressure arises at the freezing sites as the excess water, produced by the 9% volume increase of water upon freezing, is expelled into the surrounding pore network. For a fully saturated non-air-entrained material, this hydraulic pressure becomes high and causes cracking if the tensile stress reaches the material strength. However, in an air-entrained concrete, the air pores act as reservoirs in which the expelled water from the freezing sites can enter. The air pressure inside the air pores is approximately equal to the atmospheric pressure, and consequently the expelled water that enters is depressurized and freezes instantaneously. As long as there is enough space for the ice crystals to form inside the air pores, they will also remain at atmospheric pressure (e.g., Powers and Helmuth, 1953; Zuber and Marchand, 2004; Coussy, 2005). As a consequence of this extra space for the excess water, the hydraulic pressure arising at the freezing sites is reduced. However, the magnitude of the pressure depends on the distance from the freezing sites to the air pores, as well as on the permeability of the material and the rate of ice formation. Powers (1949) proposed a spacing factor that is related to this distance, which can be used to estimate the efficiency of an air pore system. There are several other spacing factors available in the literature, some of them, including Powers spacing factor, have been reviewed by Snyder (1998). The review showed that the model proposed by Lu and Torquato (1992) outperformed all other spacing equations but, nevertheless, Powers spacing factor is still widely used and is for example the adopted model for air pore spacing in ASTM C457 (2016). Another important aspect to consider is that the air pores are gradually filled with ice as the temperature decreases. As soon as an air pore is fully saturated with ice, it loses its function as a reservoir for the expelled water, which means that the effective spacing factor of the air pore system increases. This in turn accelerates build-up of hydraulic pressure in the material.

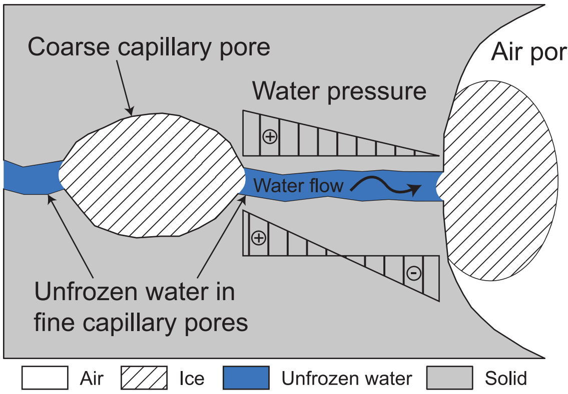

Fig. 1. Conceptual illustration of the effect of the air pores during freezing of concrete. The upper pressure distribution correspond to the case where the air pore solely acts as a reservoir for the expelled water and the lower distribution to the case when it also acts as a cryo-pump. Based on Zeng et al. (2016).

The hydraulic pressure theory alone cannot explain all observations that have been made in freezing tests of concretes and cement pastes. For example, a larger contraction than the pure thermal contraction is usually observed when freezing concrete with a well-distributed air pore system. To explain this, Powers and Helmuth (1953) proposed the theory of microscopic ice lens growth. Concerning the effect of the air pores on these observations, Coussy (2005) explains that these also act as cryo-pumps, meaning that water is sucked into the air pores from the surrounding capillary pores. This pumping effect is a result of the local thermodynamic equilibrium between the ice crystals inside the air pores and the liquid water in contact with these, which requires that the water is depressurized below atmospheric pressure. As a consequence, water flows to the air pores and they, therefore, also act as pumps in the material during freezing. Furthermore, several studies have shown that the degree of water saturation in concrete exposed to free water and subjected to freeze-thaw cycles absorb more water than the same concrete in isothermal conditions (e.g., Sandström, 2010; Rosenqvist, 2016). Also these observations can at least partially be attributed to the cryo-pump effect, since the access to an outside reservoir means that additional water can be sucked into the material. The two effects of air pores in concrete subjected to sub-zero temperatures explained above are conceptually illustrated in Fig. 1. The figure shows a single coarse capillary pore in which ice has formed, which is connected with an air pore through a finer capillary pore still containing unfrozen water. The upper pressure distribution corresponds to a case where the air pore solely acts as a reservoir for the expelled water from the freezing site, whereas the lower distribution corresponds to a case where it also acts as a cryo-pump.

3. Multiphase model for freezing

Concrete is herein considered as a multiphase deformable porous medium consisting of the four phases: liquid water (w), ice (i), gas (g) and solid (s). To describe the behaviour of the multiphase system upon freezing, a set of balance equations for mass, energy and linear momentum must be established. The starting point of the derivation is the general macroscopic balance equations for a generic porous medium derived by Gray and