CHARACTERIZATION OF DISTRIBUTED DAMAGE IN CONCRETE USING ADVANCED IMPACT-ECHO METHOD

R.A. Livingston[1], A.M.Sutin[2], N. McMorris[3], M. Ceary[3] and A.M. Amde[3]
[1]Office of Infrastructure R&D, Federal Highway Administration, McLean VA,22101, USA
[2] Davidson Laboratory Stevens Institute of Technology, Hoboken, NJ, 07030, USA
[3]Civil and Environmental Engineering Dept., University of Maryland, College Park, MD, 20742, USA

ABSTRACT

The extent of damage caused by delayed ettringite formation has not yet been established. A field study of damaged bridges has been initiated in the state of Maryland involving both destructive and nondestructive test methods. To characterize the physical damage in the form of distributed microcracking, a modified version of the impact echo test was used. This used the attenuation of the echoes as the parameter to quantify the damage rather than the pulse velocity. The successive peaks in the waveforms were fitted to an exponential decay model and Q factor was calculated. The Q factor was then used as the damage variable. Surveys were carried out on 12 concrete bridges across the state of Maryland. On apparently undamaged concrete, it was possible to obtain reasonably good fits to the data. The Q factor was typically higher than 15 which is consistent with negligible microcracking. However, waveforms taken on damaged concrete often were too distorted to permit a good fit using a simple high pass filtering method. Preliminary work using more advanced signal processing methods suggests that it is possible to extract the parameters even in damaged areas by using data windowing to eliminate the early transients, band pass filtering around the resonant frequency and using both positive and negative peak amplitudes. The preliminary measurements show decreasing of Q factor due to crack presence.

1 INTRODUCTION

The phenomenon known as delayed ettringite formation (DEF) has been observed in a number of concrete structures. It is associated with damage in the form of distributed microcracking, but the exact relationship is still controversial. One reason for the continuing controversy is the scarcity of data from actual damaged structures, Thomas[1]. Therefore, to get a better idea of the extent of damage from DEF, a systematic field survey has been conducted on a sample of bridges in the state of Maryland. Unfortunately, the only methods for identifying the presence of ettringite are destructive, requiring samples of concrete to be taken for analysis in the laboratory. Nevertheless, in this survey, two nondestructive methods were also used: potassium autoradiography and impact-echo. The former uses the storage phosphor image plate method to quantify the amount of potassium present from the natural radioactivity of potassium-40 (^{40}K), Livingston[2]. The impact-echo method was used to estimate the amount of microcracking, based on the attenuation of ultrasonic pulses. Although neither of these nondestructive methods provides a direct measure of DEF, they give indirect evidence of damage and causative factors.

2 METHOD

The impact-echo technique uses a small impactor consisting of a small steel ball on a spring to launch a broadband ultrasonic pulse into the material. As the pulse passes through the target, it will be reflected off interfaces and the echoes will be detected by a piezoelectric transducer. This is covered by a spring-loaded disk to provide good coupling to the surface. This avoids the need for applying a liquid or gel couplant. The resulting time history or waveform will thus show a series of peaks indicating the arrival of the echoes Fig. 1. In the conventional method, the time it takes for the echo to return is used to estimate the distance to the interface, which may be either the backside or a crack, according to the equation:

$$t = \frac{2L}{v_p} \qquad (1)$$

where t = time of arrival, L = distance from surface to the interface and v_p is the speed of the P-wave (compression wave). This equation can be used to determine distance, if the sound velocity in the material is known, or conversely, the speed of sound if the distance is known. In practice, instead of using the actual times of arrival, the waveform is converted into a frequency spectrum using the Fast Fourier transform, and the distance is estimated using the frequency of the fundamental frequency peak:

$$f = \frac{\beta v_p}{2L} \qquad (2)$$

where *ß* is a geometric factor, 0.96 in the case of a slab, Sansalone[3].

The approach used here does not involve locating a specific feature such as a structural crack, but rather quantifying the distributed microcracks. These cause scattering and absorption of the sound waves, which results in reduction of the amplitudes of the echo peaks. Previous research has shown that all cracks, having a crack opening larger than about 0.025 mm (0.001 in) will begin to scatter stress waves, Cheng[4]. As more cracks develop and open beyond 0.025 mm, they will transmit less energy across the crack and instead cause an increased amount of stress wave scattering. This will result in a more rapid decrease in stress wave intensity with time than is caused by divergence (beam spreading) alone. When cracks reach 0.08 mm (0.003 in) in width they become distinct cracks, and no energy is transmitted across the crack, Sansalone[3].

As each successive echo arrives its amplitude is less than the previous one, and the series of peaks can thus be fitted by an exponential decay function, as shown in Fig. 2, Kesner [5]. The

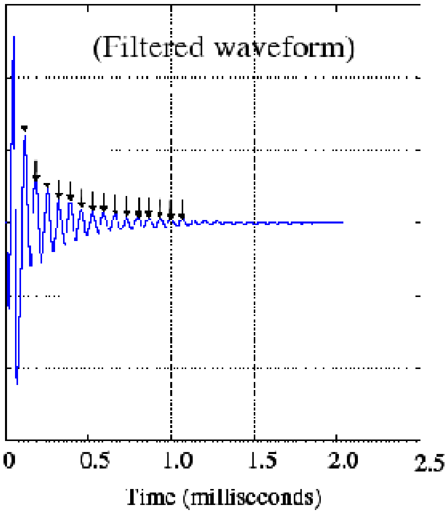

Figure 1: Impact-echo waveform, arrows indicate echoes

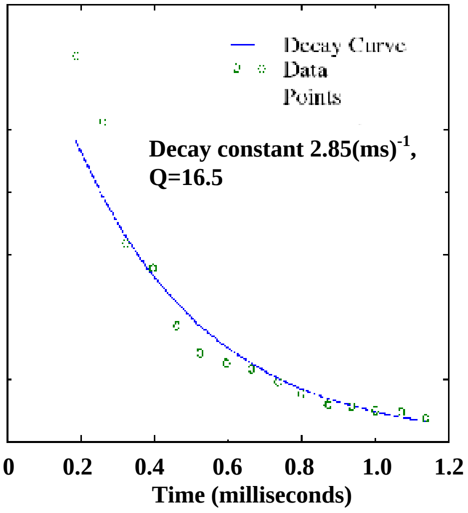

Figure 2: Exponential fit to peaks in data of Figure 1

decay constant obtained by this curve fitting thus becomes a measure of the amount of attenuation and hence the microcracking damage. For a valid fit, there should be at least 10 individual peaks. The Q factor is then calculated using the decay constant α:

$$Q = \pi f / \alpha \tag{3}$$

To relate the observed Q factor to actual damage, a laboratory study was conducted using slabs of concrete with varying levels of microcracking. The area density of microcracks was determined by neutron radiography of slices of cores taken from the slabs. The amount of attenuation increases as the decay constant increases. A value for the Q factor more than 16 indicates little or no microcracking.

3 FIELD APPLICATION

In a pilot study for a survey of bridges in the State of Maryland, 12 concrete bridges out of a total of 822 were selected for measurement by the impact-echo technique, Amde[6]. For each bridge, points were measured in a grid covering both damaged and undamaged areas.

To calculate the decay constant for a given waveform, the waveform must be filtered to remove the effects of low frequency modes of vibrations. These modes are apparent in the waveform as large amplitude, low frequency displacements superimposed upon the higher frequency displacement pattern caused by the multiple P-wave echoes. To remove the low frequency modes of vibration, a high-pass Butterworth filter can be used. For example the effect of a 5th order Butterworth filter is shown in Figs 3a and 3b.

On apparently undamaged concrete, it was possible to obtain reasonably good fits to the data. The Q factor was typically more than 10, which is consistent with negligible microcracking. However, for deteriorated concrete distortions of the waveforms made it difficult to obtain enough points for a valid fit as shown Figs 4 and 5 for signal recorded in damaged concrete. In these cases simple high pass filtering was not enough and more advanced methods had to be used. This in-

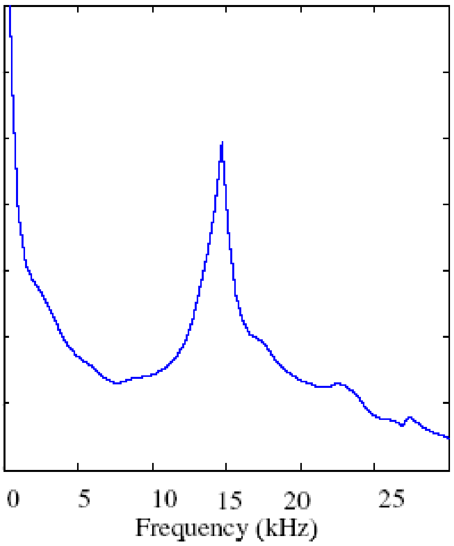

Figure 3a: Raw frequency spectrum

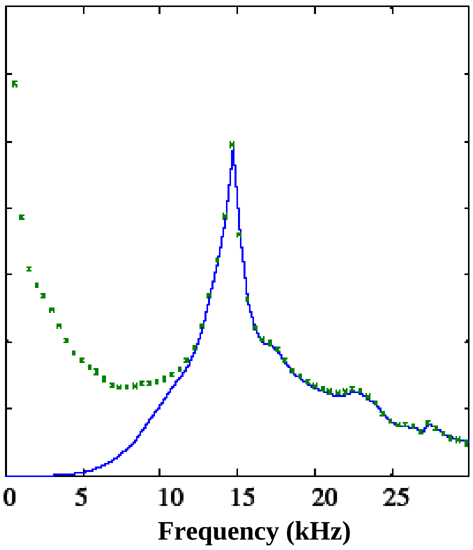

Figure 3b: Highpass-filtered frequency spectrum

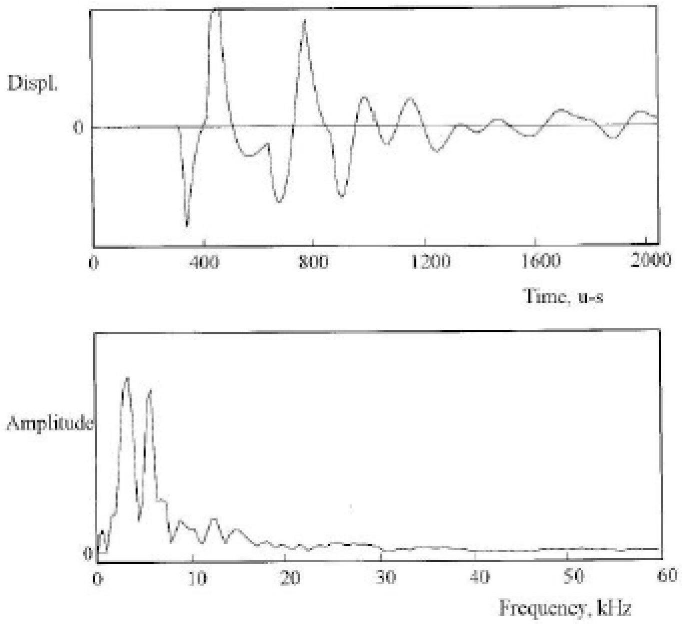

Figure 4: Waveform and frequency spectrum, Point 1-6, Greentree Road bridge

included windowing the data to exclude the early transients by using only the second half of the wave. Next a bandpass filter was applied with the central frequency of the filter chosen near the maximum of the spectrum and with a bandwidth about 50% of the central frequency. The result is shown in Fig. 6. The series of echoes is much more visible. With the peaks clearly identifiable, both positive and negative amplitudes were selected and were plotted in a semi-logarithmic graph, Fig.7. The decay constant obtained is 0.26 $(ms)^{-1}$ (Q = 6.2) compared to the value of

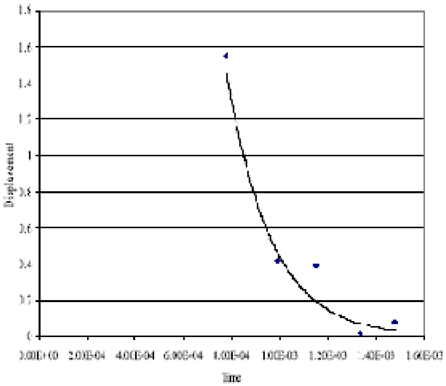

Figure 5: Fit to peaks in waveform of Figure 4, $y = 1.026e^{-5453x}$

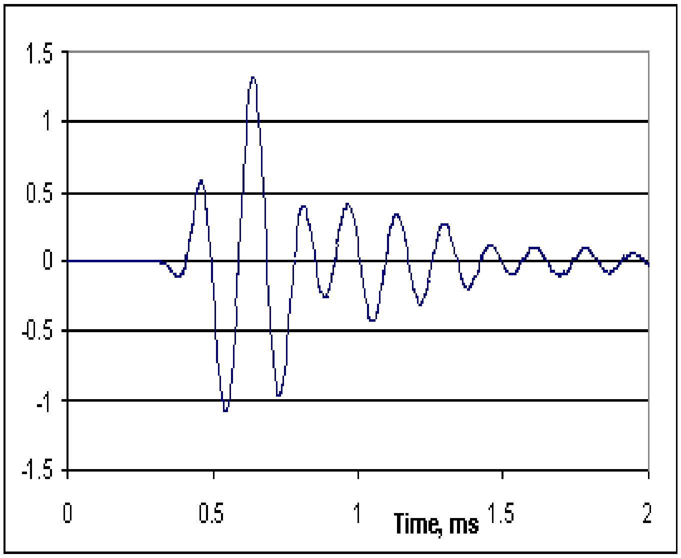

Figure 6: Bandpass filtered version of Greentree Road 1.6

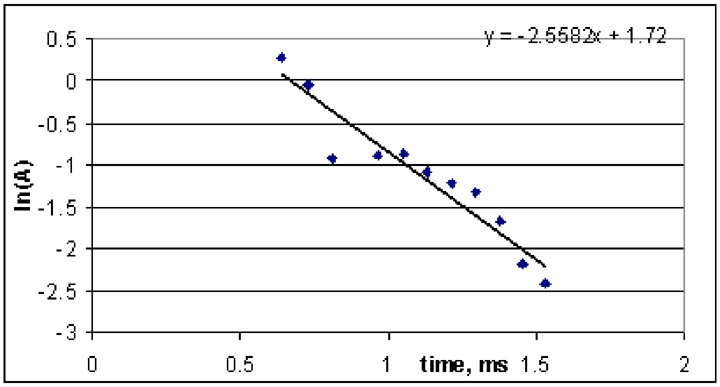

Figure 7: Semi-logarithmic plot of peaks in Figure 5.

$0.55(\mathrm{ms})^{-1}$ found with the highpass filter.

4 CONCLUSIONS

A modified version of the impact echo test was used to characterize concrete damage in the form of distributed microcracking. This used the attenuation of the echoes as the parameter to quantify the damage rather than the pulse velocity. The successive peaks in the waveforms were fitted to an exponential decay model. The decay constant was then used as the damage variable. Surveys were carried out on 12 concrete bridges across the state of Maryland. On apparently undamaged concrete, it was possible to obtain reasonably good fits to the data. The Q factor was more than 15, which is consistent with negligible microcracking. However, waveforms taken on damaged concrete often were too distorted to permit a good fit using a simple high pass filtering method. Preliminary work using more advanced signal processing methods suggests that it is possible to extract the parameters even in damaged areas by using data windowing to eliminate the early transients, band pass filtering around the resonant frequency and using both positive and negative peak amplitudes.

5 ACKNOWLEDGEMENTS

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