

INVESTIGATION OF INTERFACIAL LOSSES IN CONCRETE WITH LASER ULTRASONICS

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INTRODUCTION

Laser ultrasonic techniques are used to investigate interfacial losses in concrete. The experimental methodology uses a pulse ruby laser for optical generation and a heterodyne interferometer for laser detection. Concrete is a heterogeneous material made up of both fine and coarse aggregate. The presence of this aggregate, in addition to voids and flaws, causes elastic wave scattering in concrete. This study examines the propagation of ultrasonic waves in both "plain" mortar and concrete. In addition, it develops a one-dimensional model for the losses due to the interface between the mortar and the aggregate. Laser ultrasonic techniques are essential for this study because they allow for the broad band generation and detection of ultrasonic waves without influencing their frequency content.

The optical generation and detection of elastic waves has proven to be an effective method of nondestructive evaluation and material characterization in metal components. These laser techniques have the potential for a wide variety of applications, but they are most likely to succeed in those cases where they provide distinct advantages over traditional ultrasonic methods. Foremost among these advantages is that laser ultrasonics is capable of the non-contact, broad band generation and detection of elastic waves. This profile of laser ultrasonics makes it ideally suited for the characterization of concrete. One of the most widely used methods of ultrasonic evaluation in concrete, the pulse velocity method, only uses the arrival time of an elastic wave propagating through a known distance of concrete. This measured arrival time is used to calculate the longitudinal wave velocity which is directly related to the concrete elastic modulus and density. However, ultrasonic waves contain much more information than just arrival times. Quantitative ultrasonic techniques, such as laser ultrasonics, use both the time and frequency contents of these elastic waves, and can fully determine the concrete's material condition and structural integrity.

This paper presents the results of a study that uses laser generation and detection techniques to examine the propagation of ultrasonic waves in concrete. This work specifically examines the effect of the aggregate/mortar interface on an ultrasonic wave's frequency content. This research first determines the effect of aggregate size on frequency content by

examining four different concrete mixes. These mixes have the same approximate strength, but their maximum aggregate size varies from 3.81 cm to 0.952 cm. The frequency contents of experimentally measured ultrasonic waveforms are examined with respect to propagation distance and maximum aggregate size. Next, one-dimensional interface specimens are used to measure ultrasonic losses that occur in the aggregate/mortar interface. These one-dimensional test results are compared to analytical predictions to determine the influence of the interface on ultrasonic wave propagation.

BACKGROUND REVIEW

The article by Gaydecki et al. [1] examines the propagation and attenuation of ultrasonic waves in concrete by studying the frequency content in discrete time windows of experimentally measured pulses. Kim et al. [2] investigates the attenuation and dispersion of ultrasonic waves in both concrete and mortar with a broad band generation source, a glass capillary break, combined with a pin-type, piezoelectric transducer for detection. Jacobs and Johnson [3] examine the use of laser ultrasonics for the nondestructive evaluation of concrete.

EXPERIMENTAL PROCEDURE

Four different concrete mixtures are examined to determine the influence of aggregate size. Each mixture is made with different coarse aggregate, but has the same Portland Type I cement and fine aggregate (passes through a No. 4 sieve). The water-to-cement ratio of all four concrete mixes is held constant at 0.55 to obtain an approximate strength of 2.75×10^7 PA. The four aggregate types are, according to the Standard Sizes of Coarse Aggregate for Highway Construction: well graded No. 57, poorly sorted No. 6, plus No. 81 and No. 89. The corresponding maximum aggregate sizes are 3.81 cm, 2.54 cm, 1.27 cm and 0.952 cm. Concrete samples are cast in plastic forms, 35.56 X 10.16 X 10.16 cm, and kept at 100% humidity for 30 days. Individual specimens, 5.08 cm and 10.16 cm, are cut from the 35.56 cm length of each block. Four different one-dimensional interface specimens are used: plain mortar, 1.63 cm thick; two plain aggregate (granite), 1.49 and 2.45 cm thick; and a mortar/granite composite, 4.66 cm total thickness (granite: 1.56 cm and mortar: 3.10 cm). The smallest width or height dimension for these one-dimensional specimens is 10.16 cm.

The instrumentation for laser generation of ultrasound includes a Q-switched, pulse ruby laser, a photodetector for triggering and a focusing lens. The Q-switching feature of this laser emits a spatially Gaussian, 30 nanosecond pulse with a wavelength of 694.3 nanometers. The energy of this pulse is 108.3 millijoules with a standard deviation of 4.5 millijoules. Light from this pulse is used as a trigger. This trigger time (from the ruby pulse) marks the instant that the ultrasonic waves are generated, and is needed to calculate elastic waves velocities in the concrete. In addition, the photodetector is used to measure the amplitude of the ruby pulse; this amplitude is used to verify the consistency of the output energy for each ultrasonic waveform generated. The beam diameter that strikes the specimen is regulated by using a focusing lens, which allows for modifications in the spot size of the laser source. Laser detection of ultrasound is accomplished with a heterodyne interferometer that is described in detail in [4].

A number of improvements are utilized to increase the signal-to-noise ratio of the detection system. First, a tunable band pass filter is used to remove extraneous noise; all experiments are high-pass filtered at 75 kHz and low-pass filtered at 2.2 MHz. Secondly, a small amount of reflective tape is applied to the specimen at the point of observation to increase the amount of reflected light obtained by the interferometer. This tape has no effect

on the measured ultrasonic waveforms and greatly improves the signal-to-noise ratio. Thirdly, a constrained liquid source mechanism is used to increase both the strength and directivity of the optically generated body, ultrasonic waves. The generation surface is treated with a small amount of light oil, covered by a glass slide. This allows for an ablation like generation, without any of the associated surface damage. This generation source is highly repeatable and, as previously discussed, produces an ultrasonic pulse concentrated in a single lobe which propagates normal to the surface. In addition, spatial averaging is introduced in order to obtain a more representative sample of each concrete specimen. All measurements are repeated four times; for each case, the specimen locations of the generation and detection sources are moved, but their relative separation distance remains constant. These four waveforms are averaged, and these average signals are used in all of the following results.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to investigate the frequency content of the measured ultrasonic waveforms, a consistent rectangular (boxcar) windowing scheme is developed. The Fast Fourier Transform (FFT) of the first 10μsec (which represents 500 discrete time points) of signal is used to examine the frequency content of the waveform. This 10μsec window is used in all the frequency results that follow because it includes the concrete material effects but eliminates the unwanted geometric effects such as reflections off the specimen boundaries. In order to make a relative comparison of the signal strength within a bandwidth of the frequency spectrum, the Root Mean Square (RMS) of the FFT is defined as

$$RMS=(\sum[Y(f)]^2)^{1/2} \quad (1)$$

where $Y(f)$ is the FFT magnitude at a discrete frequency point, f , and the summation is implied over the frequency. In all examples, the RMS values are calculated by summing over the same bandwidth, from 75 kHz to 2.2 MHz.

The first set of experiments show the effect of propagation distance on body waves by examining elastic waves that propagate through the 5.08 cm and 10.16 cm specimens of each aggregate type. A qualitative comparison between the waveforms that propagate through 5.08 and 10.16 cm shows the highly attenuating nature of concrete; there is a decrease in signal strength by a factor of ten for a waveform that travels the additional 5.08 cm. These results, as well as the dependency of signal frequency content on propagation distance are discussed in detail in [3]. In summary, the RMS value is directly dependent upon propagation distance; the greater the distance traveled, the smaller the RMS value. In addition, the higher frequency portion of the original signal is scattered and lost as a wave propagates through the concrete. For example, the maximum frequency that propagates through 10.16 cm of No. 89 concrete is approximately 500 kHz, while the maximum for the 5.08 cm distance is on the order of 1.0 MHz.

These experiments are also used to investigate the effect of aggregate size on frequency content. The wavelength, α , is related to frequency, f , and the longitudinal wave speed, c_L , as

$$\alpha_L = \alpha f \quad (2)$$

By using a longitudinal wave speed of 3,657 m/sec, the wavelengths will vary linearly, as a function of frequency, from 3.66 cm for 100 kHz, to 0.366 cm for 1 MHz. Consider a simple scattering model where the aggregate are considered as scatters. In this model, the portion of the original ultrasonic waveform with wavelengths less than the largest aggregate size will be

scattered, while those larger than the largest aggregate size will pass through unaffected. For this simple aggregate scattering model there should be cut-off frequencies of approximately 380 kHz for No. 89, 290 kHz for No. 81, 140 kHz for No. 6 and 90 kHz for No. 57. The validity of this scattering model is not shown in [3]: there is no consistent relationship between frequency content and aggregate size. In fact, the frequency content of all of the mixtures is much higher than the wavelength-scattering relationship predicts.

The reason for this apparent anomaly in these higher frequency ultrasonic waves is that there is a very small difference in the impedances (where impedance is defined as the mass density times wave speed) of the mortar and the granite aggregate. When a wave strikes the interface between two media of different materials, part of the wave is reflected and part of the wave is transmitted across the interface. The amount of transmission and reflection is dependent on the relative impedances of each of the two materials. For demonstration purposes, examine a one-dimensional interface. Following Achenbach [5], the amplitudes (coefficients) of the reflected waves for a mortar to granite interface and the subsequent granite to mortar interface are calculated to be 0.09 and -0.09, respectively. It should be noted that a reflection coefficient of 1.00 represents total reflection, while a reflection coefficient of 0.00 represents total transmission. The low reflection coefficients calculated for the mortar-granite interfaces indicate that a vast majority of the wave disturbance is transmitted through the aggregate. This one-dimensional analogy validates the observed lack of correlation between frequency and aggregate size; aggregate size is not the critical factor in determining the frequency content of ultrasonic waves in concrete.

The interface specimens are used to experimentally investigate this transmission and reflection relationship. The time history of an ultrasonic waveform (longitudinal) that propagates through 1.63 cm of mortar is shown in Fig. 1. This signal is compared to the time

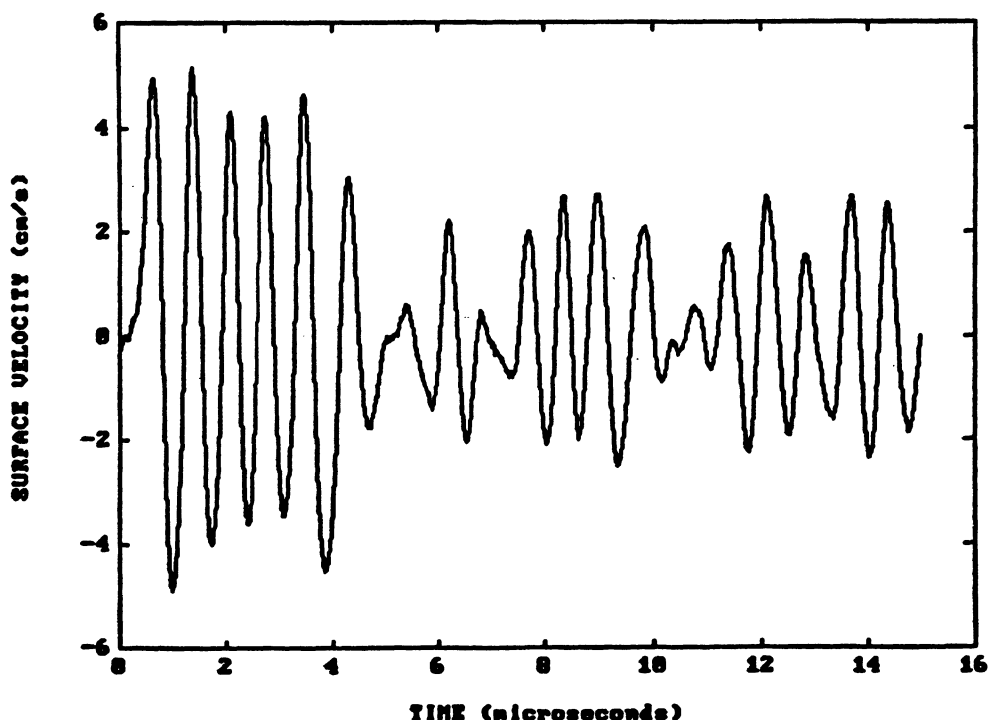


Figure 1. Longitudinal wave that propagates through 1.63 cm of mortar

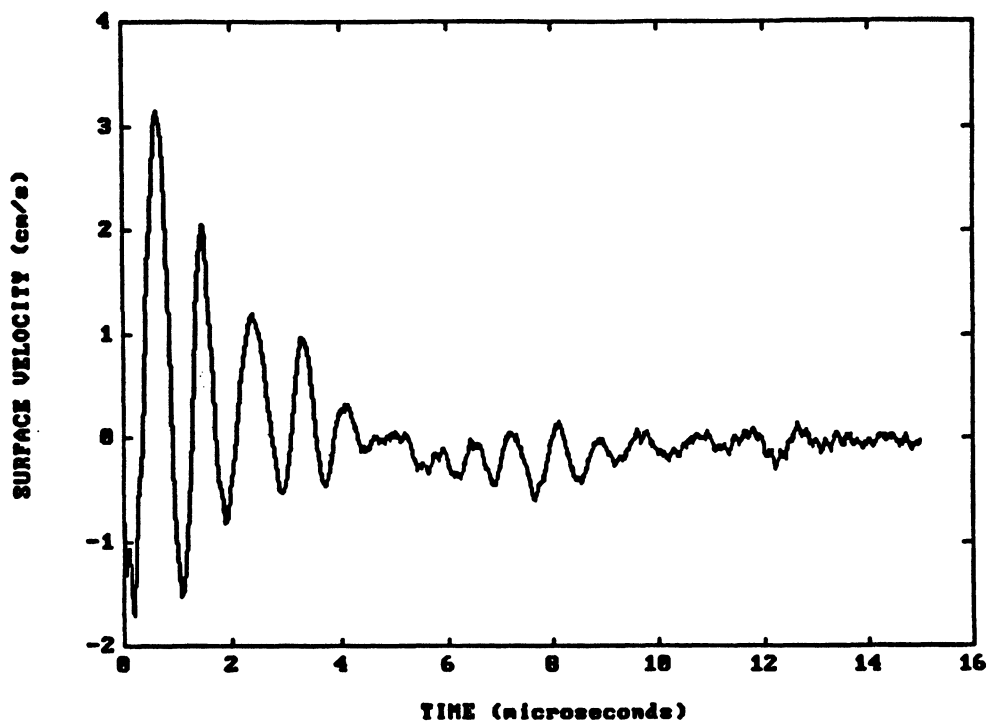


Figure 2. Longitudinal wave that propagates through 1.49 cm of granite

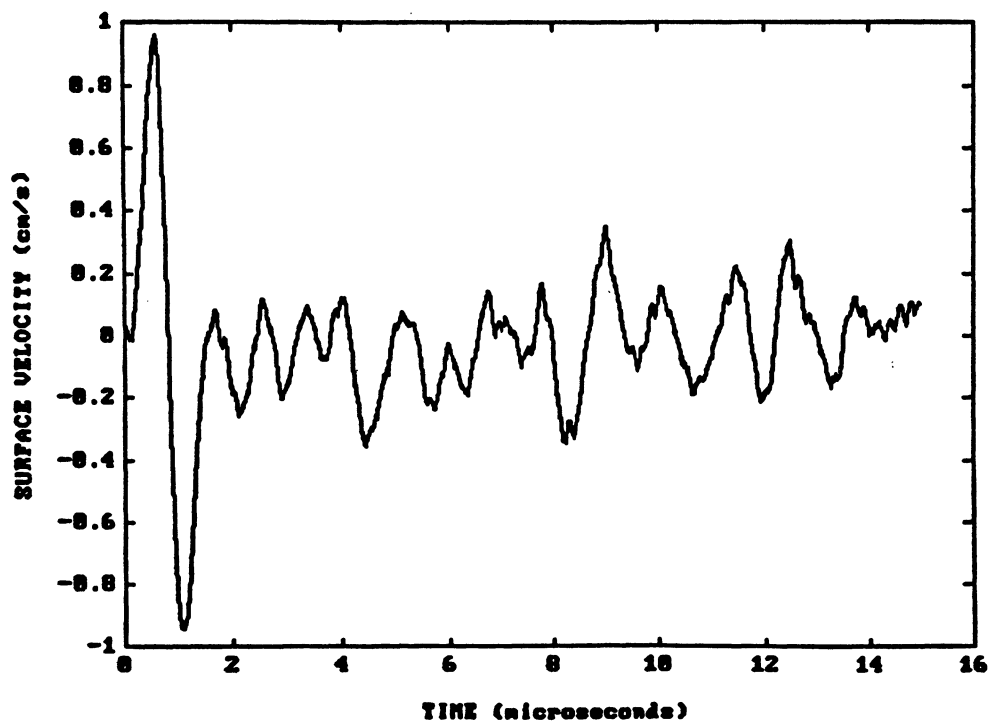


Figure 3. Longitudinal wave that propagates through 4.66 cm of mortar/granite composite

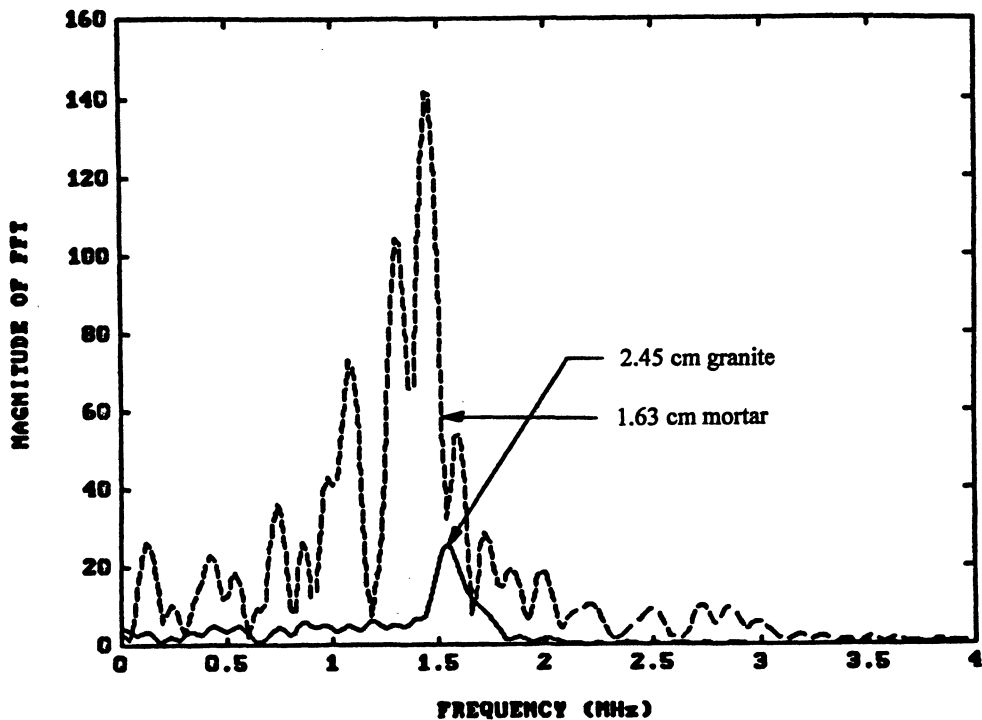


Figure 4. Comparison of frequency responses through 2.45 cm, granite and 1.63 cm, mortar

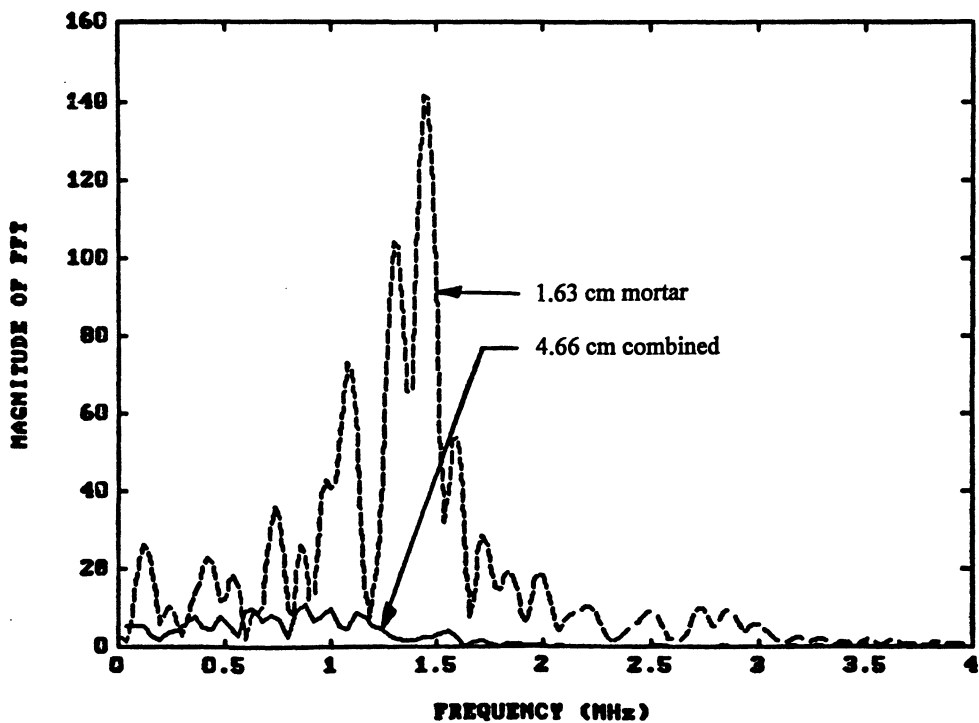


Figure 5. Comparison of frequency responses: 1.63 cm, mortar and 4.66 cm, composite

history of a longitudinal wave that propagates through 1.49 cm of granite (Fig. 2) and the time history of a longitudinal wave that propagates through 4.66 cm of composite mortar/granite (Fig. 3). In addition, Figs. 4 and 5 compare the magnitudes of the FFT's of the first 10 μ sec of signal for the mortar, granite and composite mortar/granite specimens.

A qualitative comparison between the signal amplitudes of Figs. 1 and 2 and that of Fig. 3 shows that there are significant losses associated with the mortar/granite interface; these losses are much greater than those predicted by the one-dimensional reflection coefficient of 0.09. It is also interesting to note the difference in signal shapes: Fig. 1 is typical of the waveforms measured in concrete [3]; Fig. 2 shows a distinctive asymptotic decrease in signal amplitude; and the dominant feature of Fig. 4 is the single cycle of signal. The comparisons of frequency responses in Figs. 5 and 6 show the magnitude of the losses associated with the mortar/granite interface are much greater than those predicted by the simple one-dimensional model; the FFT magnitude of the composite mortar/granite specimen is a factor of ten lower than the plain mortar magnitude.

CONCLUSION

This paper explores some of the potential advantages of laser ultrasonics for the nondestructive characterization of concrete by investigating losses through concrete interfaces. Specific conclusions of this research are:

1. It is possible to optically generate and detect ultrasound in concrete.
2. The frequency content of these ultrasonic waveforms is dependent upon propagation distance.
3. Aggregate size is not the critical factor in determining the frequency content of an ultrasonic waveform.
4. Greater losses exist than those that are predicted by a simple one-dimensional model.

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