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Ultrasonic scattering measurement of air void size distribution in hardened concrete samples

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HIGHLIGHTS

- Favorably compare ultrasonic scattering measurement with ASTM C457 test results.
- Apply combined log-normal and normal distributions for improved measurement accuracy.
- Describe small-size and large-size air void distributions of air-entrained concrete.
- Ultrasonic air void measurement can help to evaluate freeze-thaw durability.

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ABSTRACT

The size distribution of air voids in concrete has significant impacts on freeze-thaw damage. This study presented a non-destructive ultrasonic scattering technique to determine the air void size distribution in hardened concrete samples. The ultrasonic scattering theory was applied to calculate the theoretical attenuation of concrete by including the effects of the viscoelastic matrix and different sizes of air voids and aggregates. The air void size distribution was determined by using an inverse analysis to minimize the difference between theoretical and experimental attenuation of concrete. The logarithm normal distribution for large-size air voids and normal distribution for small-size air voids were selected to better represent the air void size distribution in concrete. Both the large-size range and small-size air void distributions were obtained with ultrasonic scattering techniques for hardened concrete specimens. These results were favorably compared with the petrography-based ASTM C 457 method. The comparisons indicated that the developed ultrasonic scattering technique can measure the size distribution of air voids in concrete for the evaluation of freeze-thaw durability.

1. Introduction

The durability of concrete has significant impacts on maintenance costs of the infrastructure system. Freeze-thaw damage is a major issue affecting the durability of concrete in cold region [1]. Recent theories attribute the concrete freezing damage to the crystallization pressure [2–4]. Introducing well-dispersed entrained air voids into cement matrix to accommodate the volume expansion of ice was found to be effective in reducing the crystallization pressure. To avoid destructive pressure from the growth of ice in the pores, well-dispersed air voids are provided as nucleation sites for ice. They also accommodate for volume expansion due to the crystallization. For example, Powers and Helmuth [5] found that limiting the average air void spacing to 250–300 μm is an effective way to prevent damages to a cement matrix due to the internal crystallization pressure. Thus, measuring the size distribution of air voids in concrete is very important to assess its long-term durability, since smaller air voids are more beneficial in reducing the susceptibility to the internal freeze damage [6] .

Considerable amounts of work have been conducted on the measurement of air voids in concrete. Traditionally, the specific air content in a fresh concrete mixture is measured by ASTM standard methods, including pressure based [7], gravimetric based [8] and volumetric based [9]. The air voids in hardened concrete are measured with the petrographic method [10]. However, these standard methods cannot monitor air void distribution changing with curing time nor reach adequate accuracy, especially under field conditions. The non-destructive property of ultrasound provides the potential of in situ testing of air void distribution in fresh or hardened concrete. This presented study will develop a nondestructive ultrasonic scattering method for the rapid measurement of air void size distribution in hardened concrete through

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extending Punurai et al.'s [11] and Sun et al.'s [12] work by considering material phase attenuation effects, small-size and large-size air void size ranges.

Scattering phenomenon caused by obstacles during wave propagating in different media has been constantly studied during the past few decades. Particularly, by embedding three types of spherical obstacles in an isotopically elastic solid medium, Ying and Truell [13] quantify the scattering of a plane longitudinal wave in a solid medium. Later on, the measurement of void contents using ultrasonic attenuation methods continues to progress. For instance, Stone and Clarke [14] conducted an ultrasonic attenuation study on carbon-fiber reinforced plastics to determine its void content, demonstrating that the void content and the attenuation are directly related. Sears and Bonner [15] developed a novel approach to measure the ultrasonic attenuation of compressional and shear waves in rocks and plastics using signal averaging and processing techniques. The porosity of composite materials have also been investigated [14].

Regarding the various applications of ultrasonic techniques in concrete studies, Luo and Bungey [16] determined the dynamic modulus of elasticity and Poisson's ratio of concrete by measuring the attenuation of ultrasonic compressional waves. Lee et al. [17] studied the relationship between the setting times of high performance concrete and the development of ultrasonic pulse velocities in a concrete mixture. Voigt et al. [18] measured the wave reflection of ultrasonic shear wave to monitor the microstructural development of cement mortar during hydration and found out the wave reflection are dominated by the degree of inter-particle bonding. Kewalramani and Gupta [19] predicted the concrete compressive strength using an ultrasonic pulse velocity measurement and compared this with experimental results. Punurai et al. [11,20] characterized the capillary porosity and air content in hardened cement pastes using an ultrasonic attenuation measurement. The results have good comparison with the traditional standard petrographic methods. Zhu et al. [21] investigated the effects of air voids on the ultrasonic wave propagation in fresh cement paste. Li et al. [22] investigated the feasibility of in-situ characterization of air void size distribution in concrete pavements by measuring the p-wave velocity. These studies demonstrated the feasibility and reliability of ultrasonic techniques as non-destructive testing methods in concrete research. However, the ultrasonic scattering measurement of air void characteristics need to be further developed by considering the different phases (air voids, aggregates and cement paste) and different effects of sizes.

Snyder [23,24] applied the log-normal distribution to describe the size distribution of the small entrained air voids. This distribution was further used to examine the accuracy of the air voids spacing factor. Recently, Sun et al. [12] combined Punurai's method with Snyder's work in the study on the air void fraction in concrete by assuming the size distribution following log-normal distribution. Unlike the normal distribution which is symmetrical, the log-normal distribution is an asymmetrical distribution. Different from the work of Punurai et al. [11] and Sun et at [12], this study intends to develop a theoretical attenuation model by combining normal and log-normal distributions to characterize both small and large air voids [6]. Furthermore, the results from petrography-based ASTM methods [10] were used for the verification of the ultrasonic scattering measurement of air void size distribution in hardened concrete.

2. Ultrasonic scattering theory and air voids distribution functions

2.1. Ultrasonic scattering theory for multiphase media

The ultrasonic scattering theory used to calculate energy loss caused by scattered objects was established by Ying and Truell [13]. The theory is based on the equation of motion in homogeneous solid materials when the wave function is only related to space variables,

$$\frac{1}{k^2}\nabla\nabla\cdot S+\frac{1}{\kappa^2}(\nabla^2 S-\nabla\nabla\cdot S)+S=0 \tag{1}$$

$$k=2\pi f((\lambda+2\mu)/\rho)^{-\frac{1}{2}} \tag{2}$$

$$\kappa=2\pi f\left(\frac{\mu}{\rho}\right)^{-\frac{1}{2}} \tag{3}$$

where S is the wave function, λ and μ are elastic constants, ρ is the mass density of the solid medium and f is the frequency of the scattered waves, k and κ are the parameters based on Eqs. (2) and (3). The solution of this equation can be expressed as,

$$S=\sum S_i=\sum s_i e^{i\omega t} \tag{4}$$

where S_i represents the component in the x, y and z direction respectively, s_i represents the magnitude of S_i and t represents the propagation time. The total energy loss can then be obtained by the integration of scattered waves,

$$\iint\left[\sum xr\frac{\partial S_x}{\partial t}+\sum yr\frac{\partial S_y}{\partial t}+\sum zr\frac{\partial S_z}{\partial t}\right]_{scattered\ wave}dA = 4\pi\rho\omega^3\sum_{m=0}^{2}\frac{1}{2m+1}\left[\frac{1}{k}|A_m|^2+\frac{m(m+1)}{\kappa}|B_m|^2\right] \tag{5}$$

where A_m and B_m are matrices of the spherical Bessel function, which can be found elsewhere [25]. As these two matrices decrease significantly after $m > 2$, the combination only contains the first three items in Eq. (5).

The scattering cross section $\gamma_{ij,f}^{sca}$ is defined to account for the energy loss of the transmission wave,

$$\gamma_{ij,f}^{sca}=4\pi\sum_{m=0}^{\infty}\frac{1}{2m+1}\left[|A_m|^2+m(m+1)\frac{k}{\kappa}|B_m|^2\right] \tag{6}$$

where i represents a certain size, j indicates an obstacle type, and f illustrates the frequency. The scattering cross section is related to the scattered wave frequency f because the factors k and κ are both functions of the frequency f.

2.2. Theoretical attenuation analysis with normal distribution and log-normal distribution

The work by Ying and Truell [13] provides the theoretical model to calculate the influence on the wave attenuation for obstacles like air voids and aggregates. The item scattering cross section γ^{Sca} is proposed in the model to quantify the effect on the attenuation of a certain sized obstacle under a certain boundary condition. The shape of air voids in the hardened concrete has minimal influences on its strength properties [26]. In this research, both of small air voids and large air voids are considered to be a distribution of spherical voids with different sizes. The theoretical attenuation can be expressed by combining the effects of the viscous matrix and scattering due to different sizes of air voids and aggregates:

$$\alpha_f=(1-\phi)\alpha_{a,f}+\frac{1}{2}\sum_{i=1}^{m1}n_{si1}\gamma_{i1,f}^{sca}+\frac{1}{2}\sum_{i=1}^{m2}n_{si2}\gamma_{i2,f}^{sca} \tag{7}$$

where α_f is the total attenuation coefficient of the ultrasonic wave absorbed by the hardened concrete (Nepper/m), ϕ is the volume fraction of the combination of small air voids and large air voids in the hardened concrete (%), $\alpha_{a,f}$ is the attenuation coefficient of the visco-elastic cement paste matrix in hardened concrete (Nepper/m), n_{s1} is the number of a certain sized air voids per