

A Microstructural Basis for Diffuse Ultrasound in Concrete

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Extended Abstract

Abstract

Attenuation of ultrasonic signals in concrete has the potential to carry much information about the microstructure of the material. In this work a series of concrete specimens of varying porosities and pore size distributions were internally imaged with x-ray computed tomography (CT), and then subsequently examined with through-transmission ultrasound. The CT images were used to quantify both capillary porosity of cement paste as well as internal interfaces that are likely to produce elastic wave scattering. Ultrasound signals were represented as a diffusion process such that absorption and scattering attenuation could be isolated. As implemented, the diffusion model was a poor predictor of capillary porosity, while diffusivity was a reasonable predictor of scattering interfaces. Diffusivity was found to scale extremely well with small scale porosity, which made it a good predictor of compressive strength.

Keywords: concrete, x-ray tomography, ultrasound

1 Introduction

Ultrasound has been the basis for nondestructive evaluation of concrete for decades. Its success is founded upon the fact that many characteristics of the propagating elastic wave depend on the same micro and macrostructural features that dictate the material's structural properties. However, decoding the fundamental relationship between ultrasonic wave propagation and material properties is a difficult problem for such a material. Heterogeneities exist over a wide range of length scales, leading to a strong frequency dependence in the elastic wave. Thus, for practical applications we tend to rely on simplified empirical relationships between the ultrasonic signal characteristics and the material properties of interest. In an effort to improve our understanding of the relationships between microstructural features and ultrasonic signal behavior, an experimental program was set up in such a way that concrete specimens of varying composition were imaged using x-ray computed tomography, and subsequently interrogated with through-transmission ultrasound. The general question to be answered in this work is whether we can experimentally identify and quantify the relevant microstructural features that affect attenuation of ultrasonic signals.

2 Materials & Methods

2.1 Materials

A series of nine different concrete batches were prepared as shown in Table 1. The mixes were prepared according to European standards with ordinary portland cement and siliceous aggregates. The goal for the mixes was to have a series of materials with a range of porosities from fine scale capillary porosity to coarse scale entrained and entrapped air. Capillary porosity



was controlled by varying water-to-cement ratio (w/c). Larger scale porosity was in the form of both entrained and entrapped air. 50-mm diameter by 100-mm long cylinders were cast for CT and ultrasonic work. 100 mm cubes were cast for compressive strength tests.

Table 1: Concrete Mixes Used in Experimental Program

Mix Label	w/c	Extras	f_c (MPa)	Mix Label	w/c	Extras	f_c (MPa)
MC40+MS	0.40	μ -silica	87.2	MC70	0.70		35.1
MC40	0.40		62.4	MC70+Air	0.70	Ent. air	24.6
MC40+air	0.40	Ent. air	47.7	MC75	0.75		30.6
MC45	0.45		60.0	MC90	0.90		20.7
MC45+air	0.45	Ent. air	44.4				

2.2 Methods: X-ray Computed Tomography

Two cylindrical specimens of each mix type were scanned with an industrial CT scanner. The resulting 3D volumes were 1000 by 1000 by 2024 16-bit voxels, with a voxel size of 55.4 μm . Example slice images are shown in Fig. 1.

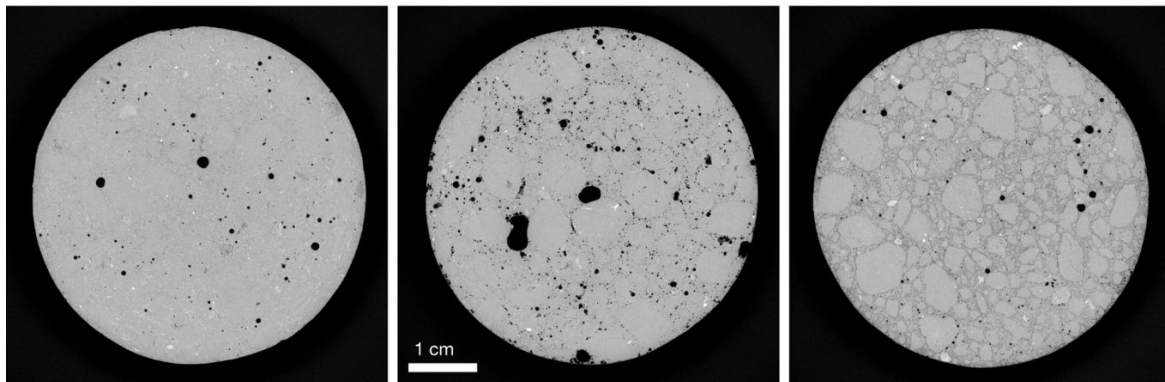


Figure 1: X-ray CT slices of different materials illustrating decreasing paste density from left to right.

2.2.1 Data Analysis

The CT data analysis focused on two material features: density of the cement matrix (i.e. small scale porosity), and density of the interfaces seen at a larger scale. In the former, the porosity is at a scale below the resolution of the CT images, but it is manifest in a lower x-ray absorption. In order to evaluate small scale (capillary) porosity, the grayscale intensity of just the cement phase was evaluated using a rule of mixtures approach [1]. Since all concrete materials used the same aggregate stock, the intensity of aggregate x-ray absorption could be considered a constant among the materials. Any difference in grayscale values (x-ray absorption) can be attributed to differences in cement paste porosity. For this work, we took the inverse of the grayscale value to be the property of interest since it scales directly with porosity. The hypothesis was that the fine scale porosity would dominate absorption attenuation of the ultrasonic signal. The second part of the analysis was to evaluate interfaces in the concrete. Specifically of interest are locations that are likely to cause scattering of ultrasonic signals. In this work an interface was defined as an “edge” in the CT image, which can be evaluated by image gradients. Directional gradients were established along the axis of the cylinder to correspond with the direction of ultrasonic wave propagation. A series of ray paths were run

along the cylinder axis, and interfaces were counted and evaluated spatially. A mean distance between interfaces was established for each material. The results of this analysis for the different mixes are shown in Fig. 2. It is clear from the analysis that the entrained air has a pronounced effect on the distance between interfaces.

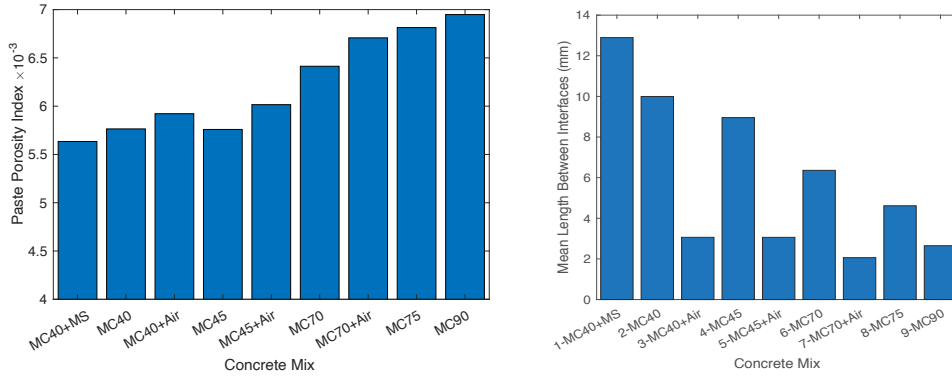


Figure 2: CT-based measurements of cement matrix porosity (left) and interface distribution (right).

2.3 Methods: Ultrasonic Testing

A through-transmission configuration was used, consisting of transducers with a 100 kHz center frequency. Pulses ranging from 100-250 kHz center frequency were used for excitation, and signals were sampled at 2 MHz. The received signal was averaged 10 times.

2.3.1 Data Analysis

The ultrasonic signals were modelled as a diffusion process [2], such that ultrasonic attenuation can be segmented into absorptive and scattering components [3]. The signals were fit to a 1D solution of the spectral energy density, E , at location r :

$$\langle E(\mathbf{r}, t, f) \rangle = \frac{P_0}{2\sqrt{D\pi t}} e^{-r^2/(4Dt)} e^{-\sigma t}$$

Where P_0 is the power spectrum of the source, D is the diffusivity, and σ is the dissipation rate. In this model, the dissipation rate represents absorption attenuation, while diffusivity represents scattering attenuation. A basic hypothesis of this work is that we should see a correlation between dissipation rate and paste porosity, and another correlation between diffusivity and number of interfaces. Results at 230 kHz shown in Fig. 3 suggest that for low porosity mixes, dissipation rate is not a good discriminator. Diffusivity shows better discrimination.

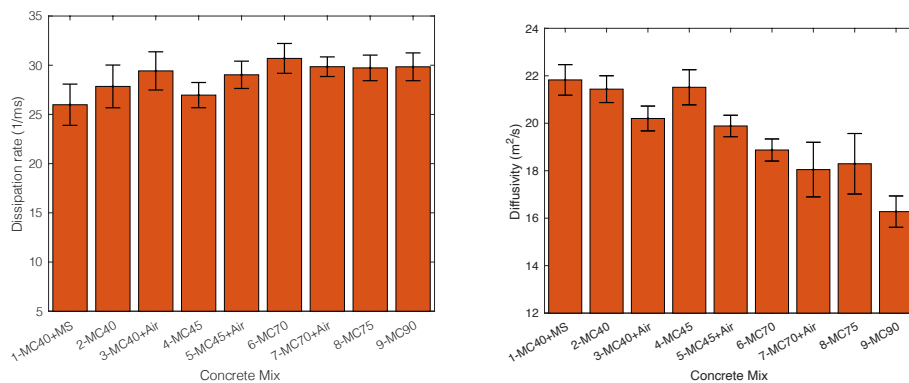


Figure 3: Ultrasonic-based measurements of dissipation rate (left) and diffusivity (right).

3 Results

The hypothesized correlations are presented in Fig. 4. Clearly, we must reject the hypothesis that dissipation rate correlates with paste porosity. If, however, we separate air and non-air entrained specimens, there is a good correlation between diffusivity and number of interfaces.

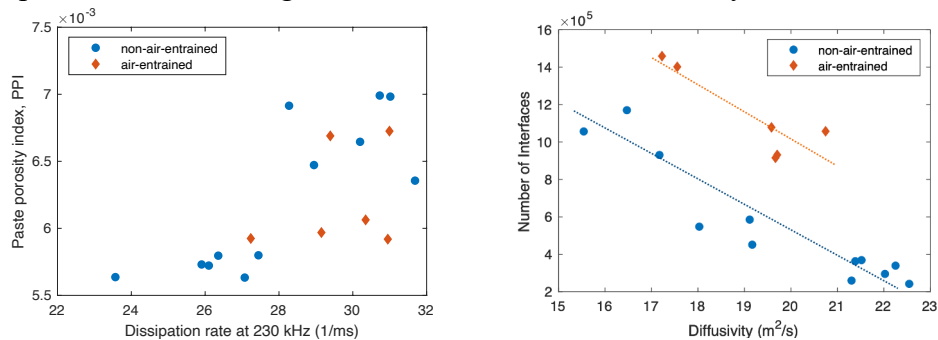


Figure 4: Correlation between ultrasonic-based and CT-measured quantities.

A surprise finding was that diffusivity was an excellent predictor of cement matrix porosity, as shown in Fig. 5. Indeed, the entrained air had little to no effect on the correlation. As capillary porosity is a good predictor of strength, it follows that the diffusivity should, by association, be a good predictor of strength. The relationship is also shown in Fig. 5.

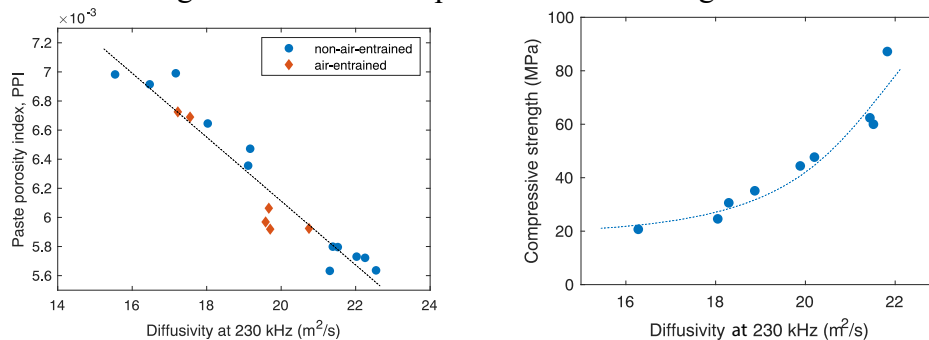


Figure 5: Paste porosity and concrete compressive strength plotted against diffusivity.

4 Conclusions

An effort was made here to make direct relationships between ultrasonic signals and the concrete microstructure that dictate properties such as strength. Such relationships are still incomplete and will require further investigations of relevant frequency and wavelength issues, as well as moisture effects.

References

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