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Poro-elastic–plastic model for cement-based materials subjected to freeze–thaw cycles

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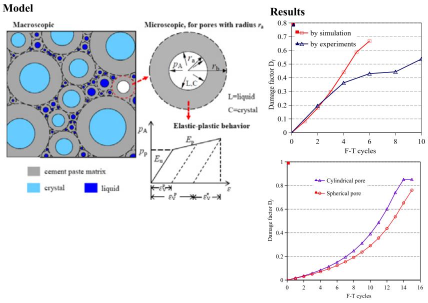
HIGHLIGHTS

- Mechanical behavior of microscopic spherical units is incorporated in the model.
- Changes in pore structure subjected to freezing/thawing are predicted.
- Pore structure and hardness measurements are carried out to verify parameters.
- Influences of pore geometry on the freeze-thaw damage are discussed.

GRAPHICAL ABSTRACT

The macroscopic porous material is assumed to be composed of microscopic spherical units in which frost stresses originated from pores. Considering the elastic–plastic behavior of microscopic units, porosity, pore size distribution and damage factor of cement-based materials after freeze–thaw cycles are predicted.



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ABSTRACT

This paper presents a poro-elastic–plastic model to predict changes in the pore structure and reduction in the mechanical property of cement-based materials when subjected to freeze–thaw cycles. In this model, the macroscopic porous material is assumed composed of a series of microscopic spherical units, thermodynamics of in-pore crystallization and unsaturated poroelasticity are employed to compute the frost stresses originated from pores (i.e., pressure in liquid and pressure in crystals), nonlinear elastic–plastic behavior is incorporated to analyze the irreversible deformation of the microscopic spherical units. Pore structure and hardness measurements are carried out to determine and verify the parameters about elasticity and plasticity. Finally, the proposed model is applied to a cement paste to predict its porosity, pore size distribution and damage factor after a certain number of freeze–thaw cycles, and influences of pore geometry on the freeze–thaw damage are discussed on the hypotheses of cylindrical pores and spherical pores, respectively.

1. Introduction

Frost damage is an important sustainability issue for concrete structures in cold regions. When the cementitious materials are subjected to freeze–thaw (F-T) cycles, internal/surface damage may occur, i.e., internal cracking and surface scaling [1–3].

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Consequently, the service performances of concrete structures are highly affected, such as reduction in the mechanical resistance and in the elastic modulus, increase in the transport properties [4,5]. The intrinsic reason for the durability issue is that F-T cycles altered the intrinsic microstructure of cement-based materials [6–9]. The microstructural changes in hardened cement-based systems after freeze–thaw cycles have been studied by many researchers using a variety of experimental techniques [10–13], and it has been proved that changes in the pore structure are crucial [6,10,13]. Due to the pore characteristics of cement-based material, it can be considered as a porous material with a wide pore size range from nanometers to micrometers [14–17].

The overall mechanical behavior of porous materials subjected to serious environmental actions can be analyzed by a poro-mechanical approach where harmful stresses originating from in-pore pressure, such as crystallization of sea-salts in dry environments and crystallization of ice in wet and cold environments [18,19]. The poro-mechanical approach can provide a comprehensive understanding of the mechanics of confined crystallization within deformable porous materials [18–25]. Using poro-mechanical approach, Scherer studied the response of saturated cement paste to mechanical and thermal strains [21]. Coussy and his co-workers developed a unsaturated poro-elasticity method to predict the mechanical behavior of the porous media accounting for the physics of the confined crystallization of ice [22], and illustrated the role of the pore size distribution and the effect of air voids in the deformation of porous materials subjected to the frost action [23,24]. Zeng et al. investigated the elastic behavior of cement-based porous materials saturated with salt solution under undrained freezing [18,25]. Although the poro-mechanical approach can provide comprehensive characterization of the mechanical behavior of porous materials, most of the studies employed a poro-elastic approach where the porous materials are assumed within elastic limit. In addition, it mainly aimed at the freezing process, while very few consider the irreversible deformation (or irrecoverable damage) of materials after freeze–thaw cycles. Cement-based materials are not ideal elastic solid in reality, irreversible deformation occurs when the stress it experienced reaches a threshold.

Cement-based materials are elastoplastic. After unloading completely, there will be residual deformation (i.e., plastic deformation) [26–31]. Karinski et al. indicated to represent the non-linear elastic–plastic behavior of cementitious composites with a multi-scale approach [27,28]. Chen et al. established a poroplastic damage model to investigate the effects of desiccation on the mechanical behavior of cement-based materials [29]. Yang et al. described the elastoplastic damage behavior of concrete under a wide range of confining pressure and different saturation conditions [30]. Based on elastic–plastic theory and fatigue damage mechanics, Liu et al. proposed a prediction model for uniaxial compressive strength of rocks against freeze–thaw action [31]. It is obvious that a number of elastoplastic models have been developed to study the mechanical behavior of cement-based materials. However, few models incorporate in the materials' elastic–plastic property to investigate the behavior of cement-based materials during F-T cycles.

This study aims to propose a poro-elastic–plastic model for cement-based material to investigate its microstructural changes and damage degree when subjected to F-T cycles. It refers to Coussy's work about unsaturated poro-elasticity at macroscopic and incorporates the plasticity of pore walls at microscopic. Using an initial pore size distribution (PSD) as input, the model can predict changes of PSD of the material under investigation subjected to F-T cycles. In the model, according to thermodynamics of in-pore liquid–crystal transition, the frost stresses originating from pores are computed through a unsaturated poro-elastic approach. According to the nonlinear elastic–plastic assumption of microscopic pore units, the permanent changes in pores resulting from the frost stresses are obtained. Unknown parameters in the model are determined from experiments. At last, the reliability of the model is verified by comparing to experimental data, and influences of pore geometry on the damage of F-T cycles are discussed where spherical and cylindrical pore hypotheses are made.

2. Modeling of changes in the pore structure of cement-based materials after F-T cycles

Frost (or freeze–thaw) damage is closely related to the microstructure of cement-based materials, and freeze–thaw can alter the intrinsic microstructure of materials, especially for the pore structure [6,10]. In this study, an initial input is the pore size distribution of the material. The following assumptions are made:

(1) The process of water/ice phase transition in pores is quasi-static. Thermodynamics of in-pore crystallization is satisfied.
(2) Cement-based materials are considered as porous materials, where the frost stresses come from pore pressure, in terms of pressure in crystals of ice p_C and pressure in liquid p_L. A poro-elastic-mechanical approach is employed to compute p_L and p_C.
(3) Consequences of F-T cycles on the porous material are assumed as the permanent change in the pore structure. An elastic–plastic approach is employed to compute the permanent change of pores at different sizes due to freezing/thawing. After F-T cycles, the elastic porosity can completely recover and the plastic porosity remains.

Based on these assumptions and the pore structure of cement-based materials, the changes in the pore structure after F-T cycles can be simulated. The flowchart of the simulation process is shown in Fig. 1.

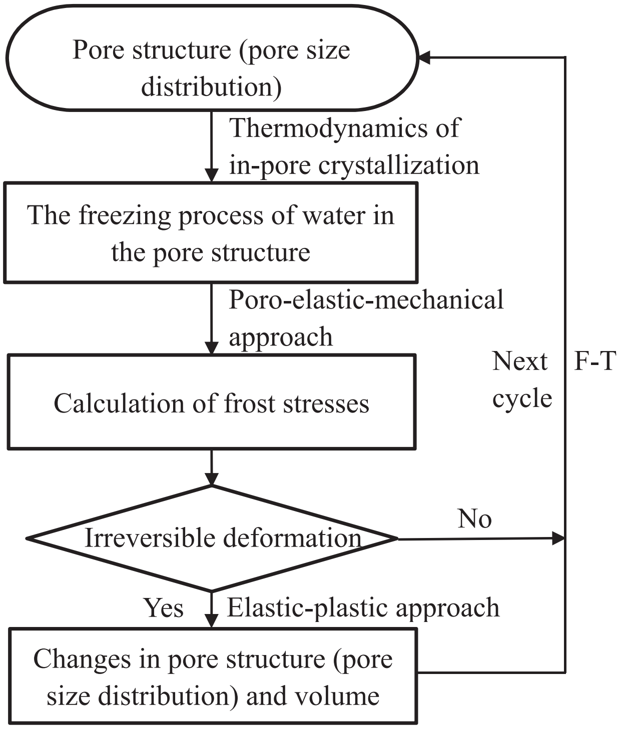

Fig. 1. Flowchart of modeling changes in the pore structure of cement-based materials after F-T cycles.