Construction and Building Materials 152 (2017) 467–483

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Measurement of air void system in lightweight concrete by X-ray computed tomography

Haizhu Lu [a], Eugene Alymov [b], Sanjay Shah [b], Karl Peterson [a,*]

[a] *Univ. of Toronto, Dept. of Civil Eng, 35 St. George St., Toronto, ON M5S 1A4, Canada*
[b] *Shawcor, 25 Bethridge Road, Toronto, ON M9W 1M7, Canada*

HIGHLIGHTS

- An active contour approach is used to inform the selection of appropriate thresholds.
- A spherical solidity parameter is used to discern between voids in paste/aggregate.
- A method is provided to unite size distributions collected at different resolutions.

ARTICLE INFO

Article history:
Received 4 March 2017
Received in revised form 28 June 2017
Accepted 29 June 2017

Keywords:
Concrete
Air void
X-ray computed tomography
Active contour line
Power law

ABSTRACT

An industrial lightweight concrete developed for pipe insulation is characterized using X-ray computed tomography to determine the size distribution of air voids within the paste fraction. Strategies to address practical difficulties are presented, particularly discerning air voids in paste from air voids within aggregate, and combining air void size distribution data collected at different resolutions. To address the first issue, a step-wise approach was employed to reduce the problem to a series of easier-to-solve two-phase grayscale threshold problems. The first step isolates a significant number of light weight aggregate particles on 2D slices using an active contour line approach and an effective threshold identified to discern between air void and solid voxels. The threshold is applied globally to the 3D data set, and the air void voxels removed. Next, a significant number of rectangular regions of interest from 2D slices are used to identify a second threshold between the solid portions of the lightweight aggregate and the paste. Finally, a 3D shape based criterion is used to isolate air voids in paste. Given the trade-off between resolution and sample size, it is necessary to conduct multiple scans using different resolutions and sample diameters in order to cover the full range of the air void size distribution. A power law curve is used to unite distributions collected at different resolutions.

1. Introduction

The term 'lightweight concrete' encompasses a variety of types used in a variety of applications but with one common underlying theme: the inclusion of air within the mixture. The inclusion of air is usually accomplished through either one, or some combination, of the following approaches: aeration of the paste fraction, inclusion of lightweight aggregate (LWA), or the omission of fines from the aggregate gradation [1]. The particular lightweight concrete sample examined here is intended for insulative coatings on pipes, and achieves its lightweight status through a combination of expanded-glass LWA, hollow glass microspheres, and entrained and entrapped air within the cement paste fraction. The distinction between entrained versus entrapped air is somewhat ambiguous, but generally made on the basis of size, with air voids ≥1 mm in dia. considered entrapped, and air voids between 0.05 and 1 mm considered entrained [2]. For the purpose of discussion, air voids within the LWA and air voids within the hollow glass microspheres are hereafter referred to collectively as 'air voids in aggregate', and the entrained or entrapped air voids within the hardened cement paste are hereafter referred to as 'air voids in paste.' Since LWA and hollow glass microspheres are added in known quantities to the mixture, only the air voids in paste remain as unknown entities. The bulk content (vol%) of the air voids in paste can be quickly and easily determined either gravimetrically through unit weight measurement if the constituent densities and mixture design are known, or volumetrically with a specialized air meter [3,4]. However, obtaining a measurement of the size distribution of the air voids in paste is more challenging. The size distribution of air voids

* Corresponding author.
E-mail address: karl.peterson@utoronto.ca (K. Peterson).

http://dx.doi.org/10.1016/j.conbuildmat.2017.06.180

in paste is usually measured using a stereological approach involving an optical microscope examination of a polished two-dimensional (2D) cross-section through the hardened concrete [5]. The use of X-ray computed tomography (CT) for reliable and routine measurement of air voids not only provides an alternative means of measurement, but also presents a unique advantage with its capacity to capture the exact three dimensional (3D) location of all objects of interest, and derive air void parameters not available to traditional 2D test methods. However, some barriers must be overcome before X-ray CT can be used in a practical manner for the measurement of air void parameters. For example, the issues of how to distinguish entrained air voids in paste from voids in aggregate, how to reliably separate air-void clusters, what volume of sample that can be treated as representative volume element (RVE), and what error propagations could arise from image processing techniques, all remain areas of active research. This study addresses some of these issues as applied to lightweight concrete.

The broad topic of pore space in concrete covers everything from nano-sized gel pores, nano to micro-sized capillary pores, and micro to macro-sized entrained and entrapped air voids, as well as cracks. While all of these categories of porosity have been studied using X-ray CT methods, given the topic of this paper, only the research more closely related to the field of air void characterization warrants further discussion.

1.1. X-ray CT air void characterization in concrete

Pixels within digital images are usually indexed with a numerical value corresponding to reflectance or other physical properties. For X-ray CT, this value (the CT Number) is related to X-ray attenuation within the material. However, the scale for this number is usually equipment dependent. For a convenient comparison of measurements from different equipment, a more practical unit called the Hounsfield Unit (HU) is often used. It is based on a linear transformation of the original linear attenuation coefficient. Values for HU collected at different scanning energies can be found for selected elements, compounds, and mixtures that are of radiological interest in databases [6]. In cases where the linear X-ray attenuation coefficient of a measured material and the machine-specific conversion factors from CT Numbers to HU are available, objects made of a known material can be easily identified. As the aforementioned conveniences are not always available, the approach has seen only limited use as applied to cement-based materials [7,8]. More often, methods purely taking advantage of the differences of grayscale intensity among phases are employed.

Weise et al. were the first to explore the potential for air void characterization using an industrial cone beam micro X-ray CT (μCT) that obtained 20 μm resolution images from an 8 mm dia. hardened mortar cylinder [9]. Although quantitative measurements were never made, they demonstrated the capability to discern air voids with diameters on the order of 100 μm. Since then, quantitative μCT measurements of bulk air content in concrete have become commonplace in the literature. However, the quantification of the size distribution or spatial distribution of air voids, has received less attention.

Cnudde et al. achieved the isolation of air voids in concrete through a manually-selected dual grayscale threshold approach [10]. The diameter of the largest voxelized sphere that could be contained within each individual air void was used as a measurement of the air void size to obtain an air void size distribution. Kim et al. were the first to compute Powers' spacing factor ($\bar{L}$) in air entrained cement paste samples using μCT [11]. $\bar{L}$ is the most commonly used geometrical parameter to describe the air void spatial distribution, and approximates a typical distance between points in the paste to the nearest air void [12]. Given the simple binary system of paste and air voids, Otsu's method of threshold determination was sufficient to discern the two phases as based on the grayscale X-ray intensity histogram [13]. After isolating air voids in the 3D reconstructed image Kim et al. distributed traverse lines over a series of extracted 2D cross-sections to determine $\bar{L}$.

Subsequent work by Yun et al. went one step further by utilizing randomly oriented traverse lines projected through 3D reconstructed images of mortars to obtain values for air content and $\bar{L}$, with the calculation of $\bar{L}$ based on values of paste content obtained from the mix design [14]. Both Kim et al. and Yun et al. also used the 3D reconstructed images to obtain air void size distributions based on the diameters of spheres that would have the same volumes as the corresponding air voids. They termed this value the 'equivalent void diameter.' Similar measurements of air void distribution were also made by Bernardes et al. and du Plessis et al., but within the context of the influence of sampling size and resolution [15,16]. Bernardes et al. make no mention of the methodology employed to isolate the air voids, and instead focus on the influence of the regions of interest (ROIs) used to sample 2D circular cross-sections through their 3D reconstructions of 20 mm dia. mortar cylinders [15]. Although never defined explicitly, the air void size distribution was expressed by the mean diameter, presumably derived from the diameters of circular intercepts of air voids intersected by the 2D cross sections. du Plessis et al. explored the influence of scan resolution and collection time on measured air void size distributions [16]. Air voids were isolated by the initial selection of the central threshold value between the grayscale histogram peaks that represented the solid and air void phases, followed by fine-tuning through manual threshold selection. du Plessis et al. then used the 3D reconstructed images to obtain air void size distributions based on volume.

Schock et al. performed scans collected at two different accelerating voltages [17]. Using this approach, the grayscale intensities for the paste, aggregate, and air void phases were sufficiently distinct to allow for manual selection of appropriate threshold levels to isolate the three phases. Voxels classified as air void, but surrounded by voxels classified as aggregate, were reclassified as aggregate and excluded from subsequent spatial calculations. Air voids composed of <8 voxels were also excluded. Finally, air voids with a sphericity of <0.85 were excluded, with sphericity defined as the ratio of the surface area of a sphere with a volume equivalent to the object to the surface area of the object [18]. For their computations of volume and surface area, all air voids were approximated as ellipsoids based on the principal and semi-principal axes.

The size and spatial distribution of air voids has also been well-explored within the context of providing inputs for finite element and other numerical modeling [19–25]. With few exceptions, minimal effort is spent describing the specific methodologies used to delineate the phases and measure the air void size distributions. In most cases, grayscale thresholding was performed either manually or by Otsu's method, with size distributions derived from spherical equivalents based on the voxelized volume of the air voids. One notable exception is the work of Elaqra et al. who employed Fourier domain band-pass filtering to enhance the edges of air voids on 2D cross-sections as extracted from the 3D reconstructed images [19]. By combining manual grayscale threshold binary images of the original and band-pass images, the air void boundaries were isolated. Another common threshold strategy involves a volumetric approach, where bulk air content is measured by an alternative means (e.g. gravimetrically or by pressure meter) and the grayscale threshold varied to minimize the difference between the X-ray CT measurement of bulk air content and the benchmark alternative measurement [26–28].