Characterization of dissipation losses in cement paste with diffuse ultrasound

W. Punurai a, J. Jarzynski b, J. Qu b, K.E. Kurtis a, L.J. Jacobs a,b,*

a School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, USA
b G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, USA

Available online 17 November 2006

Abstract

The objective of this study is to quantify the dissipation losses in cement paste using diffuse ultrasound, and then to relate these results to the corresponding values measured with a coherent ultrasound procedure. The results show a linear dependency on frequency for this energy dissipation (intrinsic absorption), and exhibit a reasonable correlation between the dissipation losses and the amount of cement paste present in a sample. In addition, there is good agreement between the air content predicted with diffuse ultrasound, and that directly measured with a standard optical technique. © 2006 Elsevier Ltd. All rights reserved.

Keywords: Diffuse ultrasound; Energy dissipation; Absorption attenuation

1. Introduction

Attenuation measurements using coherent ultrasonic waves – waves in which the measured output signal is related to the input signal in a deterministic sense – include both intrinsic absorption and scattering contributions, as well as extrinsic geometric effects (such as diffraction, spreading and specimen effects). This coupling of both absorption and scattering effects can make it difficult to link measured attenuation behavior with specific microstructure features. In contrast, statistical methods such as diffusion theory can separate (uncouple) the loss contributions due to dissipation and scattering in a material (Weaver, 1998; Anugonda et al., 2001). A diffuse ultrasound field is completely incoherent and is uniformly distributed throughout a specimen. Under these conditions, the decay of a diffuse energy field (when averaged over time or space) is entirely due to dissipation and is unaffected by both scattering and geometric effects.

The intrinsic absorption of a material can be directly related to specific material features; this relationship has been extensively studied in polymers (Hartmann and Jarzynski, 1972) and tissues (Fung, 1993), where internal friction and viscoelastic dissipation losses dominate. However, this effect is not as well understood
for the case of ultrasonic waves propagating in cement-based materials; the multi-scale, multi-phase and viscoelastic nature of these materials result in complicated ultrasonic waveforms with high attenuation. By taking a building block approach, it should be possible to characterize the absorption and scattering losses from the individual elements (such as the cement paste, aggregate or even microcracks), and then to combine them into a unified description (model) of ultrasonic wave propagation in concrete.

Cement paste – which consists of Portland cement and water, but does not include any fine or coarse aggregate – is a common bonding matrix for all types of cement-based composites. The objective of this research is to use diffuse ultrasound to quantify the dissipation losses in cement paste and then to relate these results to the corresponding intrinsic absorption values measured with a coherent ultrasound procedure. Two different cement paste specimens are examined, both with nominally identical microstructures, except that one includes entrained air voids, while the other does not. These entrained air voids, which are on the order of 1 mm in diameter, reduce the amount of cement paste in a unit volume of sample, and thus should cause a decrease in dissipation losses. By separately considering this one critical element, cement paste, it should be possible to gain a better understanding of wave propagation in cement-based materials.

2. Experimental procedure

Two 100 mm diameter by 25 mm thick cylindrical cement paste specimens were cast, one with, and one without a small volume fraction (<10%) of entrained air voids. Fig. 1 shows magnified digital images of typical areas for each of these two specimens. Following the procedure described in Punurai et al. (2006), the “cement paste specimen” was produced by mixing ASTM Type I Portland cement and water with a water-to-cement mass ratio of 0.40, while the “entrained air specimen” has the same water-to-cement ratio, but with the addition of a chemical air-entraining agent at about 0.2% of the cement mass.

![Fig. 1. Photomicrographs of the two specimens: (a) cement paste specimen; (b) entrained air specimen.](image-url)
Fig. 2 shows the experimental setup for the diffuse ultrasound field measurements. A diffuse wave field is generated with a 5 MHz broadband, 12.5 mm diameter contact transducer located at the geometric center of the specimen, while point-like (1 mm diameter) detection is accomplished with a 2 MHz broadband transducer located on the opposite side of the specimen, at a distance \( r = 40 \) mm off the axis of symmetry. The bandwidth of this source and point-like receiver combination is from 0.3 to 2.5 MHz and time-domain signals are recorded with a 25 MHz sampling frequency (30,000 point record). The time–frequency analysis is straightforward and starts by dividing each time-domain signal into several overlapping time windows (Hanning window to smooth the edges) of length \( \Delta t \). The data from each time window \( \Delta t \) is independently Fourier transformed and then the magnitude is squared to measure the power spectrum. A frequency window centered around \( f_c \) and of bandwidth \( \Delta f \) is then selected, and the energy density, \( \hat{E}(r,t,f) \), for this frequency window (and propagation path, \( r \)) is defined by summing the power spectrum of each time window in this frequency bandwidth. The expected energy density, \( \langle E(r,t,f) \rangle \) (expected value with respect to different configurations of a random media) is then calculated by averaging five different measurements made at five different spatial locations, but each with \( r = 40 \) mm.

Ultrasonic diffusion in a body is described by a second order parabolic partial differential equation (PDE) for the time evolution of the spectral energy density (energy per frequency, per volume)

\[
\frac{\partial \langle E(r,t,f) \rangle}{\partial t} - D \Delta \langle E(r,t,f) \rangle + \sigma \langle E(r,t,f) \rangle = P(r,t,f),
\]

where \( P(r,t,f) \) is the spectral source energy density, \( D(f) \) is the frequency-dependent diffusion coefficient, and \( \sigma(f) \) is the energy dissipation coefficient (frequency-dependent). The body is assumed to be isotropic – the diffusion coefficient is independent of direction – and all scattering is assumed to be linearly elastic (no energy loss during scattering). Eq. (1) predicts the ultrasonic spectral energy density in an average sense, and is similar to the heat transfer equation, but with an additional dissipation term. Finally note that this energy dissipation term, \( \sigma \), will be related to intrinsic absorption in the next section.

The experimental setup used in this research dictates a radially symmetric solution of Eq. (1) with an impulse source at the origin, \( P(r,t,f) = P_0 \delta(t) \delta(r) \). The specimen thickness is small relative to the lateral dimensions, which leads to a fundamental solution of Eq. (1) as Glicksman (1999)
\[
\langle E(r, t, f) \rangle = \frac{P_0}{4D \pi t} e^{-r^2/(4Dt)} e^{-\sigma t}.
\] (2)

3. Experimental results and discussion

Fig. 3 shows a typical plot of \(\ln(\langle E(r, t, f) \rangle)\) as a function of time for both the experimentally measured data and a theoretical fit of Eq. (2) (with \(D\tau = 60 \mu s\) and \(Df = 0.25 \text{ MHz}\)) for the cement paste specimen. The error bars are associated with both \(Df\) and \(D\tau\) and are predicted following (Weaver, 1998). Fig. 4 compares the recovered energy dissipation, \(\sigma\) (in units of \(1/\text{ms}\)) for both specimens. It is observed that these energy dissipation losses are similar for both specimens—the dissipation increases linearly with increasing frequency. Note that polymers exhibit this same linear dependence on frequency for absorption attenuation (hysteresis absorption) (Hartmann and Jarzynski, 1972). Since the specimens were cast in the same manner at the same water-to-cement ratio, it is postulated that this linear behavior is primarily due to the viscoelastic nature of the cement paste. In addition, the entrained air specimen has an approximately 7% lower dissipation than the cement paste specimen (by comparing the slopes in Fig. 4); it is proposed that the presence of the entrained air voids...
reduces the measured dissipation by an amount approximately equal to the volume fraction of entrained air voids. Note that image analyses performed on both specimens by ASTM (2000) method B indicate that the difference in air content between the samples is approximately 8% – there is good agreement between the air content directly measured with this standard optical technique and that predicted with diffuse ultrasound.

This behavior is predicted by Biwa (2001), who considered attenuation in a particulate polymer composite material with an independent (coherent) scattering model which accounts for both the scattering losses (the summation of a distribution of independent single scatterers) and viscoelastic absorption in the polymer matrix. The model in Biwa (2001) predicts a reduction in intrinsic absorption of the polymer matrix equal to the volume fraction of particles (for volume fractions under 20%); this is observed in Fig. 4. Note that Weaver (1998) observed a similar behavior in open-celled aluminum foam specimens; specimens which contain higher porosity show less dissipation and diffusivity (with increasing frequency) than specimens with lower porosity. Becker et al. (2003) also measured dissipation and diffusivity in cement paste specimens with 20–40% volume fraction of spherical glass aggregate, and found a reduction in dissipation proportional to the volume fraction of glass aggregate.

Fig. 5 shows the diffusivity values recovered for the two specimens, where diffusivity clearly decreases with increasing frequency. Again, the entrained air specimen shows lower diffusivity values than the cement paste specimen, indicating more scattering in the entrained air specimen. This observation is consistent with mean-field scattering theories (a larger number of voids causes stronger scattering). While this is a good indicator of the presence of the entrained air voids shown in Fig. 1, no quantitative conclusions are drawn from these diffusivity results; these diffusivity results are most likely dominated by the multiple reflections off of the specimen boundaries, as opposed to scattering from the microstructure (entrained air voids).

Finally, if dissipation is a measure of the intrinsic viscoelastic losses in the cement paste, then dimensional analysis suggests that dissipation, $\sigma$, is related to the absorption attenuation coefficient, $\alpha$, by $\alpha = \frac{\sigma}{c}$, where $c$ is the average wave speed of the diffuse wave field measured by the point detector. If it is further assumed that the source transducer produces a wave field which is predominantly longitudinal, the overall diffuse wave field is dominated by the phase velocity of the longitudinal wave. Previous research (Punurai et al., 2006) measures the phase velocity of longitudinal waves in the cement paste specimen as 3750 m/s for the frequency range of interest (with limited dispersion), so the dissipation values are converted to intrinsic absorption coefficients ($\alpha$) and compared to the corresponding absorption attenuation directly measured with a coherent technique (described in Punurai et al. (2006)); these results are shown in Fig. 6. There is good agreement between the two, which suggests that dissipation, $\sigma$, can be used as an equivalent measure of intrinsic (material) absorption attenuation when the phase velocity is known.

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![Fig. 5. Comparison of averaged values of diffusivity, $D$, recovered from the cement paste and entrained air specimens.](image-url)
4. Conclusion

This study uses diffuse ultrasound to quantify the dissipation losses in cement paste both with and without entrained air voids, and then relates these results to the corresponding values measured with a coherent ultrasound procedure (if the phase velocity is known). The results show a linear dependency on frequency for energy dissipation; this behavior is similar to that of a polymer (hysteresis absorption) and is primarily due to intrinsic viscoelastic losses in the cement paste. There is also a reasonable correlation between these dissipation losses and the amount of cement paste present in a sample. This study suggests that the decay of a diffuse energy field (or dissipation) complements the absorption attenuation coefficient and can be used as an equivalent measure of intrinsic absorption attenuation when the phase velocity is known. Finally, this research demonstrates a good agreement between the air content predicted with diffuse ultrasound, and the air content directly measured with a standard optical technique.

Acknowledgements

This research is partially supported by the National Science Foundation under grant number CMS-0201283 and a Royal Thai Government Scholarship to W. Punurai. The authors would like to thank Mr. Terry Vines of Lafarge in Atlanta for performing the image analyses.

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