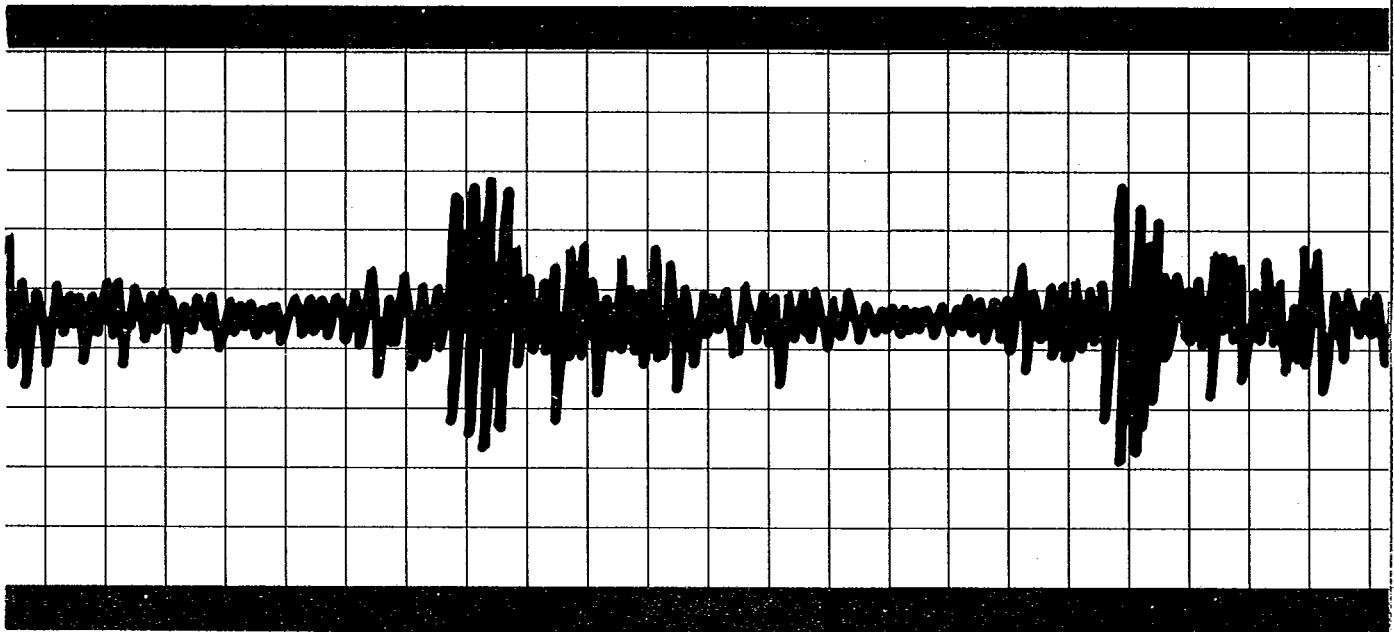


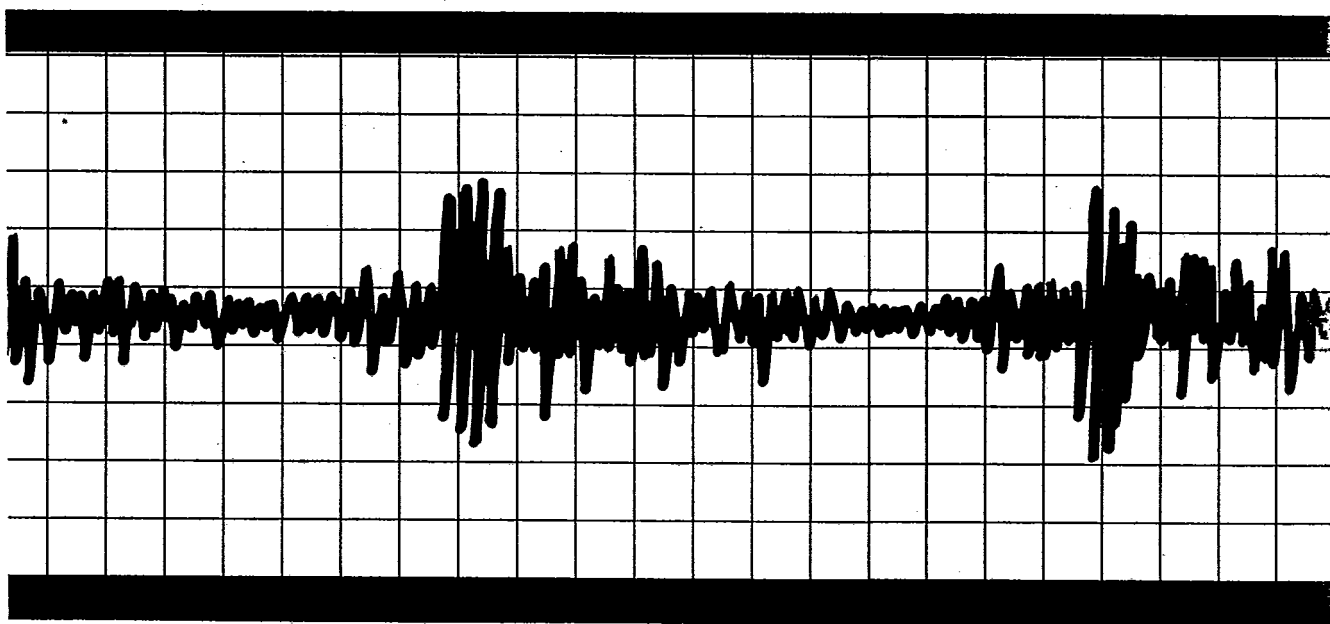
Nondestructive Testing



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PREFACE

The primary goal of Committee 228, Nondestructive Testing of Concrete, is to promote the use of nondestructive testing techniques in concrete construction and to disseminate up-to-date information on the application of these techniques. To achieve this goal, the committee has sponsored symposia to provide the latest information on the development and applications of NDT techniques.

The first symposium was held at the 1984 ACI Annual Convention. Of the seven papers presented, five were published in the February 1985 issue of Concrete International. At the 1987 ACI Annual Convention, the committee sponsored two half-day sessions. Among the large number of papers submitted, the committee carefully selected eleven technical papers for presentation. The topics range from laboratory studies and field applications to statistical analysis of data. This volume contains nine of the papers which were presented at the symposium, plus two papers which were submitted specifically for this volume.

The authors are gratefully acknowledged for their presentations at the symposium and for preparing their manuscripts for this volume. The work of the ACI staff in printing this volume is appreciated. The chairman of the symposium wishes to acknowledge the committee members who assisted in organizing the symposium. They are: Kiho Choi, Robert Jenkins, Joe O'Neill, Mary Sansalone, Phil Seabrook, and George Teodoru.

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SP 112-1

Laboratory and Field Studies of the Impact-Echo Method for Flaw Detection in Concrete

by M. Sansalone and N.J. Carino

Synopsis: A nondestructive test method has been developed for locating defects in concrete. The technique is referred to as the impact-echo method and is based on monitoring surface displacements resulting from the interactions of transient stress waves with internal discontinuities. This paper describes the technique and presents results of laboratory studies designed to evaluate the capabilities of the method. These laboratory studies were carried out on 500-mm thick slabs which contained a variety of artificial flaws embedded at known locations. Frequency analysis of recorded time-domain waveforms is explained and shown to be a quick and simple signal processing technique. Finally, results are presented from a field study in which the impact-echo method was used to investigate a 150-mm thick slab believed to contain voids.

Keywords: concretes; concrete slabs; impact; nondestructive tests; ultrasonic tests; voids

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INTRODUCTION

A nondestructive testing technique for locating flaws within concrete has been developed at the National Bureau of Standards (NBS) [1-4]. The technique involves introducing transient stress waves into a test object by mechanical impact and monitoring the dynamic displacements caused by the arrival of waves reflected from internal defects and external boundaries. A transducer located close to the impact point is used to monitor the surface displacement. Previously referred to as a pulse-echo method, the technique has come to be called the **impact-echo method**. The name "impact-echo" was adopted to distinguish the technique from traditional ultrasonic pulse-echo techniques in which one piezoelectric transducer is used both to generate the stress pulse and to monitor reflections.

This paper describes significant improvements to the original measurement technique. Previously, recorded displacement waveforms were studied in the time domain and interpretation required determining the arrival times of wave reflections [1,2]. This time-consuming process has been replaced by frequency analysis, a simpler and more efficient method for data interpretation. In addition, this paper presents the results of laboratory studies using plain and reinforced concrete plates with known flaws and results obtained from a field study of an ice-skating rink slab containing voids.

Although this paper focuses primarily on the impact-echo measurement technique and on experimental results, a major part of the NBS research program has been devoted to understanding the physics involved in the test method. Theoretical and finite element studies of transient stress wave propagation in bounded solids with and without flaws have been performed [3-8]. The understanding gained from these studies provided the theoretical basis for the interpretation of the test results which are presented in this paper.

IMPACT-ECHO METHOD

Measurement Technique

Figure 1 is a schematic representation of point impact on a plate containing a flaw at a depth T . Initially, small steel ball bearings dropped from a height of 100 to 200 mm were used as the impact source. In current work, spring-loaded impactors, which have spherically-tipped, impacting masses of 3, 5.5 and 20 g, are also used as impact sources. The force-time history of an elastic impact may be approximated as a half-sine curve, and the duration of the impact is the "contact time." The contact times produced by the ball bearings and impactors ranged from approximately 20 to 90 microseconds. The contact time is an important variable in impact-echo testing because it determines the frequency content of the input pulse [4]. The frequency content affects the size of the defect that can be detected [3]. As the contact time decreases, smaller defects can be detected and defects near the surface can be accurately located. However, as contact time decreases the penetrating ability of the stress waves also decreases. Therefore, the selection of a contact time will depend upon the intent of the particular testing situation and the flaw size to be detected.

The receiving transducer is a broadband displacement transducer which consists of a small, conically-shaped, piezoelectric element cemented to a large brass backing [2,10]. The output of this transducer is proportional to normal surface displacement. The transducer was developed for use on metal objects. In initial studies, a thin sheet of aluminum foil was used between the conical element and the concrete surface to complete the transducer circuit [1,2]. The foil was coupled to the concrete using water soluble gel, and the tip of the transducer rested directly on the foil. Grinding of the concrete was generally required to achieve proper coupling between the conical element and the surface. In current studies, the foil and gel have been replaced with a thin sheet of lead. Use of the lead, which is malleable and conforms to the concrete surface, eliminates the need for surface preparation and simplifies the experimental procedure.

In current work, the transducer is used with a high-pass filter that strongly attenuates frequencies less than 2 kHz. The filter was added to reduce the effects caused by a low frequency resonance of the transducer assembly (the large brass backing on the small conical element behaving like a mass on a spring). The use of the filter clarifies displacement waveforms and simplifies their interpretation.

Frequency Analysis

Point impact on a solid generates a stress pulse. This pulse produces compression (P) and shear (S) waves which propagate into the solid along spherical wavefronts, and a Rayleigh (R) wave

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which propagates along the surface. The P- and S-waves are reflected from internal flaws and external boundaries. In time domain analysis of displacement waveforms, the arrival time of reflected waves must be determined [1,2,5,6]. To successfully identify wave arrivals, a short duration impact must be used, and the impact point and receiving transducer must be located sufficiently far from the edges of a test object so that R-wave reflections from the edges do not interfere with waves reflected from internal reflections. Time domain analysis was found to be time-consuming and difficult for all but the simplest geometries. These problems led to the use of frequency analysis as an alternative approach for interpretation of impact-echo waveforms [3,4,7,8].

An impact-echo test on a large diameter plate will be used to illustrate the principle of frequency analysis. Impact on the surface of the plate generates a stress pulse, which is reflected back and forth between the top and bottom surfaces of the plate. Thus a transient resonance condition is created. For waveforms recorded close to the impact point, the P-wave portion of the pulse dominates the displacement waveform. Each time the P-wave arrives at the top surface of the plate it causes a downward displacement [2,3], and the waveform exhibits a characteristic periodic pattern. The time between successive downward displacements is the time, Δt , it takes for the P-wave to propagate to the bottom of the plate and return to the top surface:

$$\Delta t = \frac{2T}{C_p} \quad (1)$$

where T is the plate thickness, and C_p is the P-wave speed. The frequency of P-wave arrivals at the top surface is equal to the inverse of the travel time:

$$f = \frac{1}{\Delta t} = \frac{C_p}{2T} \quad (2)$$

This equation can be rewritten to express the thickness as a function of P-wave speed and frequency:

$$T = \frac{C_p}{2f} \quad (3)$$

Equation (3) is the basic relationship used in frequency analysis. If the P-wave speed in the plate is known and the frequency of P-wave arrivals can be determined, then the plate thickness can be calculated. This same analysis is applicable to reflections from internal flaws which also produce a transient resonance condition. Thus this is an alternative method for determining the thickness

of test objects or the depth of flaws without having to identify wave arrival times.

The frequency content of displacement waveforms is determined using the principle of Fourier series which states that any waveform can be represented as a sum of sine curves, each with a particular amplitude, frequency, and phase shift. This transformation of the digitally recorded waveforms is carried out using the fast Fourier transform technique [11]. The resulting spectra show the amplitude and phase of each component frequency in the waveform.

In current work, analysis of the amplitude spectrum is used almost exclusively to interpret test results as it is quicker and simpler than time domain analysis. A waveform analyzer is used to store and process received signals. The fast Fourier transform is programmed into the waveform analyzer and the amplitude spectrum of a waveform can be obtained instantaneously. For the results presented in this paper, waveforms were recorded using a 2 microsecond sampling interval (500 kHz sampling frequency) and they contained 1024 sampling points. The digital spectra obtained from these waveforms had a frequency difference between adjacent points of 0.488 kHz.

CONTROLLED FLAW STUDIES

Frequency Analysis

To illustrate the application of frequency analysis, results are shown from impact-echo tests on a 500-mm thick concrete plate (2.0 x 4.5 m in plan) in which were embedded, at known locations, 25-mm thick, rigid polyurethane disks. These disks simulate planar flaws. This was the same test specimen used in the time domain studies presented in References [1,2]; concrete properties and plan and elevation views of the plate are given in these references.

A series of displacement waveforms (500 points shown) and their corresponding amplitude spectra are shown in Fig. 2. The waveform and spectrum in Fig. 2(a) were obtained over a 200-mm diameter disk located 127 mm below the top surface of the plate. Figures 2(b) and 2(c) were obtained over 500-mm diameter disks located 258 and 380 mm deep, and Fig. 2(d) was obtained over a solid portion of the plate. Notice how the peaks in the spectra shift from 14.2 kHz in Fig. 2(a) to 3.42 kHz in Fig. 2(d) as the depth of the interface increases from 127 to 500 mm. In Fig. 2(a) two peaks are evident. The lower frequency peak at 3.42 kHz corresponds to reflections from the bottom of the plate (compare Figs. 2(a) and (d)); this frequency will be referred to as the thickness frequency. In this case, the small diameter disk reflects the higher frequency components of the propagating waves; the lower frequency components with longer wavelengths, travel around the disk and are reflected at the bottom surface of the

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plate. Thus both reflecting interfaces can be identified in the spectrum.

Figure 3 shows the known depths of the disks plotted versus the inverse of twice the peak frequencies in the corresponding spectra. As expected from Eq. (3), the points fall approximately on a straight line; the slope of the best-fit line is the P-wave speed and has a value of 3530 m/s. In this case, the depths of all the interfaces were known. In actual testing, it is the depth of the interface that must be determined. Therefore, the P-wave speed in a test object must be a known.

Previously it was thought that the through-transmission, pulse-velocity method (ASTM C 597 [12]) could be used to independently measure the P-wave speed in concrete [1,2]. In the pulse-velocity method, a transmitting transducer and a receiving transducer are located on opposite sides of a test object, and the time for a pulse of ultrasonic waves to travel from the transmitter to the receiver is measured. The ultrasonic pulse velocity is obtained by dividing the distance between the transducers by the travel time. However, it was found that when the ultrasonic pulse velocity (obtained using 50-mm diameter, 54 kHz transducers) was used to calculate the depth of reflecting interfaces (Eq. 3), the calculated depths exceeded the actual depths. Direct comparisons were made between ultrasonic pulse velocities measured through the thickness of solid concrete plates and the P-wave speed calculated from the thickness frequencies obtained from impact-echo tests on the same plates. This comparison showed that the P-wave speeds calculated by the impact-echo method were approximately 10 percent slower than the ultrasonic pulse velocities. Reference [3] presents a detailed discussion of this discrepancy, which currently cannot be explained. The important point is that in impact-echo testing, the P-wave speed must be determined from an impact-echo test on a part of the structure where the thickness is known. This speed can then be used to accurately determine the depth of internal interfaces in other parts of the structure.

Effect of Reinforcing Steel

Figure 4 is a plan view of a 500-mm thick concrete plate (2.0 x 2.25 m in plan) which contained a variety of artificial flaws, including: a thin metal duct partially filled with grout; 0.075-mm thick plastic sheets to simulate cracks; and, circular and rectangular flaws cut from polyurethane foam board. A grid of steel reinforcing bars was placed over half the plate at a depth of 50 mm below the top surface; standard No. 7 and 8 bars (22.2 and 25.4 mm in diameter, respectively) were used. The coarse aggregate was crushed limestone with a nominal maximum size of 19 mm; the 28-day cylinder compressive strength was 28.4 MPa. The P-wave speed in the plate was obtained from an impact-echo test over a solid portion of the plate. (In this case, the sampling interval was 5 microseconds.) The thickness frequency was 4.1 kHz and the computed P-wave speed was 4100 m/s.

Preliminary studies of concrete plates containing only steel bars were carried out to gain an understanding of how reinforcing steel would effect the results of impact-echo tests [3]. Two important conclusions came out of this study:

- (1) The frequency peak corresponding to reflections from a concrete/steel interface occurs at half the frequency value corresponding to reflections from a concrete/air interface. The explanation for this behavior has been presented [3]. Thus the apparent depth of a steel bar calculated using Eq. (3) is twice the actual depth.
- (2) The contact time of the impact determines the effect of the steel bars on impact-echo results. If the primary intent of the testing is to locate reinforcing steel, short duration impacts must be used. Waves produced by shorter duration impacts contain significant high frequency (or shorter wavelength) components¹ [4]. These high frequency components will be reflected by the bars. If, however, the primary intent of the testing is to find flaws in reinforced concrete, the effects of the steel can be minimized by using impacts with longer contact times. Longer duration impacts will not contain the high frequency components that can be reflected by small diameter bars.

Voids in Reinforced Concrete

Figure 5 shows results obtained from a series of impact-echo tests along a section of the 500-mm thick reinforced concrete plate which contained two 200-mm diameter, disk-shaped flaws. Figure 5(a) shows the plate cross-section with the test points numbered 1 through 7. The spacing between points was 200 mm. Each test location indicates the position of the receiving transducer which in every case was located over the intersection of two bars. The impact point was located about 50 mm from the transducer. A mechanical impactor was used, and the contact time was approximately 40 microseconds.

Figure 5(b) shows the waveforms obtained at points 1 through 7. It is obvious that the waveform for point 6 contains closely-spaced oscillations which are not present in the other waveforms. The close spacing of the oscillations indicates that a flaw is located close to the surface. Similarly, the waveforms for points 2 and 3 also exhibit more close-spaced perturbations than the other waveforms, indicating that a flaw is present. If time domain analysis were used, each of these waveforms would have to be analyzed to determine wave arrival times [2]. However, as has been shown, frequency analysis is much simpler and quicker.

¹The highest frequency of components having significant amplitude is approximately the inverse of the contact time.

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Figure 5(c) shows the spectra obtained from the waveforms in Fig. 5(b). Notice first that all spectra contain a high amplitude peak at or near 3.91 kHz which is the P-wave thickness frequency. However, the spectrum for point 3 contains an additional peak at 7.81 kHz and the spectrum for point 6 contains an additional peak at 15.9 kHz. Using Eq. (3) and the P-wave speed in this plate, these frequency values give calculated flaw depths of 260 and 126 mm, respectively, which agree with the known depths of the flaws. Notice that the spectrum for point 2 also contains additional peaks near 8 kHz, even though the test point is not located over the 260-mm deep flaw. This is because point 2 is located close enough to the flaw to be affected by waves diffracted from the edge of the flaw [1,3]. In a systematic scan, such as carried out in this example, it is generally easy to determine the approximate extent of a flaw. Spectra obtained near the edges of a flaw (point 2) show a scatter of peaks near the frequency corresponding to the flaw depth, while spectra obtained directly over a flaw (points 3 and 6) exhibit a single, large amplitude peak at the frequency corresponding to the flaw depth. A more subtle indication of the presence of a flaw is the shift of the value of the P-wave thickness frequency peak to a slightly lower frequency when the test point is located directly over a flaw. Notice that in the spectra for points 3 and 6 the low frequency peak is at 3.42 kHz instead of at 3.91 kHz as obtained over the solid portions of the plate. This shift occurs because the waves must travel around a flaw before being reflected at the plate bottom. The travel path of the waves increases, and thus the frequency of wave arrivals is slightly less.

Simulated Crack

Figure 6 shows results obtained from a series of tests along a section of the plate containing a 0.075-mm thick plastic sheet (300 mm x 1 m in plan) which was used to simulate a crack. The plastic sheet was placed in the fresh concrete at a depth of approximately 300 mm during casting of the plate. Figure 6(a) shows the cross-section containing the plastic sheet and the series of test points which were numbered 1 through 9. Spacing between points was 100 mm. In this case, the transducer was located over the intersection of two reinforcing bars for odd numbered tests and directly over a single bar for even numbered tests. The impact point was located a distance of 50 mm from the transducer. A mechanical impactor was used, and the contact time was approximately 80 microseconds.

Figure 6(b) shows the waveforms obtained from this series of tests. In this case, the presence of the flaw is much more difficult to detect than in the series of waveforms shown in Fig. 5(b) for two reasons: (1) The planar disk-shaped flaws made of rigid foam act as air voids producing strong reflections because nearly 100 percent reflection occurs at a solid/air interface. In contrast, the plastic sheet allows stress transfer across the simulated crack; thus reflections produced by the simulated crack are weaker. (2) The contact time of the impact was twice as long;

in waveforms generated by longer duration impacts, displacements caused by each wave overlap and the response becomes smoother [3,4]. A close look at Fig. 6(b) shows that there are perturbations (identified by arrows) in the waveforms for points 6, 7, and 8 which are not present in the other waveforms. However, it would be difficult to determine the depth of the flaw from these waveforms.

In contrast, a look at the spectra in Fig. 6(c) quickly reveals the presence and depth of the flaw. Spectra 6, 7, and 8 each contain a peak at 7.81 kHz produced by P-wave reflections from the surface of the simulated crack. The crack depth is calculated to be 260 mm. As in the previous case, all spectra contain the thickness frequency peak at 3.91 kHz produced by P-wave reflections between the top and bottom surfaces of the plate. However, this peak does not shift to a lower value over points 6, 7, and 8, which indicates that the waves travel directly across the simulated crack.

The interpretation of the results shown in Figs. 5 and 6 is typical of the authors' current approach to the analysis of test results. Time domain waveforms are used as indicators of the presence of flaws, while amplitude spectrum analysis is used to accurately determine the depth of flaws. The important point is that amplitude spectrum analysis is quick and generally simple; one does not need to be an expert in wave propagation to interpret the results.

Other Flaw Studies

Figures 5 and 6 showed responses obtained from only two of a variety of types of flaws contained in the 500-mm thick concrete plate. A detailed discussion of the results obtained from the other types of flaws in this plate is given in Chapter 7 of Reference [3]. Using frequency analysis, the authors were able to determine the depth of a vertical surface opening crack and the orientation and depth of flaws placed at angles to the surfaces of the plate. Also a hollow metal duct could be distinguished from a fully grouted duct. Although these studies were not comprehensive, the results showed the ability of the impact-echo to detect these types of flaws under laboratory conditions. The next step was to test the technique under field conditions. The following section describes the results of a study of an outdoor, ice-skating rink slab which was believed to contain voids.

FIELD STUDY

The impact-echo technique was used on a concrete slab (approximately 130 to 150-mm thick) which contained 16-mm diameter cooling pipes spaced 100 mm on center and located about 50 mm below the top surface of the slab. The slab also contained 13-mm diameter (No. 4) reinforcing bars placed 300 mm on center in both directions. The depths of the two layers of bars were

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approximately 53 and 66 mm. The slab was cast on a layer of rigid foam insulation. Portions of the slab were known to contain pockets of unconsolidated concrete below the cooling pipes. These pockets were believed to have lateral dimensions on the order of 50 to 100 mm. The objective of the study was to determine whether the impact-echo method could detect the presence of these small voids.

Preliminary Laboratory Study

Prior to conducting field tests, a laboratory study was performed in which a mock-up of the actual slab was built and tested. The mock-up was built so that experience could be gained using the impact-echo method to test a thin slab containing small voids. The 150-mm thick laboratory slab contained a 16-mm diameter pipe, 13-mm diameter reinforcing bars, and a small void below the pipe created from rigid foam insulation board. The depth of the void was 80 mm and the slab was cast on a 50-mm thick layer of foam insulation board. Figure 7(a) shows the cross-section of the laboratory slab.

A series of tests was performed at 25-mm intervals along the length of the pipe as shown in Fig. 7(b). At each test point, the impact point and receiving transducer were each located about 25 mm away from the centerline of the pipe so that they straddled the pipe. Because of the smaller slab thickness and flaw size as compared with previous studies, a shorter contact time was required. The impact source was a 5-mm diameter steel ball, and the contact time was approximately 20 microseconds. The P-wave speed in the specimen was determined to 3810 m/s.

Figure 8 shows the amplitude spectra obtained from waveforms recorded at points 16 through 25. (The void was located beneath test points 20 through 24.) In addition to frequency, the horizontal axis in Fig. 8 shows the depths corresponding to various frequency values for the P-wave speed of 3810 m/s (Eq. 3). The thickness frequency for the solid plate is 12.7 kHz, and a peak at this frequency is the dominant peak in the spectra obtained at points not located over the void (16 through 19). Note that the spectra for points 16 through 19 are similar; this is the pattern to be associated with the unflawed portion of the slab. The spectra obtained over the void (except for point 24) are distinctly different in two ways: (1) the thickness frequency peak is often split into a series of peaks; and (2) there are relatively large-amplitude peaks occurring between 20 and 40 kHz which are associated with waves reflected and diffracted from the top of the void. The spectra for points 20 through 23 are clearly different from those obtained over the unflawed portion of the slab. Thus it was concluded that the impact-echo technique should be capable of locating small voids (50 to 100 mm in size) beneath the cooling pipes in the actual slab.

Field Tests

Three regions of the skating rink slab were selected for testing. In the test areas, grid patterns were laid out with 100 x 100 mm spacings. The areas were chosen so that two were located in the portion of the rink believed to contain voids and one was located in the portion believed to contain sound concrete. The impact source was a 5-mm diameter steel ball as in the laboratory tests. The slab surface was smooth; therefore, no problems with rough surfaces were encountered. However, because of dust and dirt on the surface of the slab, vacuum grease was used between the slab surface and the lead strip to achieve better coupling of the transducer to the slab surface. The thickness of the slab was determined from holes where cores had been taken. Impact-echo tests were performed adjacent to the holes, and the P-wave speed was found to be 4000 m/s.

Figure 9 shows amplitude spectra obtained along a single gridline in one of the three regions. These tests were obviously carried out over sound concrete because all the spectra are similar and there is a single dominant peak (excluding the 0.5 kHz peak caused by resonance of the transducer assembly) corresponding to the P-wave thickness frequency. These spectra are compared with spectra obtained over regions of the slab containing voids.

Figures 10 and 11 show spectra obtained along two adjacent gridlines in a region of the slab believed to contain voids. In Fig. 10, spectrum D reveals the presence of a void. The P-wave thickness frequency peak is split into multiple peaks, and high amplitude peaks occur between 25 and 40 kHz. Spectra obtained at test points F and G also may indicate the presence of a void, although this cannot be said with certainty. In these cases, the thickness frequency peak is split into multiple peaks, but no significant peaks occur in the higher frequency range. Notice that all the other spectra are generally similar to those in Fig. 9 indicating that the concrete at those points is sound. In Fig. 11, spectra E and G clearly indicate the presence of voids.

Spectra obtained from the skating rink slab show the same characteristics as the spectra obtained from the laboratory specimen. In the laboratory, the spectra obtained from sound concrete were distinctly different from those obtained over the section of the concrete containing a void. The same differences appear in the spectra that were obtained in the field study. Therefore, although cores could not be taken to verify the impact-echo results, the comparison with laboratory results gives confidence that the impact-echo method successfully located small voids within the 150-mm thick slab under field conditions.

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SUMMARY

The results of studies using the impact-echo testing technique for flaw detection in concrete were presented. Laboratory controlled-flaw studies showed that the impact-echo method can be used successfully to locate voids and simulated cracks in reinforced concrete. A field study of a slab containing voids showed that the impact-echo technique can be used successfully under field conditions.

Frequency analysis of the displacement waveforms was explained and shown to be a simple and efficient technique for interpretation of test results. Using the frequencies of the high amplitude peaks in amplitude spectra, the thickness of plates and the depth of flaws within plates were accurately determined.

To obtain accurate results using the impact-echo method, it was shown that the P-wave speed must be determined from an impact-echo test on a part of the test object of known thickness. The pulse velocities obtained using the ultrasonic, through-transmission method are approximately 10 percent higher than P-wave speeds obtained using the impact-echo method.

Additional laboratory and field testing of the impact-echo method is essential so that experience can be gained under a wide variety of test conditions and for the various types of flaws typically found in concrete structures. Tests need to be carried out on structures other than slabs, so that effects caused by various geometries can be determined. Also, additional analytical studies are needed to understand the interaction of transient stress waves with various types of flaws.

In summary, these studies have demonstrated the potential of the impact-echo technique for flaw detection in slab-like, concrete structures. It is hoped that after further analytical studies and laboratory and field tests are completed, the method will come into use as a routine technique for nondestructive testing of concrete.

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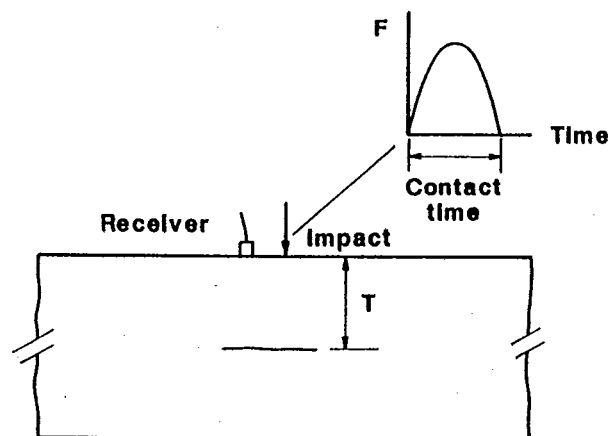


Fig. 1--Point impact on a plate containing a flaw

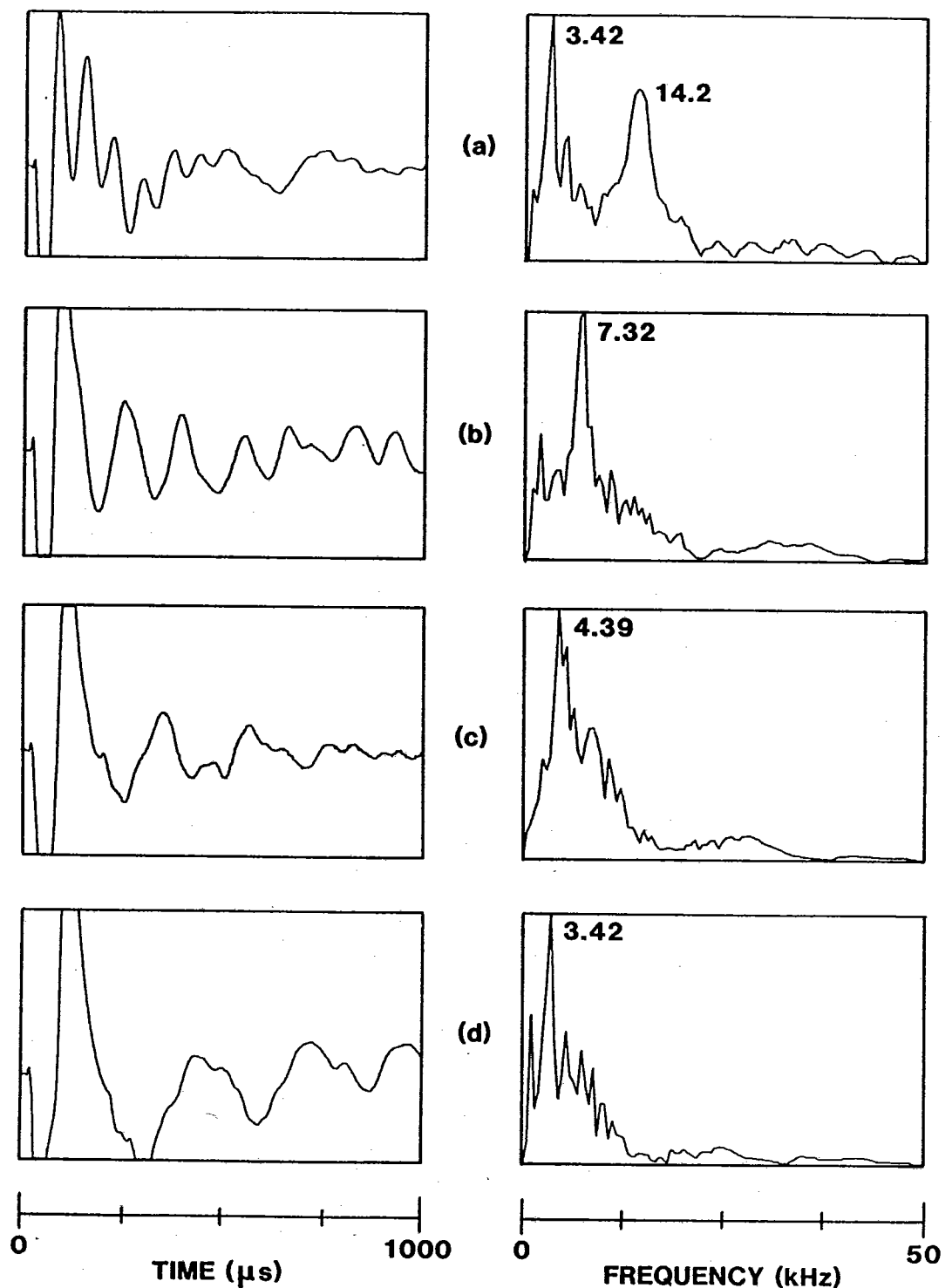


Fig. 2--Waveforms and spectra for flaws at depths of (a) 127 mm, (b) 258 mm, and (c) 380 mm; and unflawed 500 mm thick plate

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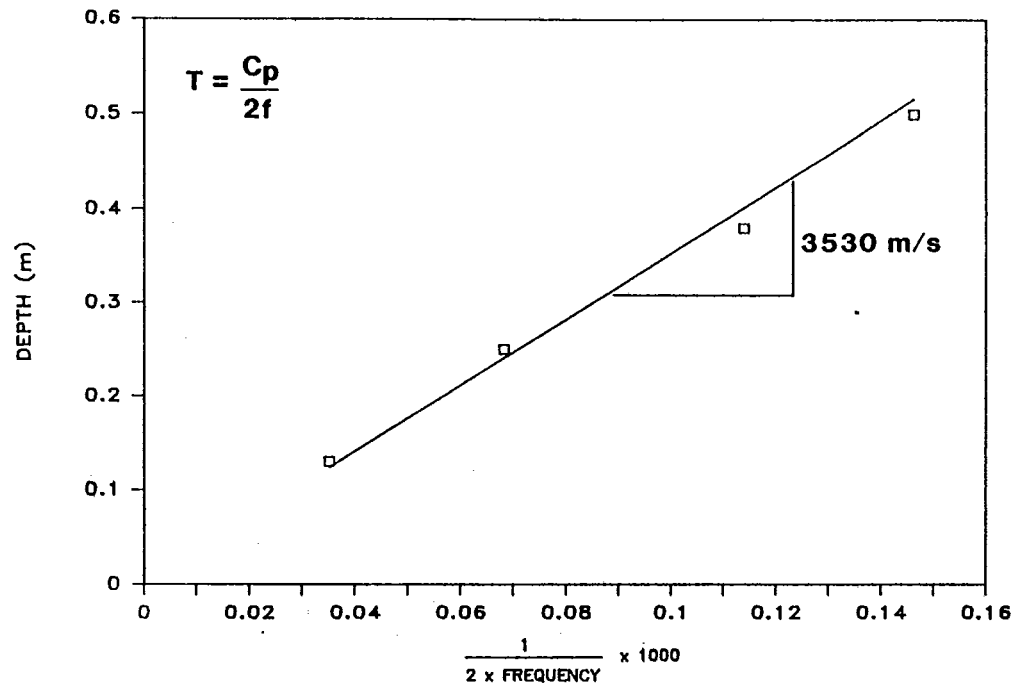


Fig. 3--Relationship between depth and inverse of frequency

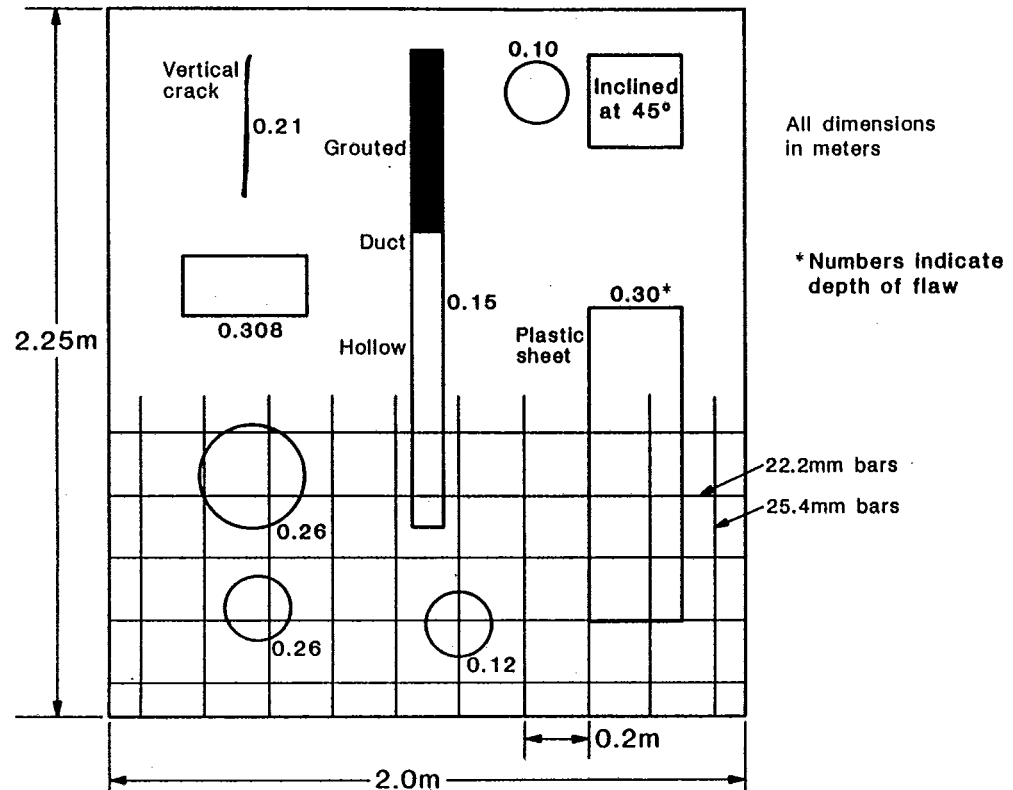


Fig. 4--Plan view of 500 mm thick reinforced concrete plate

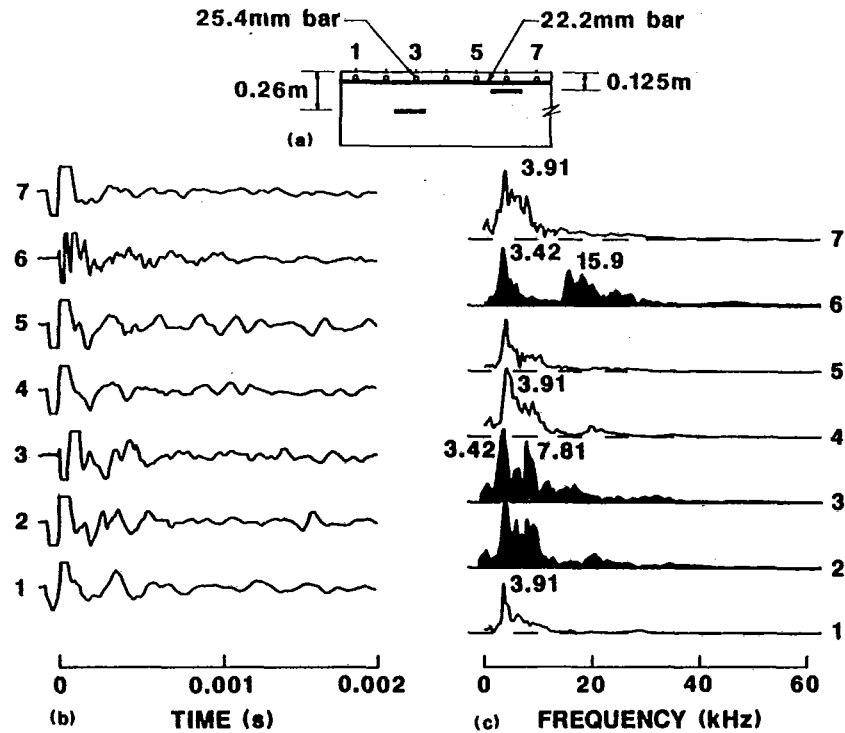


Fig. 5--Results from section of plate containing 200 mm diameter voids: a) cross section, b) waveforms, and c) spectra

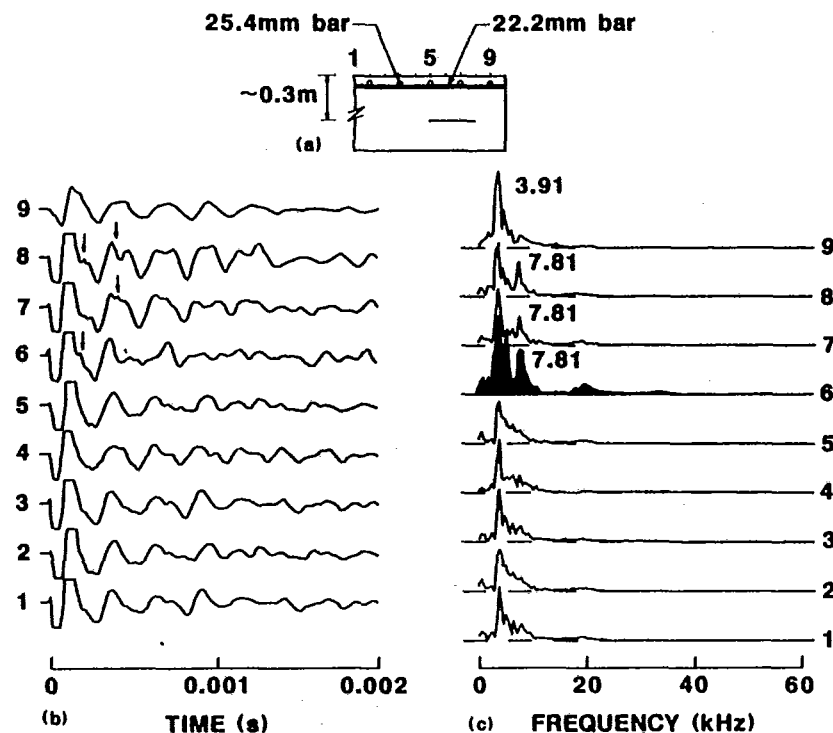


Fig. 6--Results from section of plate containing a plastic sheet: a) cross section, b) waveforms, and c) spectra

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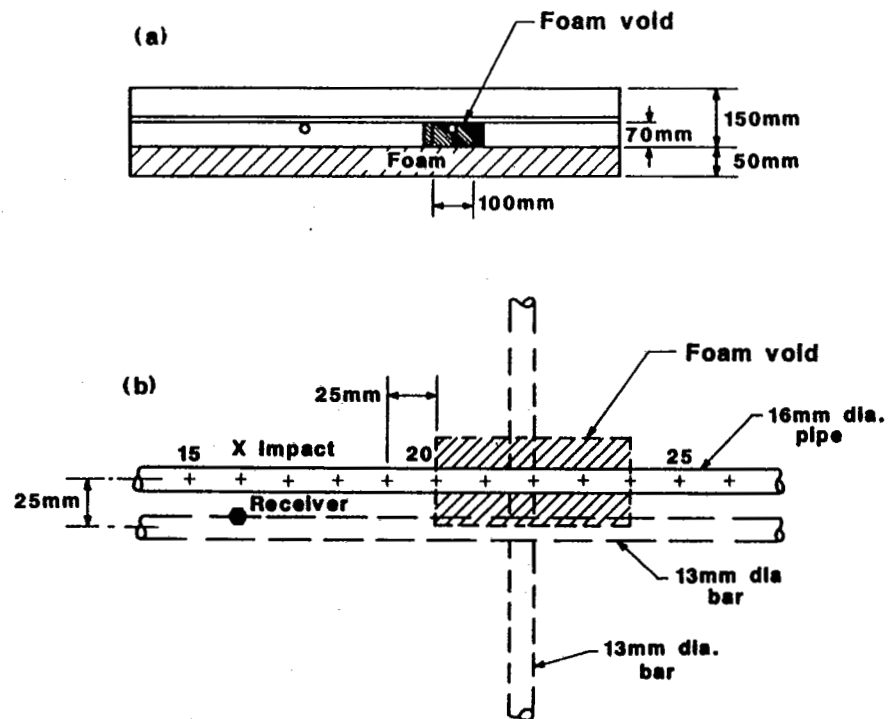


Fig. 7--Laboratory mock-up of ice-skating rink slab:
a) cross section, b) location of test points

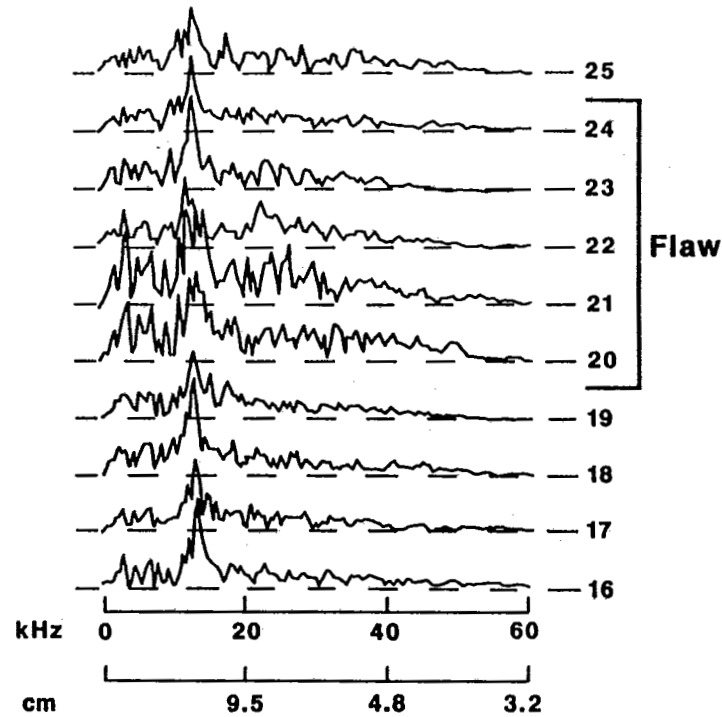


Fig. 8--Spectra for test points 16 through 25 on laboratory slab

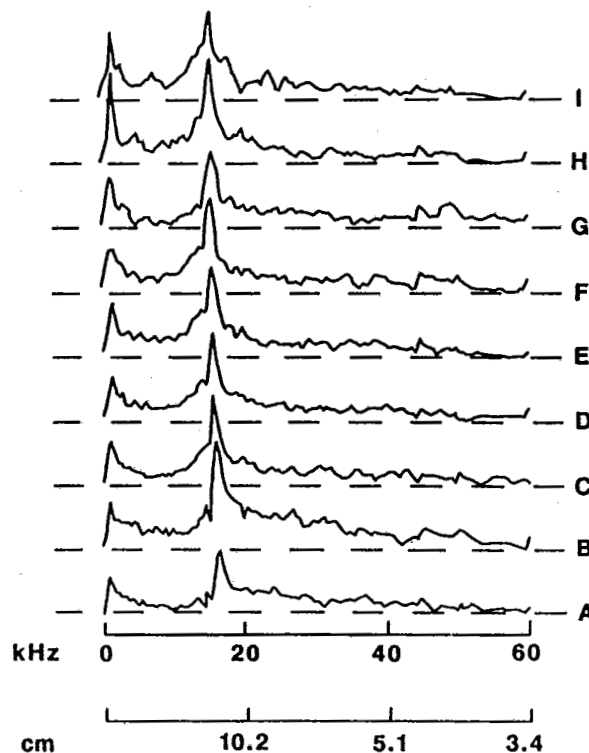


Fig. 9--Spectra from sound portion of ice-skating rink slab

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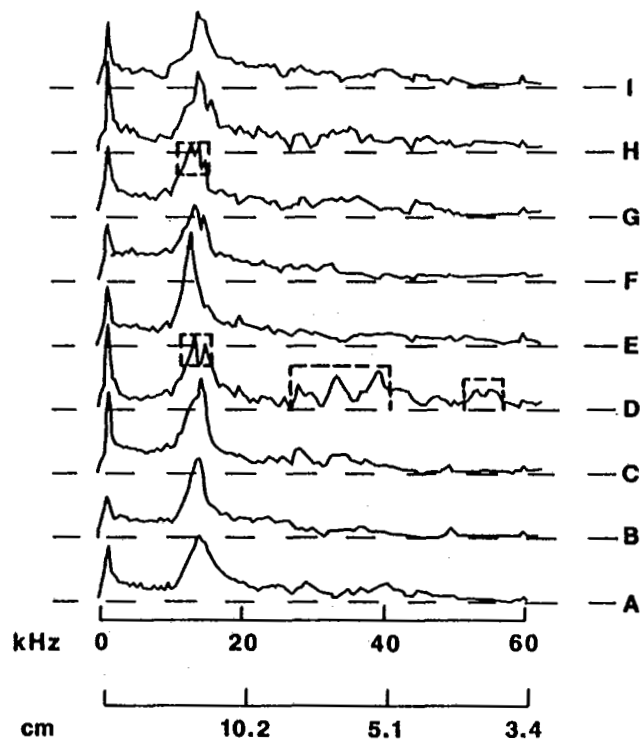


Fig. 10--Spectra from portion of ice-skating rink slab believed to contain voids

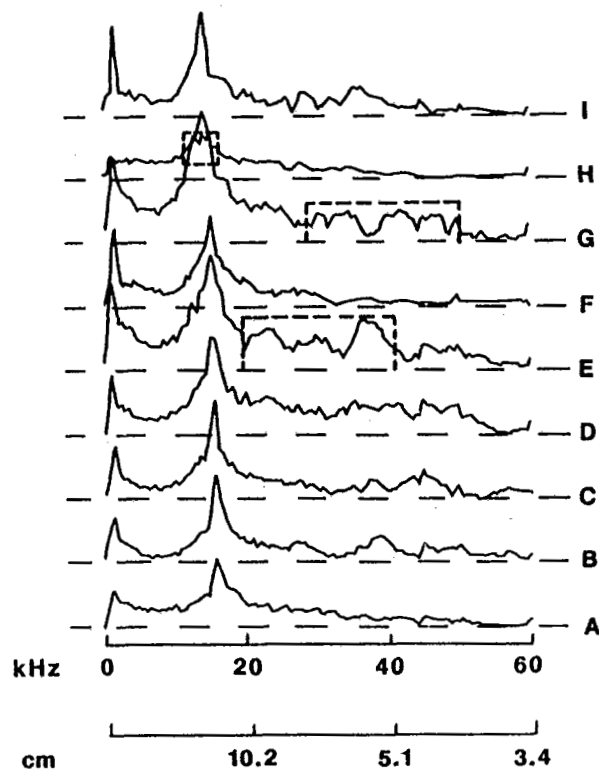


Fig. 11--Spectra from portion of ice-skating rink slab believed to contain voids

SP 112-2

Developments in Ultrasonic Pitch-Catch and Pulse-Echo for Measurements in Concrete

By A.M. Alexander and H.T. Thornton, Jr.

Synopsis: A new improved prototype ultrasonic pitch-catch (two-transducer) and pulse-echo (one-transducer) system has been developed for concrete. Signal generation and detection is done with piezoelectric crystals. A literature search revealed that no piezoelectric pulse-echo system had been developed for the ultrasonic range (>20 kHz) and that pitch-catch measurements needed further development. No commercial system could be found on the market for making pitch-catch measurements. Only about 10 references that deal directly with ultrasonic pitch-catch measurements in concrete were located. There are none that deal with ultrasonic pulse-echo.

Although investigators have made progress in understanding the problems associated with the development of pulse echo for concrete, the heterogeneous nature of concrete and the state-of-the-art of ultrasonic materials and techniques prior to the present have prevented the development of a practical system like that used for homogeneous materials. The literature revealed that resolution was poor due to long pulse lengths (high Q value) for the transducers. Investigators had problems with interfering Rayleigh waves at low frequencies. Signal-to-noise ratios (SNR) ranged from only about 2 to 6. The latest state-of-the art transmitter (Ohio State University) had a diameter of 18 in. (457 mm) and a mass of 40 lbs (18 kg). Measurements showed extraneous signals other than the desired longitudinal mode due to mode conversion in the transducers. Also these transducers lacked the proper focal length, directivity and sensitivity.

Research by the U.S. Army Engineer Waterways Experiment Station (WES) has resulted in the development of a 200-kHz pitch-catch system with a signal to noise ratio of 18 and a pulse-echo system with a SNR of 8. The mass and dimensions of the improved system have been significantly reduced from the prior state-of-the-art system. The WES system has the lowest Q (shortest ringing time and widest bandwidth) and therefore the shortest pulse length on record. This system works well for making thickness measurements of portland-cement concrete pavement and can indicate the presence of voids.

Keywords: concrete pavements; evaluation; measurement; nondestructive tests; thickness; transducers; ultrasonic tests; voids

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INTRODUCTION

Ultrasonic measurements in concrete structures with two accessible sides in which a transducer is mounted on each side is a well-established technique, but no system is known to the authors to be commercially available for making measurements of velocity from one side to the other where only one surface is accessible. Work done by various investigators since 1948 has contributed to the development of knowledge and expertise in this area. The inherent heterogeneous nature of portland-cement concrete (PCC) has complicated the development of a system. A practical ultrasonic pulse-echo nondestructive testing (NDT) system would increase the available means for evaluation of the condition of concrete structures, especially those accessible from only one surface. All of the references located by the authors prior to 1985 reported using two-transducer systems (pitch-catch) rather than pulse-echo (one-transducer) systems. Only ultrasonic pulse techniques are referred to in this report because continuous wave techniques do not have the potential for operator simplicity. Impact systems of the resonant frequency and pulse-echo type will be discussed in a later report.

Quality Factor

An understanding of the quality factor or damping factor (Q) of a transducer is necessary for a proper understanding of the ultrasonic pulse echo method. Pulse echo systems require that the pulse length be short in the time domain (low Q) which means that the spectrum will be broad in the frequency domain. The following illustrations show two cases. The first pulse was produced by a transducer with a Q of 15.8. It will oscillate or ring for about 15.8 cycles before dying out (Figure 1a.). Its frequency spectrum will be narrow as shown in

Figure 1b. The transducer pulse shown in Figure 1c. was produced by a transducer which has a Q of 5.5. It will ring for about 5.5 cycles before dissipating. Its spectrum shown in Figure 1d. will be broad.

The ratio of the amplitudes of any two successive cycles shown in Figure 1a. is defined as the damping coefficient (A_1/A_2). The logarithm of the damping coefficient is called the logarithmic decrement (δ). And finally, Q is linked to the logarithmic decrement by the following relationship (1).

$$Q = \pi / \delta$$

$$Q = \pi / \ln(A_1/A_2)$$

$$Q = \pi / \ln(1.22) = \pi / .199$$

$$Q = 15.8$$

Q is also defined as the resonant frequency divided by the bandwidth between the half-power points as shown in the two frequency plots (Figure 1b and 1d).

$$Q = f / B \quad B = f_2 - f_1$$

$$Q = 200 \text{ kHz} / 12.66 \text{ kHz}$$

$$Q = 15.8$$

A very convenient definition for use in the time domain states that the number of cycles required for the pulse to ring down to 4% of its original amplitude is equal to the Q of the transducer (2). For example a transducer with a Q of 100 will resonate for just over 100 cycles before dying out.

Pulse Length

In order to understand the concept of resolution for a thickness measurement in concrete consider the travel distance of the ultrasonic pulse between the top and bottom surface of a concrete plate in terms of wavelengths. For a pulse having a resonant frequency of 200 kHz in concrete with a velocity of 15,000 ft/sec the wavelength is calculated by using the following equation.

$$v = f \cdot \lambda \quad \lambda - \text{wavelength}$$

$$\lambda = v / f$$

$$\lambda = 15,000 \text{ ft/sec} / 200 \text{ kHz}$$

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$$\lambda = .075 \text{ ft}$$

$$\lambda = .9 \text{ in.}$$

A concrete plate having a thickness of 9 in. would be equivalent to 10 wavelengths thick. Since the ultrasonic pulse must travel down and back for the pulse echo technique it would be equivalent to a travel distance of 20 wavelengths.

We noted above the ultrasonic pulse echo requires a short pulse. How short is sufficient? If the concrete is being tested with a 200 kHz transducer, then how small must the Q of the transducer be in order to obtain proper resolution? The pulse length in the material will be as many wavelengths as the Q of the transducer. That is, a transducer with a Q of 3 will have a pulse length equal to 3 wavelengths. Each cycle of the pulse is, of course, one wavelength. In the example above the pulse length would be $Q \cdot \lambda$ or $3(.9 \text{ in.}) = 2.7 \text{ in.}$

The first point to be made is that the pulse length must be shorter than the distance traveled (twice the thickness of the plate), otherwise the transducer would still be "talking" and interfering with the process of "listening" for the echo. Let us assume that only one transducer is being used and it must act as the transmitter and receiver. At the time the transducer is excited by the pulser the stress pulse begins to enter the concrete. Once excited the transducer will respond until it has delivered its' characteristic pulse length determined by its' Q. After that the transducer is in a quiet state and is capable of detecting an echo although the echo may be many times lower in amplitude than the original transmitted pulse. It is therefore necessary that the transducer cut off its transmitting so that it will be in a relaxed state for receiving. So if the thickness of the plate element is 20 wavelengths then the Q of the transducer must be less than 20 or the small amplitude echo will never be detected since the transducer will still be transmitting while it should be receiving.

The second point to be made is that the pulse length must be less than the depth to the first discontinuity. If the depth of a flaw is only 2 wavelengths deep (1.8 in.) then the Q of the transducer must be less than 2 so that the transducer is in a quiescence state for detecting the echo. It is possible to get around this problem by utilizing a standoff (3). A standoff is a block of material between the transducer and material being tested that increases the arrival time of the first echo. Also it follows that the pulse length must be shorter than the distance between any two discontinuities in the body of the concrete if one desires to resolve the two reflecting interfaces.

History

Bradfield (4) first reported measuring the thickness of 1-in. (25-mm) and 2-in. (50-mm) thick concrete plates with a 2.5-ft (0.75-m) magnetostriction nickel rod. A transmitter coil developed the wideband acoustic pulse and another coil picked up the echo. The longitudinal pulse generated was about 12 microseconds in width and had the shape of one cycle of a sine wave. The center frequency was near 80 kHz. The signal to noise ratio (SNR) was very low and the acoustical mismatch of the nickel rod to the concrete was inefficient in the transfer of energy. This represents the first report of an ultrasonic pitch-catch measurement made on concrete known to the authors.

Jones (5) reported that Bradfield encountered three main difficulties: (1) scattering by aggregate at higher frequencies, (2) surface-wave interference at low frequencies, and (3) a small number of wavelengths present in the total path length making it necessary to produce a short, highly damped pulse (wide bandwidth). He also noted an upper frequency limit of 200 kHz for concrete when the thickness is 2 ft (0.6 m) or less and when the nominal maximum size of the aggregate is 3/4 in. (19.0 mm) and the wavelength is about 1 in. (25 mm).

Bradfield and Woodroffe (6) reported a significant advance in pitch-catch measurements in concrete using 100-kHz barium titanate longitudinal mode mosaic transducers. Both transmitter and receiver were normal to the concrete surface. By smoothing the surface and applying a layer of grout flattened by a sheet of glass they were able to measure thru 18 in. (0.46 m) of concrete with a SNR of about 5 to 6. The measurement is shown in Figure 2. The transmitter and receiver dimensions were about 2.5 by 4 in. (64 by 102 mm) each. The height was 1 in. (25 mm). Large area transducers are required for the low frequencies in concrete to give directivity to the ultrasonic beam. Therefore mosaic transducers were constructed by Bradfield from smaller standard elements. The expense of manufacturing large pieces is prohibitive. The long ring time of the transmitter ruled out the possibility of using a common transducer. The Q of the barium titanate was 90 in air and 5 on the concrete.

An input pulse width of 50 μ s. (5 wavelengths of a 100 kHz signal) would correspond to a pulse length and hence resolution of 9-in. (203 mm) in concrete having a velocity of 15,000-ft/sec (4573 m/sec). The location of the first discontinuity can be resolved to within one wavelength. However subsequent discontinuities must be separated by the resolution distance of 9-in. or they will be obscured by the ringing caused by the first-returning echo. Neither electrical nor acoustical matching was done. Although this reference represents the first recorded pulse-echo measurement (pitch-catch) made on

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concrete using piezoelectric materials, the report lacks significant detail for other investigators to follow with ease.

Bradfield and Gatfield (7) reported thickness measurements with a set of variable-angle longitudinal mode transducers. One hundred-kHz transducers of barium titanate were mounted on Perspex (plastic) shoes covering a total area of 3.5 by 4.5 in. (89 by 114 mm) for each transducer. The height of the transducers was about 10 in. (252 mm). The ceramic was loaded on the back face with litharge (lead oxide, PbO) and rubber to reduce the Q. Lateral ringing of the transducer however created unwanted interference. They obtained an error of 2% on a 12-in. (300-mm) thick layer of concrete. However, the signal was preceded by unwanted surface waves almost equal in magnitude to the desired longitudinal wave as shown in Figure 3. The transmitter pulse precedes the first timing mark (10 μ s each) by 150 μ s. The large dimensions of the driving mechanism necessary to vary the angle of the transducers prevented practical usage of the system outside the laboratory.

Canfield and Moore (8) reported that the difficulty of building a pulse-echo system lay with the transducer development. They were able to measure the thickness of a 5-in. (127-mm) concrete plate with pitch-catch transducers but no practical instrument was perfected. They also met with difficulties of surface-wave interference and high Q (narrow bandwidth) transducers that rang for an excessive time. They used lead zirconate titanate (PZT) which resonated at 83 kHz. It is difficult to damp crystals at low frequencies as the attenuation of damping materials decreases as the frequency is decreased.

Howkins (9) reported the results of about 4 years of research by the Illinois Institute of Technology Research Institute on the development of an ultrasonic pulse-echo system for concrete. Their final pitch-catch system was used to measure the thickness of a 7-in. (178-mm) thick concrete plate using two epoxy discs with barium-titanate ceramic rods (100 kHz) embedded in the epoxy and mounted on fixed-angle wedges (see Figure 4). About 44 rods were in each epoxy disc and both transmitter and receiver were mounted on fixed-angle wedges. Each transducer was 3 in. (75 mm) in diameter. A sharp onset for the echo was present with a SNR of about 5 to 6. However the Q was about 20 or more and since the period of each cycle is 10 μ s for a 100 kHz signal the pulse length would be over 200 μ s. This created too much blind time for detecting echoes that are closely spaced. For a 15,000-ft/sec (4573 m/s) velocity in concrete this pulse length would be 3 ft (3.28 m) in the concrete. As explained previously the long pulse length would not permit a single transducer measurement to be made. Pitch-catch measurements, however, permit the transducer to have a larger Q since the receiver can be "listening" while the transmitter is "talking."

Howkins made a significant contribution by explaining the physics involved in making an ultrasonic pulse-echo measurement in a composite material like concrete. Although he found 150 references on ultrasonic measurements in concrete only 6 of them had information about pitch-catch measurements in concrete. He also noted that the common nondestructive measuring techniques used for homogeneous materials were not applicable to concrete. With few exceptions investigators had relied upon direct application of transducers designed for homogeneous and fine-grained materials such as aluminum and steel. He suggested going back to fundamental principles.

McMaster led a research program at Ohio State University over a period of 8 years and developed the first field system (10, 11, 12, 13). Golis built an 18-in. (457-mm) diameter ring transducer (200 kHz) for measuring pavement thickness. The 3-in. (75-mm) diameter receiver was placed into a 5-in. (125-mm) diameter hole in the center of the transmitter. As in the previously cited research, the surface wave energy prevented flaw detection measurements, but the SNR of 5 was sufficient to measure pavement thickness within 2 or 3 percent. The system had a low Q of 3 and used lithium sulfate for the receiver. Barium titanate was used initially for the transmitter, but this was later changed to PZT. A concentrated effort by the Ohio State University (OSU) team was made to document their work that permitted others to follow up with less effort. No commercial unit was ever marketed although a patent was obtained on the system. Typical signals (14) in Figure 5 show a high frequency pip (small circle) which is the echo on an extraneous larger amplitude lower frequency waveform.

The U.S. Army Engineer Waterways Experiment Station (WES) obtained one set of the transducers built by OSU. The Pennsylvania State Highway Department donated one of their transmitters that was in need of repair. Two lithium-sulfate receivers were also received but could not be repaired. After restoration of the transmitter and the purchase of a new receiver the system was restored to operation. However, low-frequency energy obscured the higher frequency echo energy. A strong 40-kHz frequency was present probably due to a resonance in the housing. By using a high-pass filter with cutoff at 100 kHz the signal shown in Figure 6 was obtained (15). The center frequency of 180 kHz became the dominant energy and echoes were obtained on a 9-1/4 in. (235-mm) thick concrete slab. The SNR was about 4 to 5 and the Q of the transmitter is about 4. However, the calculated near-field length is several feet. Extreme interferences occur within the region of the near field and it is desirable that the length of the near field should be shorter than twice the thickness being tested. For pavement thickness of about 9 in. (230 mm) a smaller diameter transmitter of about 4 to 8 in. (100 to 200 mm) would reduce the near field length and be more efficient. Also the mass of over

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40 lb (18 kg) for the transmitter and the need to use about 500 mL of couplant liquid suggests a new design.

Claytor and Ellingson (16) measured the thickness of a refractory concrete slab 12 in. (300 mm) thick using two 250-kHz PZT-5A ($Q=75$) transducers with a liquid buffer between the ceramic and the concrete to reduce surface wave energy. Each mosaic transducer was 7.0 in. (178 mm) in diameter. Seven 2-in. diameter discs were embedded in a 20% tungsten/epoxy mixture by volume for each transducer. The transducer rang for about 300 μ s at 96 kHz. This represents a Q of over 20 (see Figure 7). They noted that progress had been hampered in developing acoustic techniques for concrete due to poor characterization of test materials, a lack of calibration and response curves for transducers, and the difficulty of conducting experimental tests on large structural objects.

DEVELOPMENTAL WORK

In 1983 Thornton and Alexander made a literature search to determine the state-of-the-art of ultrasonic pulse echo in concrete. The results of this study (15) confirmed the findings of previous investigators, i.e., that the main effort in pulse-echo development should be in the area of transducer development and the reduction of the Q of the transducer.

It was found that tungsten-loaded epoxy will provide better damping for piezoelectric materials such as PZT. The high acoustic impedance of the tungsten matches that of the PZT and a backing made of a 2:1 mixture of tungsten and epoxy by weight (17) will produce a minimum of reflections returning from the backing to the piezoelectric crystal. This is necessary to produce a wide bandwidth transducer. In the lower frequency range, suitable for working in concrete, backing materials for piezoelectric elements have low damping values and it becomes difficult to design a transducer with the necessary bandwidth. The damping naturally lowers the sensitivity but a significant reduction in the sensitivity is due to the fact that the sound pressure generated from a transmitter is directly related to the square of the frequency. For this reason impacts are sometimes used to generate sonic and ultrasonic energy in the low frequency spectrum required for concrete (18, 15). However, this report focuses only on information about the generation and detection of ultrasonic signals with piezoelectric materials.

Receiver

Out of the family of lead zirconate titanate piezoelectric types, PZT-5H has the lowest Q of them all. It has a Q of 65 in air. A transducer array of 8 plate elements of this type, each poled in the thickness direction to produce a longitudinal mode of vibration, was bonded to an aluminum plate. Each

piezoelectric element was 1.5 by 1 by .25 in. (37.5 by 25 by 6.25 mm). The metal plate was .25 by 4.5 by 5.0 in. (6.25 by 112.5 by 125 mm) and the elements were arranged in a configuration to form an array that was 3 by 4 in. (75 by 100 mm). The piezoelectric elements were bonded to the metal plate with silver epoxy. The side having the large face was bonded to the metal plate. The ends of each element was acoustically isolated from the others with a strip of mylar. This was done to prevent the elements from bumping against each other and producing erratic noise. The remainder of the side of the metal plate not covered by the PZT was painted with epoxy to provide electrical insulation between the metal and the tungsten backing that was to follow. Each of the 8 elements were electrically connected in parallel by soldering a common lead wire to the top electrodes. All of the bottom electrodes were tied to the aluminum plate and the metal served as the ground connection. The base plate was then installed on an aluminum housing having the same width and length as the plate and having a height of 3.5 in. Mylar was then used to cover the inside walls of the housing and tungsten loaded epoxy was placed to a height of 1 in. over the piezoelectric elements.

The frequency of the transducer before damping was 312 kHz. After damping the frequency was reduced to 200 kHz but with a very wide bandwidth. The frequency response covered a large band from 50 kHz to at least 500 kHz with the response at all those frequencies only slightly below that at 200 kHz. However the response curve was not smooth but had an irregular wave-like pattern with broad peaks at a number of frequencies below 200 kHz. The transducer would not operate in the pulse echo configuration because the transmission would not cease so that the transducer could be quiet for receiving. It seems that PZT may have too much mode conversion for it to generate a dominate longitudinal mode. PZT has a transverse mode coupling coefficient of .65. This means that transverse modes are excited along with the longitudinal mode with the spurious energy being a large percentage of the wanted energy. We determined that the transducer would operate very well as a broadband receiver in a pitch-catch configuration. The high activity of transmission of PZT is a desirable property but may only be useful for high Q ultrasonic system such as through-transmission systems which do not require short pulse lengths and are not affected by mode conversion.

Transmitter

Lead metaniobate (EC-82) has some desirable properties which we sought to explore in the next transducer. The low Q of lead metaniobate is 11 in air without damping. Also the acoustic impedance of lead metaniobate is closer to concrete and will provide better acoustic matching than PZT. This transducer array was bonded to a faceplate of Lucite rather than metal in an effort to reduce ringing due to vibration in the faceplate.

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Plastic has much higher damping as a material than metal. The transducer was constructed of four piezoelectric elements having dimensions of 2.35 by 2.35 by 0.28 in. (60 by 60 by 7 mm). All four elements were bonded with an adhesive of Loctite 326 to a 1/4 in. (6-mm) thick plastic plate to form a square pattern of 4.7 in. (120 mm). A thin copper sheet was inserted between the piezoelectric elements and the faceplate to provide a ground connection. The electrodes on the top side were joined electrically with a lead wire soldered to each of the four elements. The thin copper sheet provided the ground connection for the bottom electrodes.

The undamped longitudinal resonant frequency was 200 kHz in air. It dropped to 190 kHz after being attached to the plastic faceplate. The Q in air was 11 and dropped to about 2-1/2 when the plastic plate was in contact with the concrete. Since the Q was such a desirably low value there was no need to provide external damping on the back face.

Pitch Catch Measurements

When the EC-82 was used as the transmitter and the PZT-5H used as a receiver, a SNR ratio of 18 was obtained when measuring the thickness of a 9-1/4-in. thick (235-mm) concrete plate element (air-backed) with 3/4-in. (19.0-mm) nominal maximum size aggregate. No surface preparation was done and castor oil was used for the couplant (see Figure 8). An inductor was placed in parallel with the receiver to cancel out the static capacitance (tune the receiver). This increased the SNR ratio by 50% (12 to 18). A series inductor was added in the transmitter circuit which increased the sensitivity of the system but did not improve the SNR. Shock excitation was provided with a Model 5055 Panametrics pulser. The total system is shown in Figure 9.

A 1-3/4-in. deep (45-mm), 24-in. long (0.6-m) saw cut was made in the concrete plate to test for the presence of surface waves. When the transducers were placed on opposite sides of the cut no appreciable change occurred in the amplitude of the energy preceding the echo signal. Also, a through-transmission measurement made on the concrete plate revealed the SNR to be about 300. Therefore the noise in front of the echo is apparently due to backscattering from the 3/4-in. (19.0-mm) nominal maximum size aggregate in the concrete. The mass and dimensions of the prototype system were reduced from those of the OSU device by about 90%. The SNR was increased by 200%.

Pulse Echo Measurements

When the lead metaniobate was used in the pulse-echo configuration, i.e., using one transducer as the transmitter and receiver, an echo was received from the bottom of a 6-in. (150-mm) concrete plate. (See Figure 10.) The small number of

periods which elapse before the echo returns is a large percentage of the time required for the receiving amplifier to recover from its paralysis after being excited. Therefore it remains to be seen whether or not one transducer can be used successfully for pulse-echo measurements in concrete as is common in fine-grained materials.

PVDF Transducer

WES contracted with Argonne National Laboratory to determine the potential of the new mechanically flexible piezoelectric material polyvinylidene fluoride (PVDF) for making ultrasonic pulse-echo measurements in concrete. As the material is available in thin sheets, which individually have a higher resonant frequency than that desired for concrete, many sheets must be bonded together to lower the frequency to the range needed for concrete. The longitudinal resonant frequency of vibration of piezoelectric materials is inversely related to the thickness. The PVDF plastic material and thin aluminum sheets for the electrodes make up the laminations. There are some properties of PVDF which are desirable for the problems encountered in concrete. The material is flexible and would conform to an irregular concrete surface when present. The material is lightweight and relative inexpensive. The material has high damping and therefore will generate a short pulse at the low frequencies needed for concrete. PVDF has very good receiving properties and is weak as a transmitter. Argonne bonded 40 sheets of PVDF and metal foil together to form the transducer. Each PVDF sheet was 40 microns thick. A thin epoxy was used as the adhesive. The laminated sheets were encapsulated in RTV21.

Figure 11 shows the results of a pulse-echo measurement made with a 10-by-10 in. 280 kHz transducer on 6-in. thick section of Portland Cement concrete. The measurement was made in the pitch-catch configuration with the PVDF used as the transmitter and a small 1-in. diameter Panametrics Model A301S transducer used as the receiver. The Panametrics transducer is resonant at 500 kHz with a Q of about 3. However the transducer is not operating at resonance but receiving in the broadband portion of its' frequency response curve centered around the resonant frequency of the PVDF transducer at 280 kHz. The frequency response of the PVDF is fairly flat between 60 and 300 kHz. If shock excited it will operate at 280 kHz, and if a gated sine wave is used for excitation it can operate at any number of frequencies over the range mentioned. One can operate at a lower frequency for penetration and a higher frequency for resolution. The PVDF will also operate in the pulse-echo configuration.

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CONCLUSIONS AND FUTURE RESEARCH AND DEVELOPMENT

An ultrasonic pulse-echo system (Figure 8) for use in concrete requires large area transducers to collimate the ultrasonic beam, produce a near-field length (focal length) shorter than twice the thickness of the concrete being tested, and suppress interfering surface waves. The piezoelectric material should match the acoustic impedance of the concrete as closely as possible or the faceplate should have an intermediate impedance between that of the material and the concrete. The piezoelectric materials should be chosen to have high activity constants for the transmitter and receiver because of the high attenuation of the concrete. The piezoelectric material should have a low Q to reduce ringing or it will require a proper backing of tungsten loaded epoxy to reduce the Q . The piezoelectric material should have low mode conversion like lead metaniobate to prevent generation of signals other than the desired longitudinal mode.

Concrete requires that a transducer operate at 200 kHz or below. This means that in thicknesses of 1 ft (300 mm) or less the concrete thickness is only equivalent to a few wavelengths so that the pulse can only be 1-2 cycles in length. The high capacitance of the mosaic transducer and the accompanying low impedance generally require shock excitation rather than a sinusoidal burst in order to introduce enough energy. The pulser should be designed to have a pulse width that matches the center frequency of the transmitter. At the present state-of-the-art, pitch-catch measurements rather than pulse-echo should be made to gain full efficiency. Finally both transmitter and receiver should be tuned electrically with inductors to improve SNR and sensitivity.

WES future plans include tests to determine the effects of the degree of backscatter on specimens of varying deterioration. Although the activity that precedes the back wall echo appears to be noise, it is acoustical (not electrical interference) energy and may reveal the degree of microcracking in deteriorated surfaces. Presently, the system has a sufficiently large SNR to detect back-wall reflections successfully and can be useful for making pavement and floor slab thickness determinations. Continuing improvements in the SNR should make it possible to detect smaller cracks, voids, and discontinuities.

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COL Dwayne G. Lee was Commander and Director of WES during the preparation and publication of this paper. Dr. Robert W. Whalin was Technical Director.

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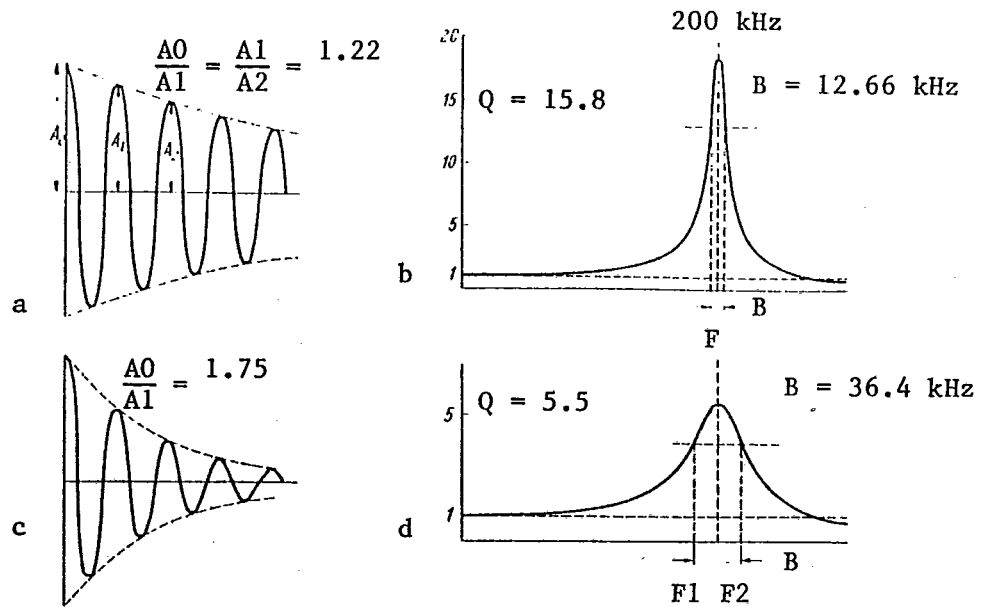


Fig. 1--Damping factor (Q) is illustrated both in time domain and frequency domain

A-Transmitter Pulse
(0.0 μs)

B-Surface Waves

C-Reflected Longitudinal
Wave (226.0 μs)

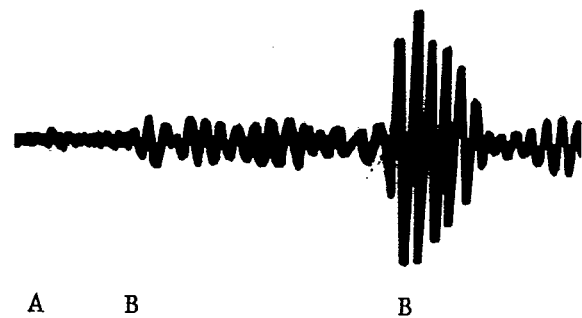


Fig. 2--Pitch-catch measurements on PCC with 100 kHz barium titanate transducers from Bradfield Woodroffe, 1953

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A-Time Mark 150 μ s after
Transmitter Pulse

B-Surface Wave (185 μ s)

C-Reflected Longitudinal
Wave (281 μ s)

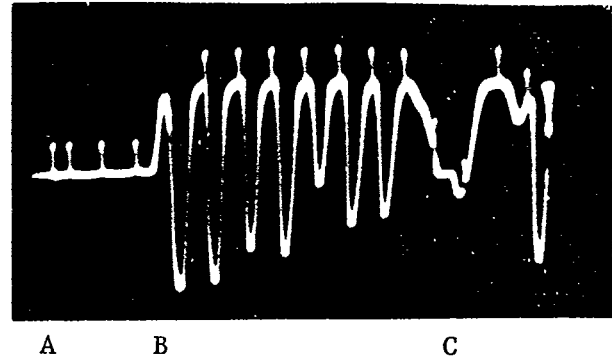


Fig. 3--Pitch-catch measurements on PCC with 100 kHz barium titanate transducers from Bradfield and Gatfield 1964

A-Transmitter Pulse
(0 μ s)

B-Surface Wave
(110 μ s)

C-Reflected Longitu-
dinal Wave (188 μ s)

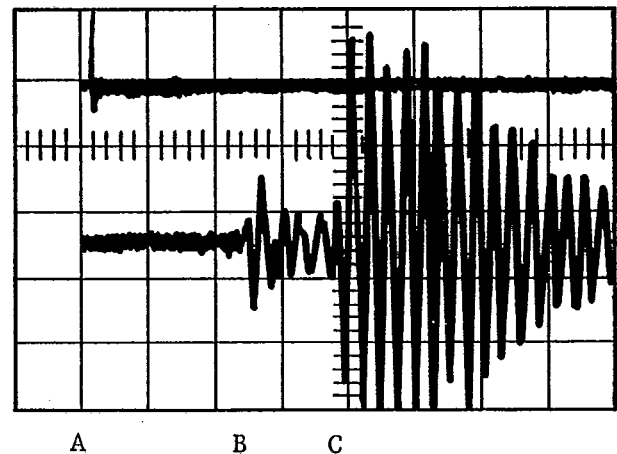


Fig. 4--Pitch-catch measurements on PCC with 100 kHz barium titanate transducers from Howkins, 1968

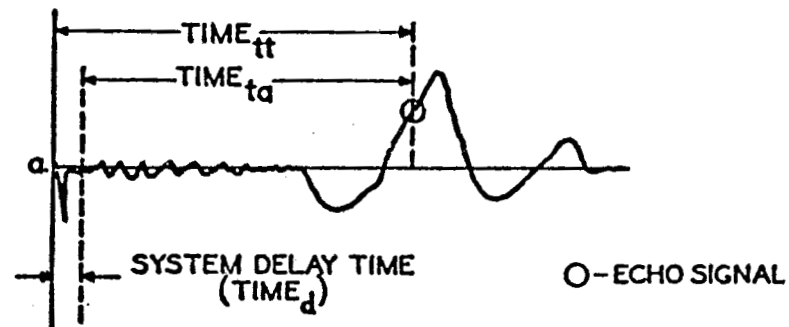


Fig. 5--Pitch-catch measurements on PCC with 200 kHz lead zirconate titanate transmitter and a broadband receiver of lithium sulfate from Golis et al, 1971

A-Transmission Pulse
(0 us)
B-Surface Wave (50 us)
C-Reflected Longitudinal
Wave (130 us)

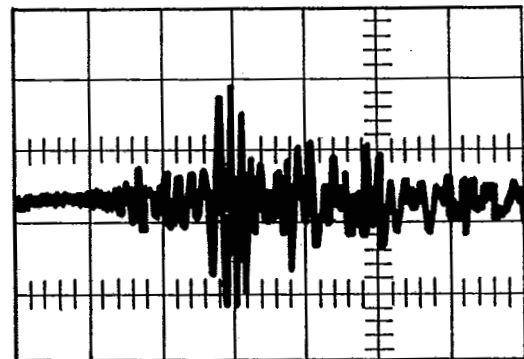


Fig. 6--Pitch-catch measurements on PCC with 180 kHz lead zirconate titanate transmitter and broadband lithium sulfate receiver from Thornton and Alexander, 1987

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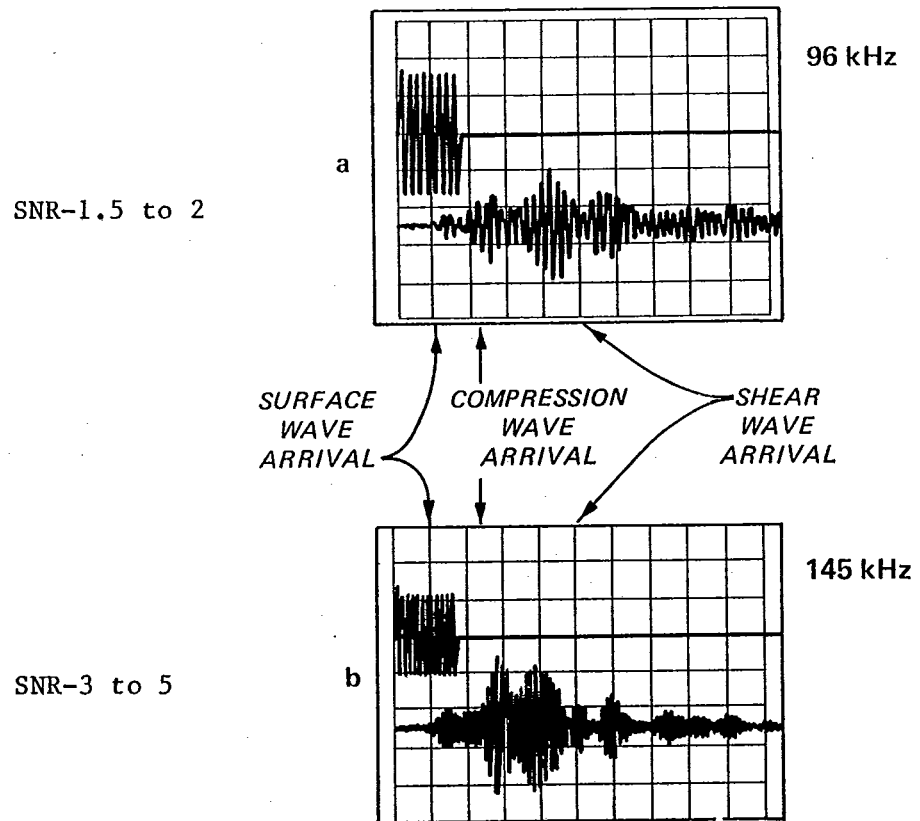


Fig. 7--Pitch-catch measurements on refractory concrete with 250 kHz transducers of lead zirconate titanate from Claytor and Ellingson, 1984

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A-Transmitter pulse
(0 μ s)

B-Backscattering with low surface wave energy
(35 μ s)

C-Reflected Longi-
tudinal Wave
(106 μ s)

SNR - 18
9/18/85

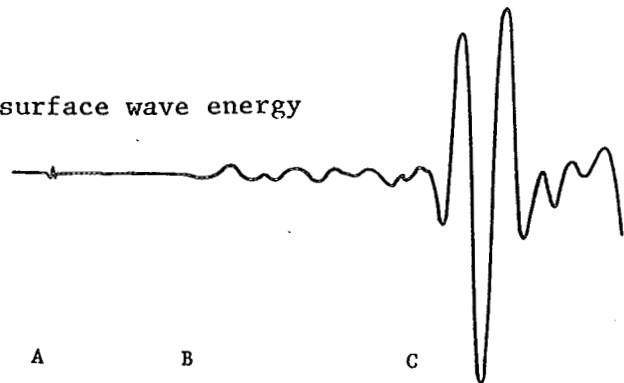
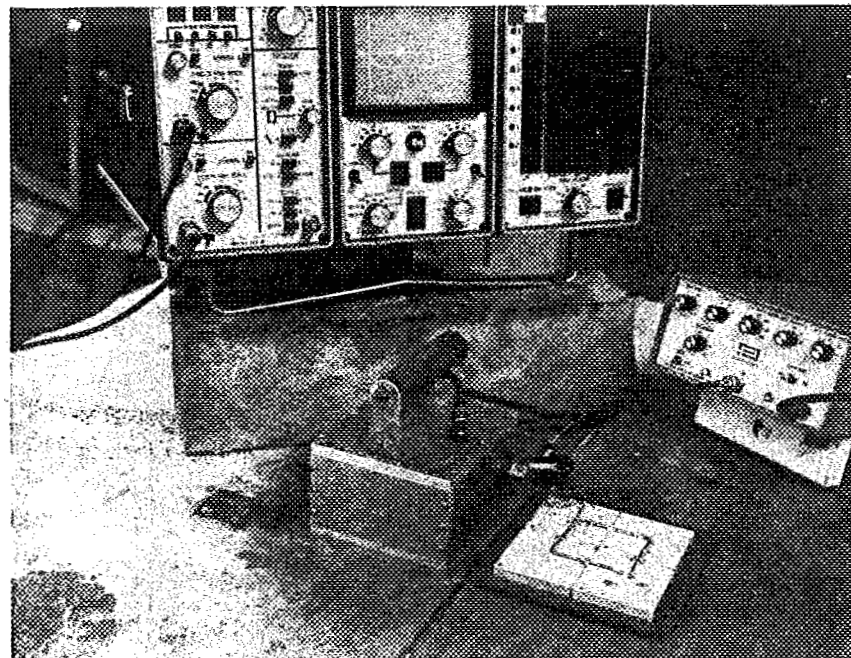


Fig. 8---Pitch-catch measurements on PCC with 190 kHz lead metaniobate transmitter and lead zirconate titanate receiver from Thornton and Alexander, 1987

D



A

B

C

Fig. 9---Ultrasonic pitch-catch system: transmitter, receiver, pulser/filter/amplifier, oscilloscope, 9.25 inch thick PCC slab

A-Receiver (PZT-5H)

B-Lead Metaniobate
Transmitter (EC-82)

C-Pulser (Shock Variety)

D-Digital Processing Oscilloscope



Documents

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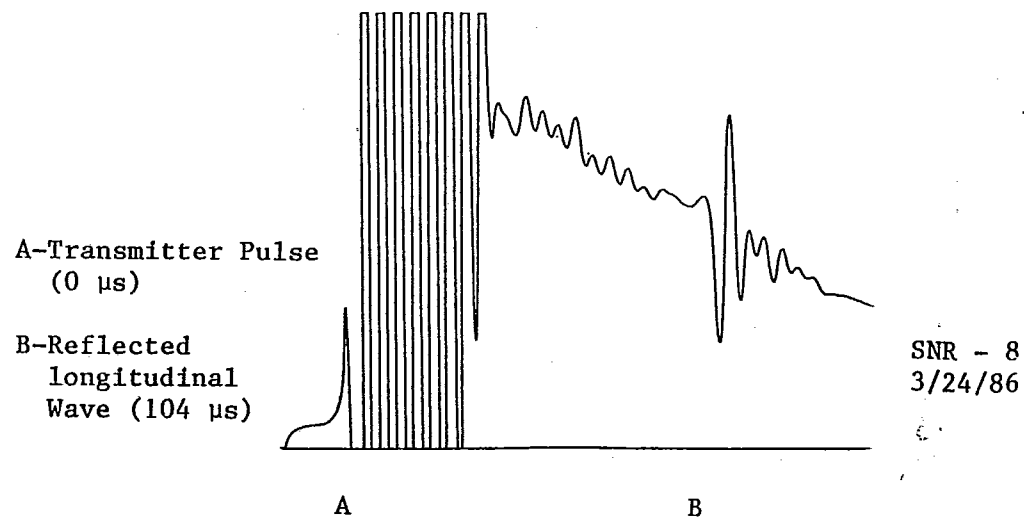


Fig. 10--Pulse-echo measurement (one-transducer) on PCC with 190 kHz lead metaniobate transducer from Thornton and Alexander, 1987

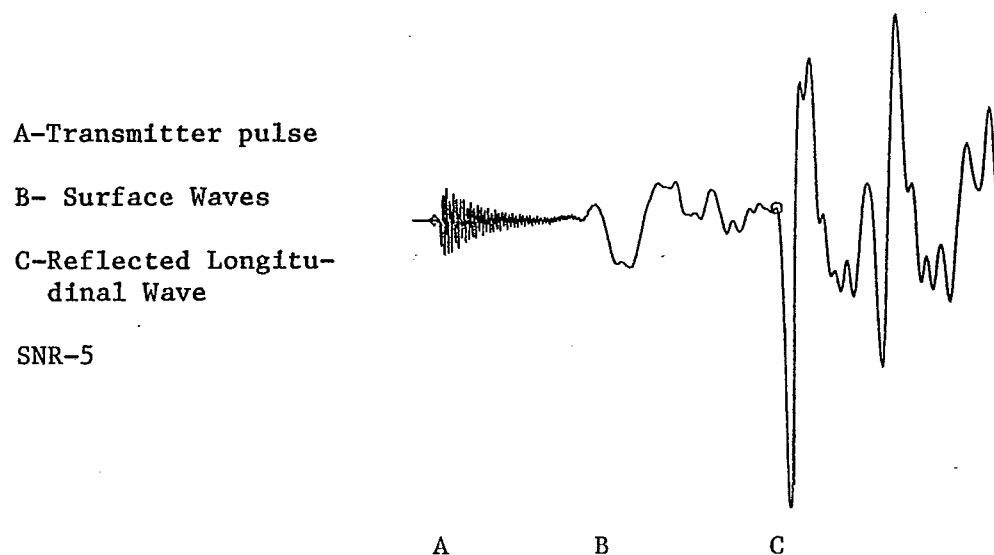


Fig. 11--Ultrasonic pitch-catch measurement on PCC with 280 kHz polyvinylidene fluoride (PVDF) transducer operating on a 6 inch thick slab

SP 112-3

Evaluation of Concrete Constituents Using Photon Radiation

by M.A. Taylor

Synopsis: Gamma ray absorption techniques were used to determine the amounts of each component in a system of mixtures (such as concrete). The technique uses photons of several energies in contrast to previous applications where only one energy was employed. The use of multiple energies contains more information than the single beam system and thus more properties can be determined.

Several possible models for cementitious materials are discussed and compared.

The paper presents the experimental determination of the initial data set needed prior to prediction experiments. One predictive technique is evaluated by comparison with "blind" tests.

Keywords: absorption; attenuation; concretes; evaluation; gamma rays; nondestructive tests

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INTRODUCTION

Because of the special manner in which it is produced, and the time-dependent nature of its properties, concrete must be tested frequently in order to assure its suitability for the many uses to which it is put. Architects, owners, suppliers, and engineers must all be confident that concrete is satisfactory when constructed but the same concrete may need to be tested again decades later when, for example, a building is to be remodelled, or used for a new purpose.

The traditional method of evaluating concrete is to take a sample from the supply during placement (e.g. companion cylinders) or from the completed structure (e.g. by coring). The sample is assumed to be representative of the parent concrete and is taken away and tested. The destructive nature of most tests means that any uncertainty can be alleviated only by taking more samples. No test can ever be repeated. The advantages of a test which would be both non-destructive and in-place are well established and much effort and ingenuity has been expended in the search for such a technique. A comprehensive view of such methods may be found in Reference 1.

This paper presents the results of preliminary studies using a technique in which multiple "beams"* of radiation are passed through a sample. The attenuation of each beam provides information on the amount of the constituents in the sample. The test can be conducted in place and can be repeated at the same location or elsewhere as many times as desired. Safety requirements are similar to those for several other low level radiation devices used in various commercial tests.

Absorption (Attenuation) of Gamma Rays by Solids

Through the wave-particle duality of modern physics, gamma rays may be regarded either as high-energy photons or as high-energy electromagnetic radiation. The term "gamma" radiation is qualitative and is usually reserved for high energy photons

* To avoid confusion with terms in nuclear physics the word "beam" here refers to an essentially monoenergetic component from the spectrum of a radiating source (see Figure 3).

produced when an excited nucleus decays to a lower energy state. The excited state may be "natural" (as in radioactive materials found in nature); or may be man-made (for example by bombarding nuclei in an accelerator). The energy of gamma radiation in relation to the entire electromagnetic spectrum is illustrated in Figure 1.

When a stream of such photons (a "beam of gamma rays") enters "solid" matter and attempts to pass through it, four principal interactions may occur. These mechanisms either absorb or scatter photons so that fewer photons emerge than entered. The mechanisms are termed pair production, Rayleigh (elastic) scattering, Compton (inelastic) scattering and the photoelectric effect. For the materials and the range of energies used in this study only the photoelectric effect need be considered. In this mechanism a gamma ray is "absorbed" by collision with an orbital electron. The energy of the photon is absorbed in breaking the bond between the electron and the nucleus. Any excess energy becomes kinetic energy of the freed electron.

The absorption or attenuation of a beam of monochromatic gamma rays by a solid is governed by the equation

$$O = I e^{-c_{12}t} \quad (1a)$$

or

$$\text{nat.log } (O/I) = -c_{12}t \quad (1b)$$

where

- I = the incident beam intensity (photon counts/second)
- O = the (output) emergent beam intensity (photon counts/second)
- t = path length through the material
- c_{12} = a constant dependent on both the given material (hence subscript 1), and the given beam energy (subscript 2). The units are (length)⁻¹ and it is termed the "linear attenuation coefficient."

(see also Figure 2).

Mass Attenuation Constant

The attenuation law may be replaced by an alternate form

$$O = I_e^{-\rho t}$$

where ρ is the density of the absorbing material.

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Obviously

$$d = c_{12}/\rho$$

d has units of L^2/M (e.g. cm^2/gm) and is termed the mass attenuation coefficient.

There are two advantages to using the mass attenuation constant rather than the linear form. First, the constant may be obtained from experiments on matter in any form (gas, liquid, solid); and, secondly, when mixtures of materials are used the mass attenuation constant for the mixture is a simple linear weighted (according to mass) multiple of the mass attenuation constants of the constituents:

The probability of absorption, per atom of absorbing material, is termed the atomic attenuation coefficient and represents the effective cross-sectional area that the atom presents to the incoming photon. The area (probability) is measured in barns. One barn is 10^{-28} square meters.

EXPERIMENTAL DETAILS

Selection of Beam Energies

As noted previously, the absorption of a beam of gamma rays of a given energy is controlled by both the energy level of the beam and the characteristics (principally the density) of the material(s) through which the beam passes. Calibration experiments such as those shown in Fig. 2 must, therefore, employ materials which exhibit the range of characteristics to be expected in the field; and it is desirable to employ beams whose energies permit accurate solution of the governing equations with minimum mathematical "ill-conditioning."

The Crocker Nuclear Laboratory on the Davis campus provided a sample of the transuranium element Europium (a mixture of Europium 152 and 154). Its emission spectrum contains several major "spikes" of photons, each with its own energy level (see Figure 3). Since the computerized equipment allows multiple beams to be analyzed as easily as one, preliminary tests were run to see which beams would be most suitable for the evaluation of cements and concretes. A typical output is shown in Table 1. The selection of the beams was based upon the amount of error (indicated by the width of the emission peak of each beam) and its consistency when compared after several tests on different samples.