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A probabilistic technique for entrained air void analysis in hardened concrete

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ABSTRACT

A novel method that utilizes the lineal-path function to ascertain a probability density function for the three-dimensional size distribution of entrained air voids directly from plane polished sections of hardened concrete is proposed. The results then treat the spacing factor in terms of a probabilistic maximum distance from a random point in the cement paste matrix to the periphery of an air void, where air voids are treated as a polydispersed sphere system. The model was applied to concretes with various air entrainment admixture types and dosages. The results suggest that the model may offer a better assessment of the system for use in assessing durability and studying admixtures, as well as providing a new tool for spatial characterization of heterogeneous and porous materials.

1. Introduction

Discovered serendipitously in the early twentieth century, air entrainment is hailed as concrete's protector against damage in cold weather. While air entrainment is crucial for ordinary concrete's resistance to damage during cycles of freezing and thawing and salt scaling, the potential role of concrete quality in recent failures in both the accelerated laboratory test and field performance has led to renewed interest in assessing the quality of air entrainment [1–4]. In particular, questions have been raised about the quality of current metrics for assessing air entrainment [5]. Currently, the quality of an entrained air system in concrete is quantified by specific surface, void frequency, and spacing factor ($\bar{L}$). According to ASTM C457:

> …of the parameters determined with this test method … $\bar{L}$… is generally regarded as the most significant indicator of the durability of the cement paste matrix to freezing and thawing exposure of the concrete. The maximum value of the spacing factor for moderate exposure of the concrete is usually taken to be 0.20 mm [0.008 in.].

Based on the pioneering work of Powers [6], this approach has been used for five decades, having first been adopted by ASTM in 1960.

With advances in image analysis [7] and improvements in understanding of the mechanisms of air entrainment in concrete [8] and role of air entrainment in freeze/thaw damage mitigation [9,10], there seems a potential opportunity to improve upon or at least refine methods for assessing the quality of air entrainment in concrete. The size of spheres is assumed to be uniform, as is their spacing. Since the spacing factor is based on these assumptions and averaged data rather than the actual dimensional and spatial distributions of these features, it is sensitive to outliers, creating the problem of arbitrary deletion of "large" air voids during petrographic analysis [11,12]. Some recent research has examined the air entrainment characteristics of newer air entraining admixtures using ASTM C457 [9,13], thereby studying modern materials with dated techniques. Therefore, the objective of this research is to integrate microstructural statistics and image analysis to derive an improved spacing factor — one based on the reality of the distance water must migrate to reach a void site.

2. Model overview

ASTM C457 [14] describes methods to quantify parameters associated with the susceptibility of the paste portion of concrete to freeze/thaw damage. The standard assumes that the spacing factor is calculated for a system with monosized and regularly spaced porosity, resembling Fig. 1(b). Mathematically, the system is described by an ensemble of average-sized voids with an average spacing. In reality, the spatial and size distribution of entrained air voids is more likely represented by Fig. 1(a) than Fig. 1(b). With this understanding, there are opportunities to improve upon the descriptors used to assess quality of air entrainment in cement-based materials by considering them as irregularly spaced sphere of multiple sizes (polydispersed spheres), as proposed herein. Alternative spacing factors have been proposed by Philleo [15], Attiogbe [16], and Pleau and Pigeon [17]. In both [15] and [17], the spatial arrangement of the entrained air voids is assumed to follow a Hertz

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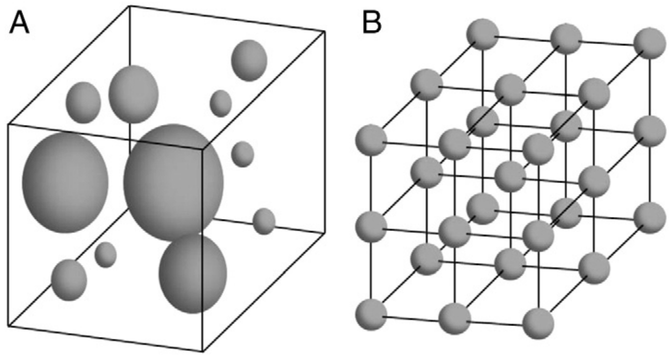

Fig. 1. Schematic showing (A) a representation of polydispersity typical of entrained air void systems in cementitious materials and (B) assumptions of the air void structure per methods provided in ASTM C457.

distribution. This suggests that the arrangement follows a Poisson process, which is only true if the spheres have zero radius. In [16], the air voids are assumed to follow a Gamma distribution with parameters related to the mean diameter and specific surface area of the spheres. However, the procedure in [16] did not accurately estimate any parameter of a simulated air void system when tested in [5]. Further, none of the aforementioned methodologies measure the size distribution directly. (For a detailed comparison of these factors, where they are shown to be unsatisfactory, see [5]).

2.1. Background

The nearest surface (NS) function provides a statistical description of the spatial arrangement between any point in the paste and its proximity to the surface of a nearby sphere (in this case, an air void). For the case of monodispersed spheres (a system of spheres all of a constant radius R), NS functions contain essentially the same information as "nearest-neighbor distribution" (NND) functions that describe the spatial arrangement between a point in the paste and the proximity to a nearest particle centroid (in this case, center of an air void) and that gives the probability of finding a point's nearest-neighbor within a shell of radius r to $(r + dr)$ from a reference point. If all particles in a system are of uniform size – that is to say the particle size distribution (PSD) is a constant – the probability then may be described by a nearest-neighbor distribution function. However, entrained air voids exist in concrete as a polydispersed sphere system, and such a monodispersed model should be viewed as an inferior descriptor even from a physical sense.

Fig. 2 illustrates the difference between a nearest-surface function and a nearest neighbor (in this case, nearest centroid) distribution function for a material with polydispersed spheres. Let point A be a random point in three-dimensional space. Let point B' lie on the surface of the sphere

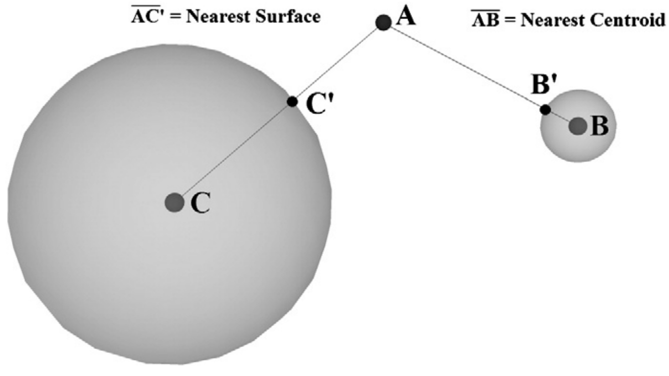

Fig. 2. Local environment about point A, elucidating the need to favor a nearest-surface function over a nearest-centroid function for describing the quality of an entrained air void system.

centered at point B at the location where line $\overline{AB}$ intersects the sphere's surface (C' is defined in kind). As line $\overline{AB} < \overline{AC}$, it defines the nearest-centroid to point A. However, as shown for the case in Fig. 1, line $\overline{AC}'$ defines the nearest-surface to point A. The nearest surface, then, is proposed to be a more appropriate descriptor of the quality of a polydispersed entrained air void system. Water is thought to move through the pore space in the cement paste to the *surface* of an air void, not to its centroid [18].

Lu and Torquato [19] first derived equations, which will be discussed in detail in Section 2.3, to describe a nearest-surface distribution for a polydispersed sphere system. The model relies on three important parameters describing the polydispersed sphere system:

1. The volume fraction of spheres, ϕ_2
2. The number density of spheres, ρ_v
3. The first three moments of the size distribution, $\langle R \rangle$, $\langle R^2 \rangle$, and $\langle R^3 \rangle$.

The following section describes a method to obtain these parameters. However, first, it is useful to describe the inherent challenge in representations of three-dimensional structures from two-dimensional data.

When sectioning cuts through a polydispersed sphere system, some large voids will be planed through their extrema, while others will be planed through cross-sections near their equators. The fundamental problem in the analysis is accounting for the fact that two circles may appear the same but come from very differently sized spheres, as illustrated by Fig. 3. For example, the two circles within the dashed box in Fig. 3 are indistinguishable from each other, despite the fact that the upper circle is cut from a much larger sphere than the lower circle. Because of the inherent challenge in reconstructing three-dimensional information from two-dimensional sections, a statistical approach is required.

2.2. Entrained air void size distribution

One classical approach to overcome this is a Saltykov method [20], or variation upon it [21], which has been used to characterize other two-phase heterogeneous materials with spherical inclusions. Saltykov presented a solution to finding the number density of spheres per unit volume by discretizing Wicksell's solution to unfolding problems of sphere size distributions. Spheres are divided into k size classes and subtracting out the number of circles counted in each size class that are likely to belong to spheres of larger size classes. However, the error magnification is

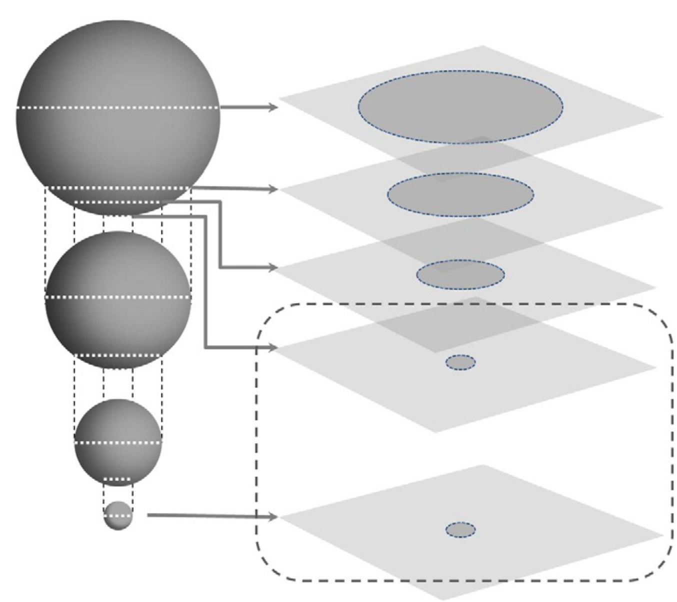

Fig. 3. Illustration of two-dimensional cuts through three-dimensional objects demonstrates that distinguishing information between the circles in the dashed-line enclosure is lost.