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A poromechanical model of freezing concrete to elucidate damage mechanisms associated with substandard aggregates

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ABSTRACT

A poromechanical composite model is developed to predict time-dependent stress and strain fields in freezing concrete containing aggregates with undesirable combinations of geometry and constitutive properties. Sensitivity of the stress fields to the aggregate and matrix constitutive parameters is assessed to inform improved concrete design. The model trends presented in this paper are in agreement with experimental results from literature. The model indicates that for both air-entrained and non-air-entrained concrete, destructive tensile stress may be triggered at the aggregate–matrix boundary, with the severity enhanced by the Mandel–Cryer effect. It is determined that high-porosity, low-permeability aggregates are most vulnerable to D-cracking.

1. Introduction

Pavements distressed by expansive aggregate-induced damage often require extensive rehabilitation after 10 years of service [1]. Expansion of aggregates in concrete pavements is often associated with freeze–thaw cycles, which can induce durability cracking (D-cracking) and popouts, as demonstrated by the several research projects sponsored by the state departments of transportation (DOTs) dealing with the topic (see, e.g., [2,3]). D-cracking, caused by freezing and thawing of water saturated concrete, typically appears as a series of closely spaced, crescent-shaped cracks along joints in concrete slabs. This type of damage is a progressive structural deterioration of the concrete that has been linked to certain types of susceptible coarse aggregates [3]. D-cracking occurs parallel and adjacent to longitudinal and transverse joints, intermediate cracks, and the free edges of pavement slabs where concrete is exposed to wet and dry cycles at both the top surface and sides of slabs. According to Stark [4], aggregates that have potential to cause D-cracking are also susceptible to popout. A popout is a conical depression created on the surface of the concrete leaving a fragment of the fractured aggregate particle at the bottom of the cavity with the other part sticking to the apex of the popout cone. While much research has already been performed studying freeze–thaw damage in concrete, the research has thus far focused primarily on empirical or semi-empirical experimental investigations of mechanisms and/or effects on structural capacity. Little work has been done to investigate the role of mechanics and constitutive properties of concrete phases in the formation and growth of damage in concrete due to freezing of aggregates. Poroelastic theory [5,6] has been used successfully to analyze concrete and cement paste characteristics [7–11], and model behavior of cement paste exposed to freezing temperatures [12–15], but has not been applied to the problem of freezing aggregates within concrete. Thus, the primary focus of this research is to elucidate the freeze–thaw damage mechanisms in concrete due to substandard aggregates in order to theoretically validate and mechanistically explain experimental findings in the literature. A simplified poromechanical model is used to predict the destructive tensile stress created in the aggregate and/or cement paste or mortar matrix associated with the freezing process.

Various studies have established that the pore characteristics of aggregates significantly influence the frost resistance of concrete [3,4,16]. According to Verbeck and Landgren, low-porosity and low permeability aggregates, typical of quartzites, marbles, and traprocks are strong enough to withstand freezing distress. However, high-porosity but low-permeability aggregates, typical of cherts with a fine pore structure, can exhibit failure due to high internal pressures within the aggregates [16]. In the same study, it was estimated that the peak pore pressure generated in low-permeability chert may be 100 times greater than in the high-permeability dolomite. Later, Kaneuji established a correlation between the pore structure of aggregates and concrete freeze–thaw durability, and attributed low aggregate durability to high pore volume and smaller median pore diameter [17]. It was noted in the study, however, that aggregate pores with radii less than 4.5 nm did not appear to contribute to freeze–thaw durability problems. Mehta and Monteiro associated D-cracking with coarse aggregates that contain high pore volume in the narrow pore size range (0.1 to 1 μm) [18]. Scherer also suggested that crystallization stress is lower for larger pores and lower crystal-pore wall contact

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angles [19]. However, as stated by Verbeck and Landgren, the high-porosity, high-permeability aggregates with coarse pore structure – if covered by mortar – can cause failure due to the high external pressure built up in the matrix [16]. Examples of such aggregates are limestones, dolomites, and sandstones. In this case, failure depends on the rate of temperature drop and the distance water must travel to find an escape boundary [16]. Several studies suggest that reducing the maximum size of D-cracking susceptible aggregate particles improves the freeze–thaw durability of concrete and slows down the rate of development of D-cracking [2–4,20]. Research by Verbeck and Landgren indicates that aggregates with higher permeability can include larger sizes without inducing freeze–thaw damage [16]. Therefore, smaller size aggregates with low porosity and high permeability perform better than the larger ones with respect to resistance to D-cracking.

As reported by Alexander and Mindess [21], the importance of aggregate coefficient of thermal expansion (CTE) to the performance of concrete under thermal cycling is twofold: first, it influences the CTE of the concrete and hence thermal movements in structures; and second, it may contribute to the development of internal stresses if there are large differences between the CTEs of the various constituents. Callan stated that the durability of the concrete may be low where the difference between the CTEs of coarse aggregate and cement paste is large, and the maximum stress in that case occurs at the aggregate–matrix interfacial boundary [22]. Therefore, it is suggested that the difference between CTEs of coarse aggregate and matrix in which they are embedded should not exceed about $5.4\times10^{-6}\,°\mathrm{C}^{-1}$ [22].

2. Model

In this study, a model concrete sphere is considered with a coarse aggregate core of radius R_i embedded inside a mortar or cement paste matrix shell (throughout this report, the term “aggregate” and “matrix” will be used to represent the coarse aggregate core, and the paste or mortar shell, respectively) of outer radius R_o, as shown in Fig. 1. An elastic model incorporating free strains is first developed based on the classical elastic theory proposed by Timoshenko and Goodier [23]. It is then extended to include poromechanical constitutive properties based on the theory developed by Biot [5] and discussed by Coussy [6,13], and Coussy and Monteiro [14,15]. The elastic case considering a general ‘free strain’ is presented in Section 2.1, and then specifically refined for the case of unsaturated poroelasticity in Section 2.2. Throughout this paper, the following sign convention is used:

- Pore pressure (liquid or crystal) is positive for compression and negative for suction or tension.
- Stress and strain are positive for tension and negative for compression.
- Change in temperature, $\Delta T = T_m - T$, is positive for cooling and negative for heating, and measured with respect to the melting temperature T_m. Here, T is the actual temperature.

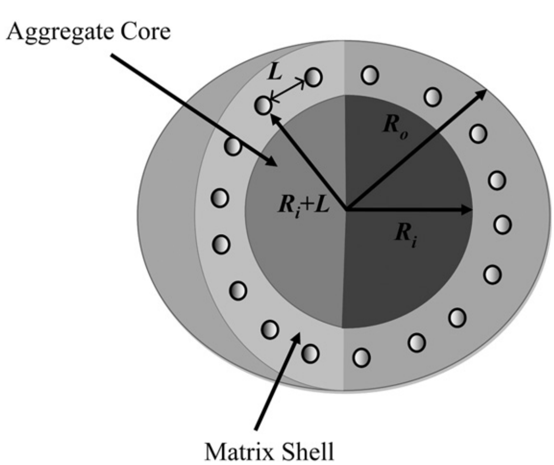

Fig. 1. Geometry of the proposed model representing a coarse aggregate core of radius R_i embedded in a cement paste or mortar matrix shell of outer radius R_o. In case of air-entrained concrete, uniformly distributed air bubbles are considered with a spacing of L.

2.1. Elastic materials

Determination of the stress and strain components given in this section follows much of Timoshenko and Goodier's work [23], with the only exception being that thermal strain is replaced by the more general ‘free strain’. A simple case of a temperature symmetrical with respect to the center, and a function of radius, r, is considered. On account of the spherical symmetry, the non-zero radial deformation (u_r) of the aggregate (denoted by superscript a) along with the radial (subscript r) and two tangential (subscripts θ and ϕ) stress (σ) and strain (ε) components in the principal directions are given by

$$u_r{}^a = \frac{(1+\nu^a)}{(1-\nu^a)}\frac{1}{r^2}\int_{r=0}^{r=r}\varepsilon_f{}^a r^2 dr + C_1{}^a r, \tag{1}$$

$$\varepsilon_r{}^a = -2\frac{(1+\nu^a)}{(1-\nu^a)}\frac{1}{r^3}\int_{r=0}^{r=r}\varepsilon_f{}^a r^2 dr + \frac{(1+\nu^a)}{(1-\nu^a)}\varepsilon_f{}^a + C_1{}^a, \tag{2}$$

$$\varepsilon_\theta{}^a = \varepsilon_\phi{}^a = \frac{(1+\nu^a)}{(1-\nu^a)}\frac{1}{r^3}\int_{r=0}^{r=r}\varepsilon_f{}^a r^2 dr + C_1{}^a, \tag{3}$$

$$\sigma_r{}^a = -6K^a\frac{(1-2\nu^a)}{(1-\nu^a)}\frac{1}{r^3}\int_{r=0}^{r=r}\varepsilon_f{}^a r^2 dr + 3K^a C_1{}^a, \tag{4}$$

and

$$\sigma_\theta{}^a = \sigma_\phi{}^a = 3K^a\frac{(1-2\nu^a)}{(1-\nu^a)}\frac{1}{r^3}\int_{r=0}^{r=r}\varepsilon_f{}^a r^2 dr - 3K^a\frac{(1-2\nu^a)}{(1-\nu^a)}\varepsilon_f{}^a + 3K^a C_1{}^a. \tag{5}$$

where, K and ν are the bulk modulus and the Poisson's ratio of the isotropic linear elastic porous material, respectively and ε_f is the free strain and a function of pore pressure and temperature.

For paste or mortar matrix, we write u_r, ε_r, ε_θ, σ_r, and σ_θ with superscript p as

$$u_r{}^p = \frac{(1+\nu^p)}{(1-\nu^p)}\frac{1}{r^2}\int_{r=R_i}^{r=r}\varepsilon_f{}^p r^2 dr + C_1{}^p r + \frac{C_2{}^p}{r^2}, \tag{6}$$

$$\varepsilon_r{}^p = -2\frac{(1+\nu^p)}{(1-\nu^p)}\frac{1}{r^3}\int_{r=R_i}^{r=r}\varepsilon_f{}^p r^2 dr + \frac{(1+\nu^p)}{(1-\nu^p)}\varepsilon_f{}^p + C_1{}^p - \frac{2C_2{}^p}{r^3}, \tag{7}$$

$$\varepsilon_\theta{}^p = \varepsilon_\phi{}^p = \frac{(1+\nu^p)}{(1-\nu^p)}\frac{1}{r^3}\int_{r=R_i}^{r=r}\varepsilon_f{}^p r^2 dr + C_1{}^p + \frac{C_2{}^p}{r^3}, \tag{8}$$

$$\sigma_r{}^p = -6K^p\frac{(1-2\nu^p)}{(1-\nu^p)}\frac{1}{r^3}\int_{r=R_i}^{r=r}\varepsilon_f{}^p r^2 dr + 3K^p C_1{}^p - \frac{(1-2\nu^p)}{(1+\nu^p)}\frac{6K^p}{r^3}C_2{}^p, \tag{9}$$

and

$$\sigma_\theta{}^p = 3K^p\frac{(1-2\nu^p)}{(1-\nu^p)}\frac{1}{r^3}\int_{r=R_i}^{r=r}\varepsilon_f{}^p r^2 dr - 3K^p\frac{(1-2\nu^p)}{(1-\nu^p)}\varepsilon_f{}^p + 3K^p C_1{}^p + \frac{(1-2\nu^p)}{(1+\nu^p)}\frac{3K^p}{r^3}C_2{}^p. \tag{10}$$