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Assessing the efficiency of entrained air voids for freeze-thaw durability through modeling

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ABSTRACT

This paper models concrete's resistance to cyclic freeze/thaw using the solution of the poromechanical problem, which describes the freezing of an individual air void surrounded by hydrated cement paste. This enables calculation of the pore pressures and the volume of water expelled into the air void upon freezing. The model was applied to concrete specimens with entrained air voids with polydispersity in size, and subjected to water absorption, thereby simulating a cyclic freeze/thaw laboratory test. The mean and maximum pore pressures obtained by the simulation were compared to a series of experimental tests per ASTM C666, and results suggest the model may be used to predict satisfactory durability in the laboratory test. This framework may be useful tool to study the effects of porespace and entrained air void size distribution on concrete's freeze/thaw durability. Furthermore, it allows for a theoretical basis for assessing the entrained air void system parameters.

1. Introduction

A system of tiny, well-dispersed entrained air voids has long been understood to provide saturated concrete with a means of resistance to sustained damage during cycles of freezing and thawing. Pioneering work in the scientific study of air entrainment was done by Powers in the 1940s [1,2], who proposed the hydraulic pressure model. Powers theory proposes that ice forms in the capillary pores (i.e., pores ranging in size from around 10–10,000 nm) within the hydrated cement paste (HCP) matrix during freezing. A hydraulic pressure arises as water is expelled from the freezing sites in the pores into the entrained air voids in order to account for the increase in volume due to ice formation. If the tensile strength of solid matrix cannot accommodate the associated hydraulic pressure, cracks develop. Scherer studied the crystallization pressure of freezing water [3], and numerous studies investigated the hydraulic pressure theory by a thermoporomechanical approach [4–7].

In addition to pressure theory, Powers also proposed a spacing factor, $\bar{L}$, related to the fraction of paste within some distance of an air void (and not, despite the popular misconception, the distance between air voids [8]), as well as a means of calculating $\bar{L}$ from petrographic analysis of plane polished sections of hardened concrete. Powers tentatively concluded that concrete should withstand his laboratory freeze/thaw test if $\bar{L} < 250$ μm. This approach was adopted by as ASTM C457 [9] in 1960 (in what follows, $\bar{L}$ is referred to as the ASTM spacing factor; other literature refers to it as the Powers spacing factor). Fig. 1 shows the assumptions that are made in the determination of $\bar{L}$. While the actual entrained air void size system is a polydisperse sphere system resembling Fig. 1a, the ASTM standard assumes that the entrained air void system consists of monosized and regularly spaced porosity, resembling Fig. 1b. The spacing factor $\bar{L}$ is calculated as the distance from the center of a cubic cell to the periphery of an air void, as in Fig. 1c (alternatively, the minimum distance between the peripheries of two opposite-corner entrained air voids is $2\bar{L}$).

The potential role of concrete quality in recent failures in both the accelerated laboratory and field performance has led to renewed interest in assessing the quality of air entrainment [10]. $\bar{L}$ is also sensitive to outliers; for example, see chapter 4 of [11]. The results of laboratory tests have challenged the efficacy of the ASTM C457 spacing factor [12]. Alternative spacing factors have been proposed by Philleo [13], Attiogbe [14], and Pleau and Pigeon [15]. Each of these spacing factors was studied in [8], where they were all found to insufficiently estimate statistical parameters for a theoretical system of entrained air voids. A key finding of [8] was that the theoretical nearest-surface model by Lu and Torquato [16] had the potential to outperform existing statistics of the entrained air void system and spacing. In [17], Mayercsik et al. argued that advances in technology and theory since the mid-twentieth century presented a potential opportunity to improve upon methods for assessing the quality of air entrainment in concrete. Drawing on the nearest-surface model, a novel spacing factor, $\overline{M}$, was proposed.

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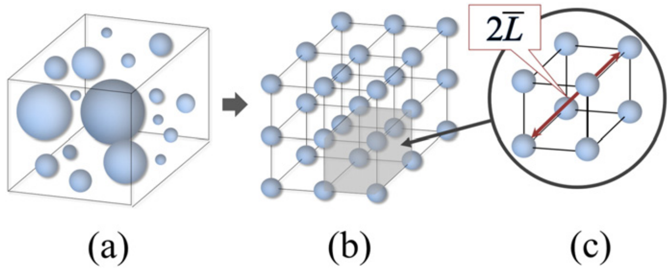

Fig. 1. Schematic showing (a) a representation of polydispersity typical of entrained air void systems in cementitious materials and (b) assumptions of the air void structure per methods provided in ASTM C457, with (c) definition of $\overline{L}$ shown for a single cell.

The formulation of $\overline{M}$ takes into account the full three-dimensional size distribution of the entrained air voids which is reconstructed directly from two-dimensional plane, polished sections of concrete. Results in [17] suggest $\overline{M}$ has the potential to outperform $\overline{L}$.

The objective of this study is to give $\overline{M}$ a theoretical treatment based on poromechanical considerations. This frees $\overline{M}$ from purely empirical limits based on observations from laboratory performance, and instead allows any theoretical bounds on $\overline{M}$ to be based on the mechanics and physics of porous solids. Experimental results obtained by procedure A of ASTM C666 (described subsequently) are used as comparison. While studies have applied thermoporoelasticity to the paste in the periphery of a single air void [7,4], this paper models systems of air voids. In so doing, the effect of polydispersity is captured. For example, in [5], the periphery of paste surrounding a single air void was assumed to be equal to the maximum boundary set on $\overline{L}$, while this contribution outlines a first-order technique to determine the sphere of influence of each entrained air void.

ASTM C666 describes two relatively rapid laboratory procedures (procedures A and B) to determine a concrete's resistance to cyclic freezing and thawing [18]. In procedure A, the test is conducted on concrete prisms which are fully immersed in water and subjected to a number of freeze/thaw cycles (typically 300 cycles), while in procedure B, the samples are frozen in air and thawed in water. Procedure A has the advantages over procedure B of avoiding the displacement of water during cycles, ensuring a high degree of saturation, and reducing the minimum amount of water to be cooled or heated. Therefore, procedure A tends to be more common than procedure B [11]. Both procedures specify that the dynamic Young's modulus should be measured periodically (not exceeding 36 cycles between measurements) throughout the test. A durability factor (DF) is calculated as the ratio between the current dynamic Young's modulus and the initial dynamic Young's modulus. The standard advises that measurement should terminate if the dynamic Young's modulus drops below 60% of its initial value (i.e., DF < 60%). Cyclic freeze/thaw *failure* is ill-defined by the ASTM C666 standard; however, admixture standards ASTM C260, ASTM C494/C494M, and ASTM C1017/C1017M-07 offer guidance, specifying that the ASTM C666 durability factor of a mixture with and without admixture should not differ by >20%. This suggests the critical durability factor should be between 70% and 80%. In this study, failure was determined in this test whenever a specimen's current dynamic Young' modulus decreased below 80% of its initial dynamic Young' modulus.

In this contribution, the damage evolution is hypothesized to arise from tensile stresses which develop due to crystallization pressures acting on the paste. The tensile stresses arise due to freezing, and result in local cracking of the solid hydrated cement paste matrix. A good relationship was found in [19] between the amount of cracks on polished sections of concrete exposed to freeze/thaw cycles and the measured durability factor of those concretes in the rapid freeze/thaw test. The analytical model in this contribution follows the theory developed by Coussy [4,5]. As a volume of paste freezes, the liquid in the pore space reaches pressure above atmospheric pressure. Entrained air voids limit this pressure buildup in the still unfrozen pore solution during freezing by acting as expansion reservoirs. Liquid water entering the entrained air void is no longer confined and instantly freezes. Ice in the air void is considered to remain at atmospheric pressure. Therefore, liquid in contact with the forming ice crystals must be at a pressure lower than that of the ice (i.e., lower than the atmospheric pressure) to satisfy thermodynamic equilibrium between the liquid water and the ice crystals. This causes liquid at a distance to be sucked toward the entrained air void. This suction will continue as long as the air void is not completely filled. It is noted that this suction causes the entrained air void to contract, as was discussed in [5] and observed experimentally in [20]. However, the magnitude of this contraction is considered a second-order effect when calculating the total volumes of entrained air voids after freezing, and has been neglected in this analysis.

It has been observed that water will continue to migrate from the surroundings into the concrete sample over time (and thus filling the air voids) when the concrete is immersed under water. Extensive work by Fagerlund [21] provides a framework in which to model this observation. The macropores (i.e., pores between 50 and 10,000 nm in throat diameter) will fill quickly due to capillary action. The entrained air voids in a concrete specimen submerged in water will not stay air-filled, but will take up water by a slow air dissolution-diffusion process. In this contribution, this process will be referred to as "absorption." Therefore, the entrained air voids in concretes undergoing ASTM C666 testing are likely to absorb water over time, particularly when using procedure A. This absorption may also contribute to damage as progressively larger entrained air voids absorb water, thereby losing their twofold efficiency as expansion reservoirs and cryopumps, and becoming ineffective. These two mechanisms are described in Section 2, where Section 2.1 describes the mass conservation and flow problem used to develop the evolution of stresses which develop in the periphery of entrained air voids during freezing, and Section 2.2 describes the absorption of water over time. Section 3 presents an experimental study of concretes exposed to freeze/thaw cycling per ASTM C666, procedure A. Section 3 includes relevant measurements of the entrained air void system size distribution and spatial arrangement parameters. Section 4 outlines a technique to apply the theoretical modeling of Section 2 to the systems of entrained air voids in Section 3. Results are presented in Section 5.

2. Mechanisms

This section presents an overview of the mechanisms by which stresses induced by freeze-thaw cycles are assumed to evolve over time in the "shell" surrounding entrained air voids: hydraulic pressure and absorption. How those two mechanisms interact will be presented in Section 4.

2.1. Hydraulic pressure

Powers hypothesized in [2] that water held in capillary pores must migrate toward the entrained air voids during freezing in order to avoid damage. This section presents a more robust treatment of the hydraulic pressure problem, in the spirit of the work presented by Coussy in [5].

Here, the problem to be solved is that of a spherical air void of radius R surrounded by a spherical shell of HCP of thickness L, modeled as a homogeneous continuum (see Fig. 3a). The porous solid surrounding the entrained air void consists of a solid matrix and porespace that is completely saturated with liquid water at time t_0, as in Fig. 2b. As time increases and temperature decreases at a constant cooling rate, ice crystals begin to form in larger pores, as depicted in Fig. 2c. Temperature is decreased at a constant cooling rate, down to −18 °C. The cooling rate is adapted from ASTM C666, which prescribes that lowering the temperature from 4 °C to −18 °C should be conducted in not <2 h and