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Effect of Inhomogeneity Parameters on Wave Propagation in Cementitious Material

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In this study, the relationship between inhomogeneity in cementitious material and stress wave parameters is investigated by measuring parameters of through transmission measurements of ultrasonic waves. Except from the inherent inhomogeneity of this type of material, the presence of damage in the form of cracks can lead to even more highlighted velocity dispersion and attenuation phenomena for specific bands of frequencies. Therefore, different contents of crack-like, film-shaped particles are included during casting of concrete to evaluate the contribution of distributed damage in the observed wave parameters. Experiments are carried out using low- and high-frequency sensors with the range of frequencies also covering those used for in-place application.

Keywords: frequency; mortar; nondestructive testing; pulse velocity.

INTRODUCTION

Concrete is under continuous action of different deteriorating parameters—thermal stress cycles due to seasonal temperature variations as well as freezing and thawing in colder environments that results in expansion and contraction. Additionally, the structural service loads, earthquakes, and the influence of environmental agents cause a distributed pattern of deterioration in the material. Because the possibility of concrete failure may have severe consequences, the issue of damage quantification is of paramount importance for civil engineering structures. Nondestructive testing techniques, specifically stress waves, have been used for many decades to estimate the damage. Features commonly used are the velocity of ultrasound through the material as well as acoustic emission activity.[1-3]

The internal condition of the material that influences the strength also influences the overall elastic properties and therefore stress-wave characteristics such as velocity and attenuation. The relationship between pulse velocity and strength has been studied extensively. Sound concrete with high strength generally exhibits high propagation velocity.[4-9] This correlation has led to the implementation of ultrasonic pulse velocity measurements to models for prediction of concrete strength.[10-13] Additionally, propagation characteristics can be correlated with distributed damage, evolved after subjection of the material to thermal cycles.[14,15] It has been shown that damaged concrete generally exhibits lower velocity than sound concrete.[14-21] Porosity also has a negative effect on velocity and transmission, acting as discontinuity that reduces the overall elastic modulus.[22,23] Although much research concerning the relation between damage and pulse velocity has been published, a unique correlation cannot not be established. This is due to the inhomogeneity of the material itself. Different cement type, water-cement ratio (*w/c*), aggregate and sand content, type and grading, and air bubbles make any mixture unique. Additionally, the form of damage is not always the same because cracks can vary from the order of micrometers to centimeters. Also, considering the orientation and the number of cracks (or the volume content of damage), it is understandable that all the previous parameters make any structure different and the task of distributed damage quantification complicated.

In addition to pulse velocity, energy parameters are considered even more sensitive to damage. For certain deterioration of concrete, wave velocity may be reduced to some extent, but the energy reduction is much more evident and starts even with slight damage accumulation.[14,15,24-26] Distributed damage has been simulated experimentally with inclusions of light material in mortar.[16,17]

In the present work, different contents of thin plastic inclusions are embedded during casting of mortar. Therefore, the correlation of wave parameters with the actual content can be investigated. Additionally, the influence of different sizes of inclusions, resembling thinner and thicker cracks, is also addressed. This work aims to increase the experimental data on this crucial subject of damage characterization using a nondestructive method.

RESEARCH SIGNIFICANCE

This study aims to highlight the dispersive nature of cement-based materials. The inhomogeneity induced by damage causes variations to wave velocity and attenuation that also depend on the excited frequency. Therefore, in addition to the widely used pulse velocity of low frequencies, concrete nondestructive testing should be enhanced by wave energy parameters and the application of different frequencies when possible. Also, the flakey shape of the inclusions used in this study to simulate damage in concrete is more realistic than the previously used ones with a spherical shape.

EXPERIMENTAL PROCEDURE

Materials

Cubic mortar specimens with 150 mm (6 in.) sides were investigated. The mortar matrix had a *w/c* of 0.5 and sand-cement ratio (*s/c*) of 3. The maximum size of sand grain was 3 mm. The density of plain mortar was 2164 kg/m^3 (135.1 lb/ft^3). The inclusions were cut from commercially available vinyl sheets of different thicknesses. The density of vinyl was assumed to be 1200 kg/m^3 (74.9 lb/ft^3) and the elastic modulus was 2.5 GPa (363 ksi) from values available in the literature. The two cases presented in this paper concern inclusions with a shape of 15 x 15 x 0.5 mm (0.59 x 0.59 x 0.02 in.) as well as 30 x 30 x 0.2 mm (1.18 x 1.18 x 0.007874 in.). The plate shape resembles actual cracks much

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closer than the spherical shape that has been used in other research works. Also, using this technique, the effect of different crack shapes and sizes could be investigated. The inclusions were added to each specimen in different volume contents after the other mortar ingredients had already been mixed. Therefore, mortar specimens with 1, 5, and 10% by volume of vinyl inclusions were produced. The mortar with the plastic inclusions was mixed for another minute in a mechanical mixer (refer to Fig. 1(a)), and then cast in the cubic molds. A pilot specimen exhibited that there was no tendency of conglomeration of the particles, as seen in Fig. 1(b). Although absolutely uniform dispersion of the inclusions cannot be guaranteed, it seems that the distribution and orientation of the particles could be considered random. The dimensions of the plastic inclusions were much larger than the sand grain dimensions; therefore, it can be assumed that the inhomogeneity of the whole material is attributed to the inclusions and not the mixture design parameters. The specimens were cured in water for 28 days and the measurements were conducted on dry specimens.

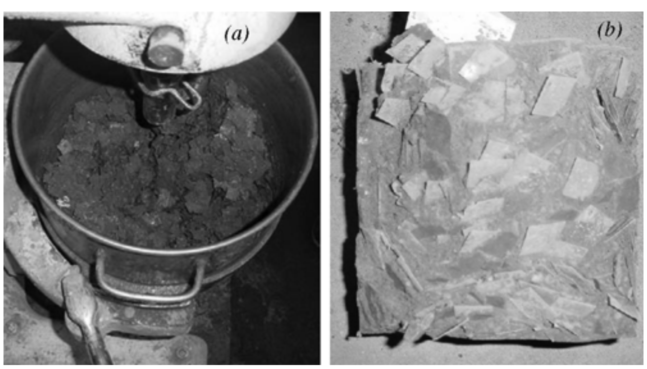

Fig. 1—(a) Mixing of plastic inclusions with fresh mortar; and (b) distribution of inclusions in pilot specimen.

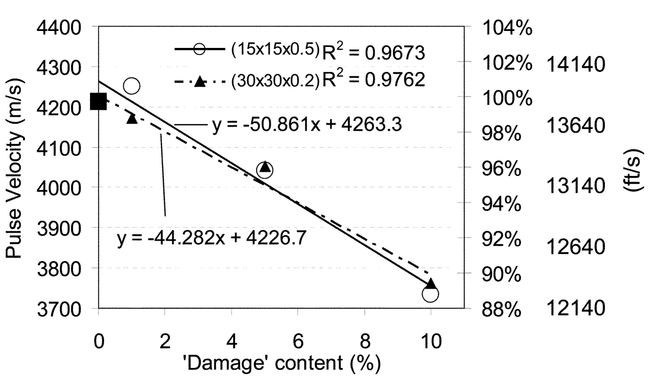

Fig. 2—Pulse velocity versus inclusion content (square symbol stands for plain mortar).

Stress wave measurements

Measurements were conducted through the thickness of the specimens (wave path of 150 mm [6 in.]) with the sensors placed on the center of the opposite sides of the cube. The direction was perpendicular to the direction of casting. The pulse generator is a commercially available model that introduces a short electrical pulse of duration less than 2 μs. It was connected to a piezoelectric transducer, with high sensitivity to the lower frequency band (below 200 kHz), commonly used for acoustic emission testing of concrete. The receiver was of the same type whereas the signal was preamplified and digitized with a sampling rate of 10 MHz. Considering the transit times measured (approximately 40 μs), the sampling interval of 0.1 μs induces an error of 0.25%. A layer of silicone was applied between the sensor and mortar specimen to ensure acoustic coupling. The measurements were repeated on the other side and results presented herein come from the average of the measurements.

Additionally, in other cases when narrow band pulses were applied, as will be described in another section, a function synthesizer of controllable output was used. This way, tone bursts of different frequency were excited, namely, 10, 30, 50, 80, 100, 150, and 500 kHz with a duration of 10 cycles. For the frequency of 500 kHz, another pair of broadband sensors were used to transmit the signal reliably.

RESULTS AND DISCUSSION

Pulse velocity

The first set of experiments conducted with the broad band pulse generator includes frequencies of up to approximately 150 kHz. The velocity presented is measured by the first detectable arrival of the receiver's waveform corresponding to what is generally regarded as pulse velocity. This parameter is measured at 4213 m/s (13,822 ft/s) for mortar. With the addition of a small percentage of vinyl inclusions (1%), the velocity does not seem much influenced (refer to Fig. 2). For higher percentages though, a certain decrease can be seen. Five-percent damage results in a velocity of 4050 m/s (13,287 ft/s) or a decrease of 4%, whereas additional inclusions to 10% by volume result in velocities below 3800 m/s (12,467 ft/s) or a decrease of approximately 11%. It seems that the velocity is sensitive enough to the crack-like inclusion percentage simulating damage. From Fig. 2, it can be said that the percentage of the inclusions is similar to the percentage of velocity decrease resulting in a linear relationship up to 10% damage. There seems to be no strong influence of the inclusions' shape, however, because smaller and thicker inclusions of 15 x 15 x 0.5 mm (0.59 x 0.59 x 0.02 in.) result in approximately the same velocity with the larger and thinner inclusions of 30 x 30 x 0.2 mm (1.18 x 1.18 x 0.007874 in.).

Considering the mortar velocity of 4213 m/s (13,822 ft/s), the density of 2164 kg/m^3 (135.1 lb/ft^3), and a Poisson's ratio of 0.2, which is typical for cement-based materials, the elasticity modulus of plain mortar is calculated at 34.6 GPa (5018 ksi) using the following well-known equation

$$E = \rho \times C_P^2 \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \quad (1)$$

where E is the modulus of elasticity, ρ is the density, C_P is the longitudinal wave velocity, and ν is the Poisson's ratio.

Using the previously mentioned elasticity value for the matrix and 2.5 GPa (362.6 ksi) for the inclusions, static homogenization models[27,28] lead to a velocity of 3954 m/s (12,972 ft/s) for the 10% inclusion specimens. Even though the Poisson's ratio cannot be the same for sound and damaged mortar, a difference of 0.05 causes small errors in velocity calculation of less than 5%.[1] The predicted value is higher than the measured, but the use of homogenization models that take into account only the volume fraction of the constituents and not their shape seems reasonable because the size of the inclusions does not seem to influence the measured pulse velocity. This kind of approach, however, is inadequate to explain features of dispersion and attenuation that will be presented in the following and are influenced by the particle size.

It must be mentioned that, as in an actual situation, velocity should not be expected identical in any measurement, even for the same material. This is due to inhomogeneity and locality of the medium. Even if damage is considered widely distributed into the medium, it is highly unlikely that it is uniformly distributed. Therefore, measurements at different points will not result in exactly the same measurements. For the aforementioned longitudinal velocity results, the discrepancy between the individual measurements at the different sides and the average were 16 m/s (15,849 mm/s [52 ft/s]) for plain mortar or less than 0.4%, whereas it increased to 49 m/s (161 ft/s) for material with 10% inclusions (1.3%). This suggests that the experimental scatter could also be studied for potential relationships with inhomogeneity if a sufficient number of measurements can be made. In any case, however, it cannot mask the decrease due to the artificial damage, which is of the order of 500 m/s (1640 ft/s). The same repeatability was exhibited for the dispersion measurements presented in the following.

Energy

As seen, pulse velocity is indicative of damage for the specimens of this experimental series. Energy-related parameters, however, are much more sensitive to the inclusions. Indeed, in Fig. 3, one can see waveforms received in the four specimens with different damage volume contents. The amplitude is certainly influenced for increasing inclusion contents. To quantify this parameter, the total energy of each waveform was calculated as the area under the rectified signal envelope. Then it was divided by the energy of the face-to-face response of the transducers. This way it was expressed as the percentage of the energy transmitted through the specimen compared with the total pulsed energy. In Fig. 4, the waveform energy is depicted versus the damage content for both inclusions' sizes. It is obvious that even 1% inclusions results in much lower energy. Further addition of inclusions diminishes the energy even more, resulting in an approximately 90% decrease for 10% inclusion content. For the case of thin inclusions of 0.2 mm (0.007874 in.), the energy is even lower. It is seen that the energy is much more sensitive than velocity to the existence of damage. The small inclusion content of 1% that has doubtful effect on velocity, as seen in Fig. 2, results in a steep decrease of energy. For larger inclusion content, the decrease is not as steep; but for both shapes, there is a considerable difference between 5 and 10% inclusions. Transmission, however, also seems to be sensitive to the shape characteristics—something that could not be explained assuming a homogeneous material. The energy transmitted by the specimens with thinner and larger inclusions is constantly lower, implying that in actual condition, not only the number of cracks but also their shape influences the measured waveforms. In the specific case of thinner inclusions, it is possible that a larger number of them is located between the transmitter and the receiver. Therefore, the signal suffers more attenuation due to multiple reflections.

In this case, exponential laws are suitable to fit the experimental data, as indicatively shown in Fig. 4. The discrepancies between the individual measurements and their average are 4.4%, 1.19%, and 0.69% for material with 0%, 1%, and 5% inclusions, respectively. It could be expected that plain mortar has the lowest deviation but, surprisingly, the specimens with vinyl exhibited even higher repeatability. Only mortar with 10% vinyl inclusions exhibited larger discrepancy, on the order of 23%, which was inevitable due to the extremely inhomogeneous nature of the material.

Generally, the attenuation behavior of cementitious materials is attributed to damping and scattering. Distinguishing between these two contributions is difficult. It can be assumed that the plastic inclusions increase the overall damping of the material due to their more viscous nature. However, they certainly increase the overall inhomogeneity of the mixture. The increased inhomogeneity has been shown to result in higher attenuation,[29-31] especially for

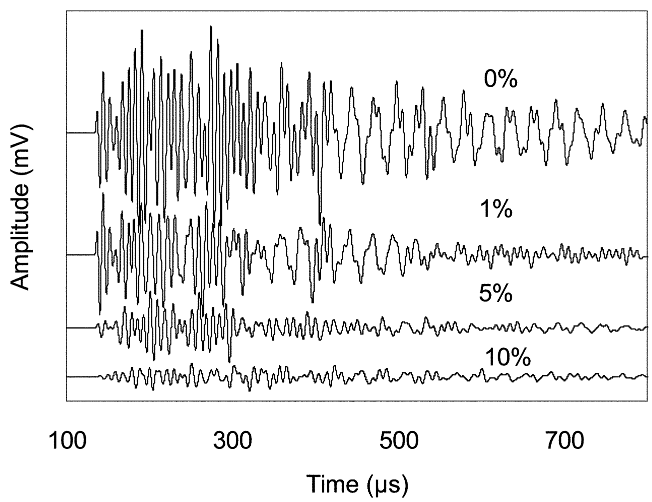

Fig. 3—Waveforms from mortar with different content of inclusions.

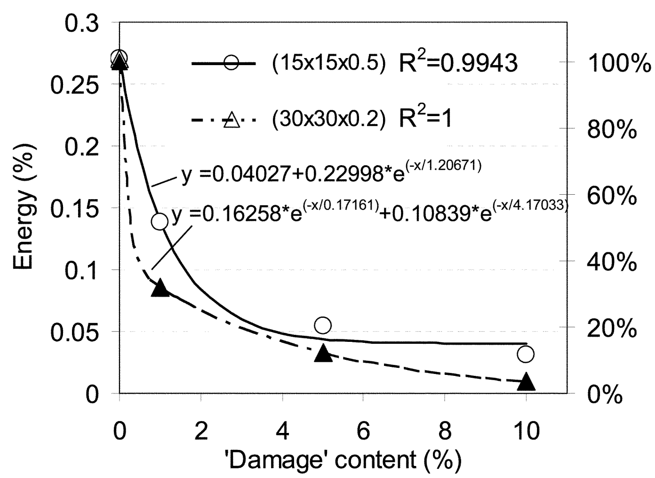

Fig. 4—Waveform energy versus inclusion content for different inclusion size.

higher frequencies. In the specific case, the crack-like films act as scatterers of wave energy, redistributing the energy to different directions. The pattern of the scattered energy depends on the shape, size, and mechanical properties of the inclusions.[32,33] Recently, it was shown that the scattering theory can very accurately predict the velocity and attenuation behavior of concrete with light inclusions simulating damage,[16,17] mortar with entrained air bubbles,[34] and the behavior of fresh mortar containing sand and air bubble scatterers.[35] This implies that scattering becomes the most dominant mechanism in inhomogeneous material, specifically in damaged concrete due to the large number of cracks that act as distributed scatterers. It is noted that although the wave energy scattering directly affects the amplitude measurements, some energy components can still survive scattered in the forward direction, leading to pulse velocities similar to the plain material. This explains why inhomogeneity, even though it reduces amplitude by orders of magnitude, has a limited influence on pulse velocity of the order of 10%.

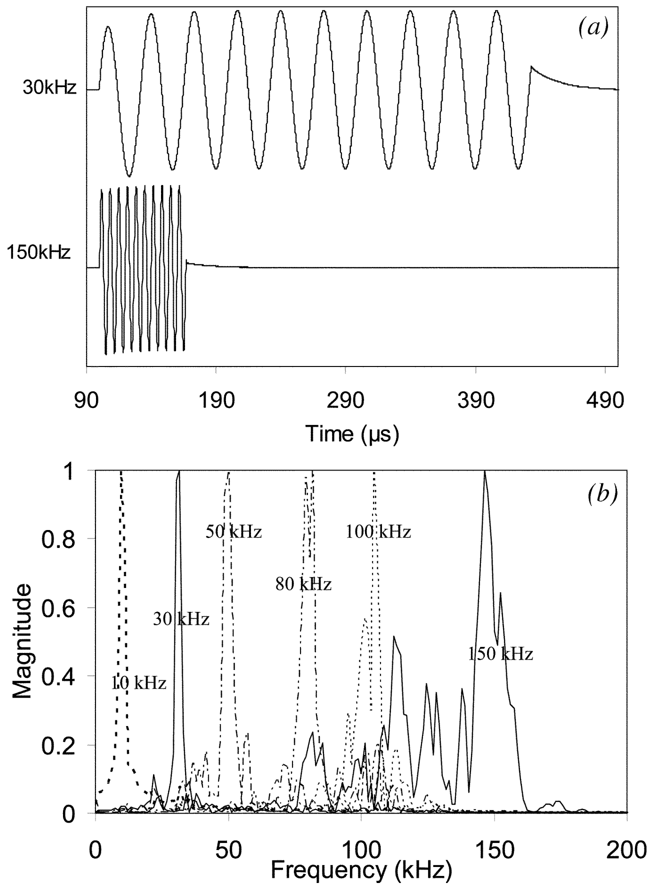

Fig. 5—(a) Examples of electric excitation signals; and (b) Fast Fourier Transform of different tone burst after propagation through mortar.

Frequency influence

Due to scattering, the material does not behave homogeneously. According to the scattering theory, the phase velocity and attenuation depend on the relation between the propagating wavelength and the scatter size.[32,33] Therefore, the influence of any scatterer (in this case, distributed cracks) could be more highlighted at different frequency bands. Thus, it is meaningful to examine the propagation of different frequency components. To this end, the function synthesizer was used along with the same resonant transducers. Tone bursts of 10 cycles and different frequencies were applied to the pulser. Because concrete is quite attenuative and any monitoring case in place is limited at large wavelengths, the frequencies applied were mainly at the lower end, that is, 10, 30, 50, 80, 100, and 150 kHz. Examples of the electric signals applied in time domain are depicted in Fig. 5(a) for 30 and 150 kHz. Also, the Fast Fourier Transform (FFT) of signals after propagation through a specimen (with 5% inclusions) are shown in Fig. 5(b). It is seen that the sensors are suitable to transmit these frequencies, whereas the content survives after propagation in the material without serious distortion. To examine the behavior at short wavelengths (below 10 mm [0.39 in.]), a frequency of 500 kHz was applied using the broadband sensors. The results exhibited that the material behaves in a dispersive way, as has been stated in previous works.[16,31,36,37] This dispersion, as seen in Fig. 6(a) and (b), depends on the amount of the inclusions. Again, 1% of inclusions do not have a clear effect exhibiting even slightly higher velocities than plain mortar. A further increase of inclusions, however, clearly decreases the velocity of any frequency band.

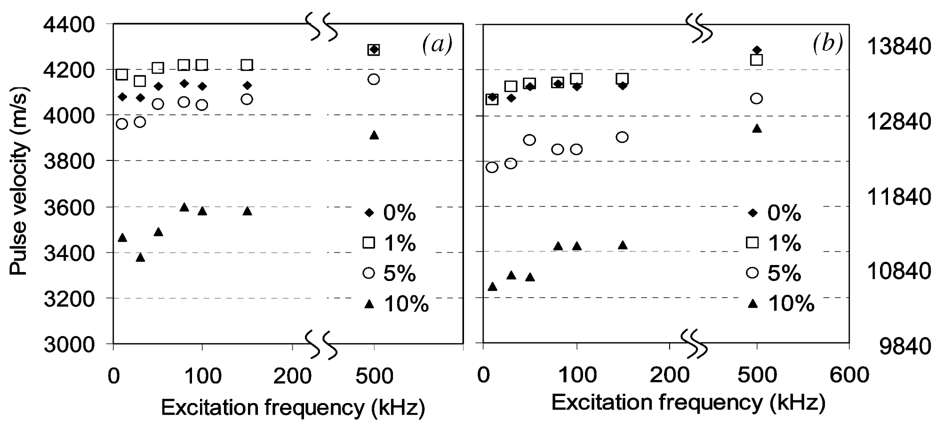

Fig. 6—Pulse velocity versus excitation frequency for different inclusion content and inclusion shape: (a) 15 x 15 x 0.5 mm (0.59 x 0.59 x 0.02 in.); and (b) 30 x 30 x 0.2 mm (1.18 x 1.18 x 0.007874 in.).

For any mixture, the velocity seems to increase with frequency. The highest velocity is measured in all specimens with the excitation of 500 kHz. In Fig. 7, an example concerning the first detectable disturbance of the waveform is depicted. Although the onset of the excitation is always synchronized (refer to the small embedded diagram in Fig. 7), this is not the case for the received signal. It is evident that as the excitation frequency increases, the transit time is shorter, resulting in the measurement of higher velocities.

It is worth mentioning that the case of 10% inclusions exhibits a remarkable increase in velocity as the frequency is elevated. Using 10 kHz pulses, the velocity for these specimens was measured approximately 800 m/s (2624 ft/s) lower than the plain mortar, whereas for the highest frequency case, the difference was less than 400 m/s (1312 ft/s). This increasing trend of velocity with frequency has been noticed in previous works for sound cementitious materials.[16,17,31] Additionally, as the inhomogeneity increases due to more aggregates[31] or plastic inclusions,[16] so does the dispersion because the increase of velocity with frequency is more abrupt. As has been measured in a recent study,[16] mortar with 30% light inclusions exhibited a phase velocity of 3600 m/s (11,811 ft/s) for frequencies of approximately 200 kHz. For frequencies approaching 1 MHz, the velocity was measured at approximately 4100 m/s (13,451 ft/s). This trend is supported by theoretical results of scattering theory. Scattering influences have been studied in different composite materials in literature. In any case, the velocity measured at higher frequencies always converges to the velocity of the matrix, whereas any discrepancy due to inclusion content is more evident at lower bands.[38,39] This seems to be the case for the present experimental series because, as the frequency increases, the velocity measured at any specimen becomes closer to that of plain mortar.

Another interesting feature is that not only the volume content but also the shape of the inclusions seems to have an influence in this case. Mortar with small but thick inclusions (refer to Fig. 6(a)) exhibits higher velocity than mortar with large but thin inclusions of the same content (refer to Fig. 6(b)). This is another indication of dispersion and scattering mechanisms that are influenced by the size and shape of the inclusions.

A detail worth mentioning is that the velocity of the pulse carrying broad frequency bands is not necessarily equal to the velocity of any narrow band pulse within the same frequency range. For example, mortar with 10% 15 x 15 x 0.5 mm (0.59 x 0.59 x 0.02 in.) inclusions exhibited a velocity of 3734 m/s (12,250 ft/s) when measured with a pulse containing frequencies of 0 to 150 kHz (refer to Fig. 2). When narrow band pulses of frequencies below 150 kHz are applied to the same specimen, however, their velocity never exceeds 3600 m/s (11811 ft/s). The different propagation behavior of different pulses is a sign of dispersion due to inhomogeneity and has been noticed previously for concrete.[31]

An important aspect of this investigation is that as the inhomogeneity increases, so does the dispersion. Plain mortar exhibits an increase of 5% in velocity between 10 and 500 kHz excitation. Mortar with 10% inclusions, however, exhibits more than a 15% increase. Therefore, the pulse velocity measured at different frequencies could be an additional parameter to enhance damage characterization.

It can be said that the limited volume of the specimens can have an effect on the measured velocities. This has been stated in different studies.[31,37] Changing the specimen dimensions can influence the pulse velocity values by even more than 100 m/s (328 ft/s).[31] The dependence of velocity on frequency, however, is not strongly influenced.[31] In any case, the purpose of this study is to examine the influence of artificial damage content; and because all the specimens are of the same size, size effects do not hinder the comparison.

Attenuation

It is well known that stress waves in concrete are severely attenuated due to the inhomogeneous nature of the material, whereas generally the attenuation increases with frequency.[16,31,34,36,40] As shown in Fig. 4 and in a number of other research studies,[14,15,25,26] this attenuation behavior

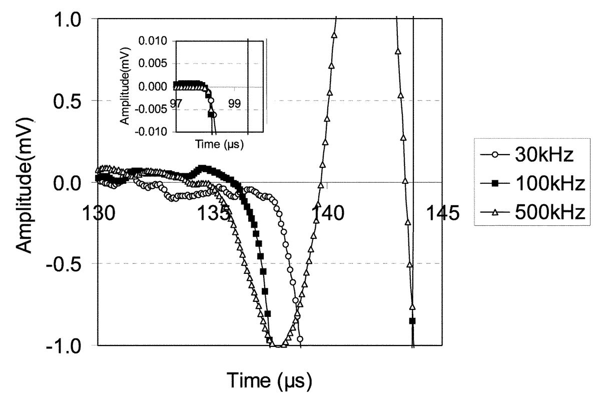

Fig. 7—First arrival according to excitation frequency. In inset figure, onset of excitation pulse.

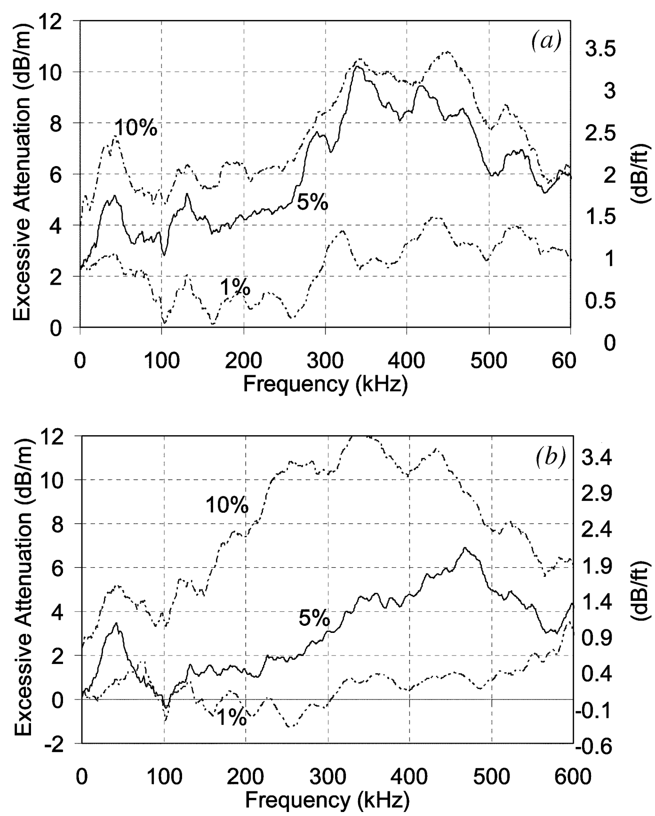

Fig. 8—Attenuation coefficient versus excitation frequency for different inclusion content and inclusion sizes: (a) 30 x 30 x 0.2 mm (1.18 x 1.18 x 0.007874 in.); and (b) 15 x 15 x 0.5 mm (0.59 x 0.59 x 0.02 in.).

is influenced by the presence of damage much more than velocity. Attenuation as a function of frequency was calculated in this study using the FFT of the specimens' signal captured by the broadband transducers. This was done to expand the information to as wide a frequency band as possible. Because the characterization of damage is investigated herein, the reference was taken from the response of the plain mortar. Specifically, if $A(f)$ is the frequency response of a specimen with inclusions and $B(f)$ is the response of plain mortar, the frequency-dependent attenuation coefficient $a(f)$ was calculated as

$$a(f) = -\frac{20}{x} \log \left(\frac{A(f)}{B(f)}\right) \quad (2)$$

where x is the wave path of 0.15 m (0.49 ft). Therefore, the excessive attenuation that is due to the existence of the light inclusions is calculated.

In Fig. 8(a), the attenuation curves of mortar with different inclusion contents are depicted for the thinner and bigger inclusions of 30 x 30 x 0.2 mm (1.18 x 1.18 x 0.007874 in.). The mortar with 1% plastic inclusions exhibits low attenuation until approximately 250 kHz, whereas the attenuation is increased for higher frequencies. In the case of 5 and 10%, attenuation is higher for the whole frequency band, especially for frequencies above 250 kHz.

In Fig. 8(b), one can see the attenuation curves for the other inclusion type (thicker). The behavior of 1% seems similar to that of thinner inclusions with somewhat lower values. The attenuation of 5% increases significantly again although not as much as the case of Fig. 8(a). Finally, the case of 10% is of particular interest because it exhibits the highest attenuation of all the mixtures presented at the frequencies of 300 to 400 kHz. The attenuation behavior below 150 kHz, however, is lower than the corresponding of the thin inclusions of 10% (refer to Fig. 8(a)). This is in agreement with the energy depicted in Fig. 4 where the frequencies included in the excitation are limited below 150 kHz. From the aforementioned, it is seen that not only the content but also the size can influence the attenuation behavior. Theoretical investigation using scattering theory is currently undertaken to explain this behavior using the actual shape of the inclusions and not the spherical approximation.

In any case, the excessive attenuation is much more indicative of the damage content than the velocity because even 1% of inclusions can be distinguished. Furthermore, discrepancies between damaged and plain mortar are clearer for frequencies above 200 or 300 kHz. This implies that when possible, higher frequency excitation should be applied for enhanced characterization capabilities.

CONCLUSIONS

In this study, an experimental series of stress wave propagation in mortar with light inclusions is described. The inclusions are thin, realistically simulating actual cracks, whereas parameters like the pulse velocity and energy are correlated with the simulated damage percentage. The main points of the investigation are as follows:

1. Pulse velocity and wave amplitude in mortar are decreased by inclusions simulating damage, as has been stated in other works;

2. Narrow band signals are appropriate to reveal the velocity dispersion imposed by inhomogeneity. Plain mortar behaves in a dispersive way with higher frequencies propagating at higher velocities;

3. Light inclusions in mortar result in more highlighted dispersive behavior; therefore, velocity measurements at different frequencies can be studied as a tool for damage characterization;

4. Energy transmission is far more influenced by the presence of damage. If reliable coupling conditions can be guaranteed in place, attenuation measurements can lead to much more accurate characterization; and

5. The attenuation of higher frequencies seems also more indicative of the damage content whereas the size of the inclusions seems to affect the attenuation curve.

REFERENCES

1. Naik, T. R., and Malhotra, V. M., "The Ultrasonic Pulse Velocity Method," *CRC Handbook on Nondestructive Testing of Concrete*, V. M. Malhotra and N. J. Carino, eds., CRC Press, FL, 1991, pp. 169-188.

2. Aggelis, D. G., and Shiotani, T., "Repair Evaluation of Concrete Cracks Using Surface and Through-Transmission Wave Measurements," *Cement and Concrete Composites*, V. 29, No. 9, Oct. 2007, pp. 700-711.

3. Shiotani, T.; Shigeishi, M.; and Ohtsu, M., "Acoustic Emission Characteristics of Concrete Piles," *Construction and Building Materials*, V. 13, 1999, pp. 73-85.

4. Jones, R., "Testing of Concrete by Ultrasonic-Pulse Technique," *Proceedings of the Thirty-Second Annual Meeting*, Highway Research Board Proceedings, V. 32, 1953, pp. 13-16.

5. Kaplan, M. F., "The Effects of Age and Water/Cement Ratio upon the Relation between Ultrasonic Pulse Velocity and Compressive Strength," *Magazine of Concrete Research*, V. 11, No. 32, 1959, pp. 85-92.

6. Gudra, T., and Stawinski, B., "Non-Destructive Characterization of Concrete Using Surface Waves," NDT&E INT, V. 33, 2000, pp. 1-6.

7. Popovics, S., "Analysis of the Concrete Strength versus Ultrasonic Pulse Velocity Relationship," *Materials Evaluation*, V. 59, No. 2, 2001, pp. 123-130.

8. Kaplan, M. F., "The Relation between Ultrasonic Pulse Velocity and the Compressive Strength of Concretes Having the Same Workability but Different Mix Proportions," *Magazine of Concrete Research*, V. 12, No. 34, 1960, pp. 3-8.

9. Philipidis, T. P., and Aggelis, D. G., "An Acousto-Ultrasonic Approach for the Determination of Water-to-Cement Ratio in Concrete," *Cement and Concrete Research*, V. 33, 2003, pp. 525-538.

10. Anderson, D. A., and Seals, R. K., "Pulse Velocity as a Predictor of 28- and 90-Day Strength," ACI JOURNAL, *Proceedings* V. 78, No. 2, Mar.-Apr. 1981, pp. 116-122.

11. Qasrawi, H. Y., "Concrete Strength by Combined Nondestructive Methods Simply and Reliably Predicted," *Cement and Concrete Research*, V. 30, 2000, pp. 739-746.

12. Kheder, G. F., "A Two-Stage Procedure for Assessment of In-Situ Concrete Strength Using Combined Non-Destructive Testing," *Materials and Structures*, V. 32, July 1999, pp. 410-417.

13. Mikulic, D.; Pause, Z.; and Ukraincik, V., "Determination of Concrete Quality in a Structure by Combination of Destructive and Non-Destructive Methods," *Materials and Structures*, V. 25, 1999, pp. 65-69.

14. Shah, S. P.; Popovics, J. S.; Subramanian, K. V.; and Aldea, C. M., "New Directions in Concrete Health Monitoring Technology," *Journal of Engineering Mechanics*, ASCE, V. 126, No. 7, 2000, pp. 754-760.

15. Selleck, S. F.; Landis, E. N.; Peterson, M. L.; Shah, S. P.; and Achenbach, J. D., "Ultrasonic Investigation of Concrete with Distributed Damage," *ACI Materials Journal*, V. 95, No. 1, Jan.-Feb. 1998, pp. 27-36.

16. Chaix, J. F.; Garnier, V.; and Corneloup, G., "Ultrasonic Wave Propagation in Heterogeneous Solid Media: Theoretical Analysis and Experimental Validation," *Ultrasonics*, V. 44, 2006, pp. 200-210.

17. Garnier, V.; Chaix, J. F.; and Corneloup, G., "Applying Waves' Propagation Modeling to the Study of Concrete Damage," *International Symposium*, *Non-Destructive Testing in Civil Engineering*, Berlin, 2003. (CD-ROM)

18. Ono, K., "Damaged Concrete Structures in Japan Due to Alkali Silica Reaction," *The International Journal of Cement Composites and Lightweight Concrete*, V. 10, No. 4, 1988, pp. 247-257.

19. Al Wardany, R.; Rhazi, J.; Ballivy, G.; Gallias, J. L.; and Saleh, K., "Use of Rayleigh Wave Methods to Detect Near Surface Concrete Damage," 16th WCNDT 2004, World Conference on NDT, Montreal, QC, Canada, 2004. (CD-ROM)

20. Malhotra, V. M., and Carino, N. J., eds., *CRC Handbook on Nondestructive Testing of Concrete*, CRC Press, FL, 1991, 360 pp.

21. Guo, J. S., and Waldron, P., “Development of the Stiffness Damage Test (SDT) for Characterization of Thermally Loaded Concrete,” *Materials and Structures*, V. 33, Oct. 2000, pp. 483-491.

22. Hernandez, M. G.; Anaya, J. J.; Ullate, L. G.; Cegarra, M.; and Sanchez, T., “Application of a Micromechanical Model of Three Phases to Estimating the Porosity of Mortar by Ultrasound,” *Cement and Concrete Research*, V. 36, No. 4, 2006, pp. 617-624.

23. Lafhaj, Z.; Goueygou, M.; Djerbi, A.; and Kaczmarek, M., “Correlation between Porosity, Permeability and Ultrasonic Parameters of Mortar with Variable Water/Cement Ratio and Water Content,” *Cement and Concrete Research*, V. 36, No. 4, 2006, pp. 625-633.

24. Popovics, S., and Popovics, J. S., “Effect of Stresses on the Ultrasonic Pulse Velocity in Concrete,” *Materials and Structures*, V. 24, 1991, pp. 15-23.

25. Suaris, W., and Fernando, V., “Detection of Crack Growth in Concrete from Ultrasonic Intensity Measurements,” *Materials and Structures*, V. 20, 1987. pp. 214-220.

26. Van Hauwaert, A.; Thimus, J. F.; and Delannay, F., “Use of Ultrasonics to Follow Crack Growth,” *Ultrasonics*, V. 36, 1998, pp. 209-217.

27. Christensen, R. M., “A Critical Evaluation for a Class of Micromechanics Models,” *Journal of the Mechanics and Physics of Solids*, V. 38, No. 3, 1990, pp. 379-404.

28. Crouch, R. S., and Wood, J. G. M., “Damage Evolution in AAR Affected Concretes,” *Engineering Fracture Mechanics*, V. 35, No. 1/2/3, 1990, pp. 211-218.

29. Landis, E. N., and Shah, S. P., “Frequency-Dependent Stress Wave Attenuation in Cement-Based Materials,” *Journal of Engineering Mechanics*, ASCE, V. 121, No. 6, 1995, pp. 737-743.

30. Otsuki, N.; Iwanami, M.; Miyazato, S.; and Hara, N., “Influence of Aggregates on Ultrasonic Elastic Wave Propagation in Concrete,” T. Uomoto, ed., *Non-Destructive Testing in Civil Engineering*, Elsevier, Amsterdam, the Netherlands, 2000, pp. 313-322.

31. Philippidis, T. P., and Aggelis, D. G., “Experimental Study of Wave Dispersion and Attenuation in Concrete,” *Ultrasonics*, V. 43, 2005, pp. 584-595.

32. Waterman, P. C., and Truell, R., “Multiple Scattering of Waves,” *Journal of Mathematical Physics*, V. 2, 1961, pp. 512-537.

33. Graff, K. F., *Wave Motion in Elastic Solids*, Dover Publications, New York, 1975, pp. 394-430.

34. Punurai, W.; Jarzynski, J.; Qu, J.; Kurtis, K. E.; and Jacobs, L. J., “Characterization of Entrained Air Voids in Cement Paste with Scattered Ultrasound,” NDT&E INT, V. 39, No. 6, 2006, pp. 514-524.

35. Aggelis, D. G.; Polyzos, D.; and Philippidis, T. P., “Wave Dispersion and Attenuation in Fresh Mortar: Theoretical Predictions Versus Experimental Results,” *Journal of the Mechanics and Physics of Solids*, V. 53, 2005, pp. 857-883.

36. Owino, J. O., and Jacobs, L. J., “Attenuation Measurements in Cement-Based Materials Using Laser Utrasonics,” *Journal of Engineering Mechanics*, V. 125, No. 6, June 1999, pp. 637-647.

37. Popovics, S.; Rose, J. L.; and Popovics, J. S., “The Behavior of Ultrasonic Pulses in Concrete,” *Cement and Concrete Research*, V. 20, 1990, pp. 259-270.

38. Aggelis, D. G.; Tsinopoulos, S. V.; and Polyzos, D., “An Iterative Effective Medium Approximation (IEMA) for Wave Dispersion and Attenuation Predictions in Particulate Composites, Suspensions and Emulsions,” *Journal of the Acoustical Society of America*, V. 116, No. 6, 2004, pp. 3443-3452.

39. Kinra, V. K., and Rousseau, C., “Acoustical and Optical Branches of Wave Propagation,” *Journal of Wave Material Interaction*, V. 2, 1987, pp. 141-152.

40. Jacobs, L. J., and Owino, J. O., “Effect Size on Attenuation of Rayleigh Surface Waves in Cement-Based Materials,” *Journal of Engineering Mechanics*, V. 126, No. 11, pp. 1124-1130.