penetrated by gas. Consequently, a useful basis is established for evaluating some of the durability properties of concrete. On the other hand, the durability properties of concrete with respect to fluids like, e.g., salt solutions are only indirectly related to gas permeability properties and other tests must be adopted.

From our testing practice we have observed that the relative humidity of the concrete has an influence on gas-permeability, but our experience so far is also that if permeability is high this influence is not significant.

Finally, it should be mentioned that this paper describes preliminary data and findings, only. More data, as well as laboratory tests will be needed to establish firm conclusions. Such work is currently being carried out.

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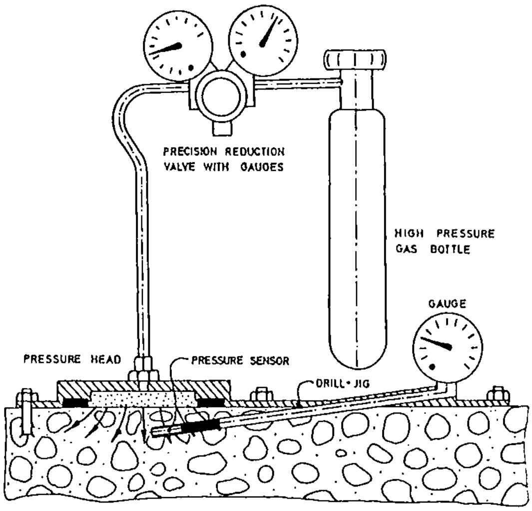

Fig. 1--Apparatus for determination of air permeability

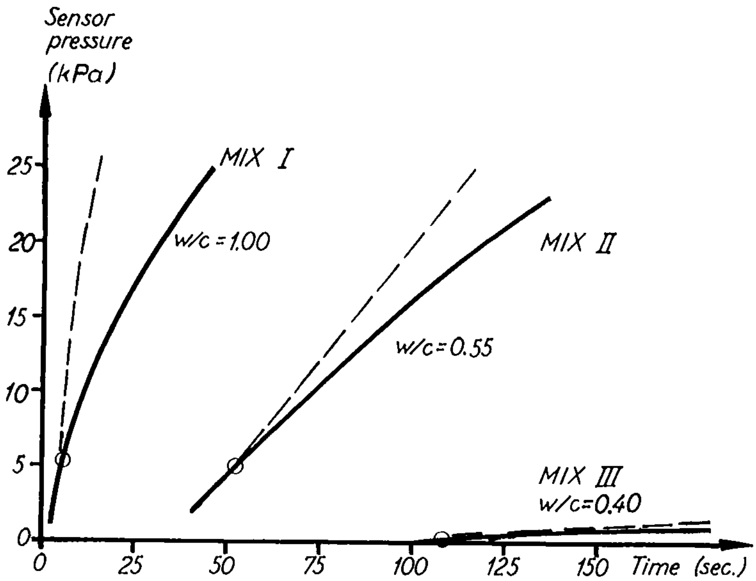

Fig. 2--Experimental permeability date for three types of concrete. Pressure increase over time for a depth of 15 mm at an overpressure of 150 kPa applied to the surface for three types of concrete. Experimental (——) and theoretical results (---)

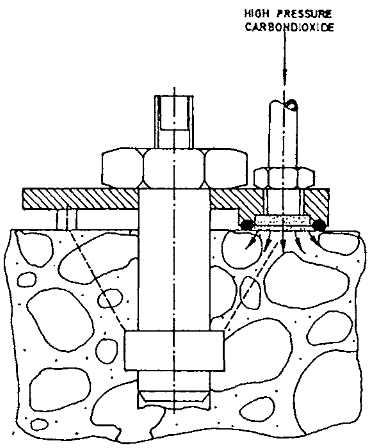

Fig. 3--Surface crack/porosity test equipment (gas bottle and reduction valve system as indicated in Fig. 1)

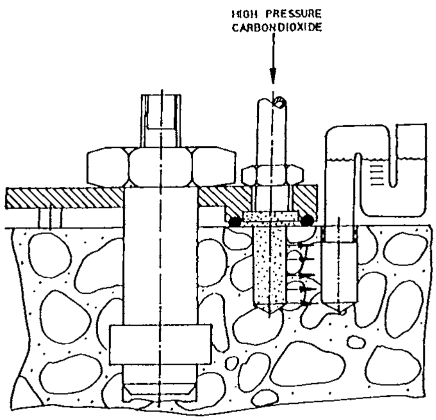

Fig. 4--Bleeding test equipment

SP 82-28

Laboratory Study of Flaw Detection in Concrete by the Pulse-Echo Method

By Nicholas J. Carino

Synopsis: A study was performed to evaluate the applicability of using the echoes from mechanically produced impact to locate hidden defects within concrete. The expected interactions of spherical waves with concrete-air interfaces are reviewed, and the results of experiments using artificial flaws in a large concrete slab are summarized. The following aspects were studied: type of impact source; distance from impact point to receiver; type of receiving transducer; depth of reflecting interfaces; and diffraction effects by sharp edges. The contact time of the impact is shown to be an important parameter for the success of the technique. The influence of the concrete thickness from impact point to the reflecting interface is an area of needed research.

Keywords: concretes; deterioration; hardened concretes; nondestructive tests; ultrasonic tests; voids.

ACI member N. J. Carino is a research civil engineer at The National Bureau of Standards. He has conducted research on a variety of NDT methods for concrete, and is an active member of ASTM committees dealing with the subject. His recent work on the maturity method earned him a U.S. Dept. of Commerce Bronze Medal Award.

INTRODUCTION

In concrete technology there is a need for nondestructive test methods for locating defects, such as voids, cracks and zones of deterioration, within hardened concrete structures. Such techniques are especially valuable for structural surveys after damage has occurred and for structural assessment prior to renovation of existing structures. In addition, these methods can be utilized in quality assurance programs of safety related structures, such as nuclear containment vessels. While radiographic methods exist, they have inherent limitations and have not found application as routine inspection methods. A promising approach is the use of the pulse-echo method which is based on monitoring the interaction of acoustic (or stress) waves with the internal structure of an object.

A previous paper discussed the fundamental principles of the pulse-echo method, reviewed past applications in testing concrete and outlined the major problems that need to be solved to develop viable techniques for widespread utilization of the method [1]. The principal difficulty in using the pulse-echo method to test concrete is the heterogenous nature of concrete. This prevents direct application of the techniques used for inspecting metal structures. The key piece of equipment that has not been perfected is a transducer that produces both a highly penetrating and a relatively narrow ultrasonic beam. The latter quality is important for reliable flaw size determination.

The U.S. National Bureau of Standards (NBS) has undertaken a study to attempt to solve the above-mentioned problems. The ultimate objective of the NBS effort is to develop standards, in terms of instrumentation and procedures, for routine utilization of the pulse-echo method to locate flaws within hardened concrete.

Two common procedures for introducing an acoustic pulse into a test object are by using an electro-mechanical transducer or by mechanical impact. While the former is desirable in terms of pulse reproducibility, the latter is attractive due to its simplicity. As there are no commercial transducers appropriate for pulse-echo testing of concrete, an objective of the NBS study is to develop such a transducer. While the transducer is being developed, we are investigating the applicability of pulse-echo testing using mechanical impact.

We begin with a review of the stress wave propagation through a solid after impact at a point on the surface. This knowledge will assist in interpreting the output signal of the receiving transducer located at some distance from the impact point. This review is followed by experimental results obtained using a large concrete slab with known internal defects.

BACKGROUND

Spherical Wave Propagation

When a stress pulse is applied to the surface of an object, the pulse will propagate into the object and, at any particular instant, its location is identified by the wave front. There are two idealized shapes of these wave fronts: planar and spherical. These idealizations give rise to what are known as plane waves and spherical waves. The properties of plane waves are constant on a given plane perpendicular to the propagation direction. Regions of plane waves can be produced in an object by using electro-mechanical transducers having large ratios of diameter to wavelength. When the transducer diameter is small compared to the wavelength, the transducer can be treated as a point source in which case the wave front is spherical. When the stress pulse is produced by impacting the surface over a small contact area, the pulse can also be assumed to propagate as a spherical wave. For the experiments reported in this paper, the spherical wave idealization is appropriate.

Figure 1(a) shows the situation in an infinite plate after impact on the top surface by a point source. The impact creates three wave modes: surface (R) waves, shear (S) waves and compression (P) waves. The S- and P- waves travel into the plate as spherical waves, each wave front travelling at its own wave speed. The ratio of S- to P-wave speed depends on Poisson's ratio of the material. For a Poisson's ratio of 0.2, which is typical of concrete, the ratio of S- to P-wave speed is about 0.61, and the surface wave speed is about 0.56 the P-wave speed. The "ray" -- a line defining the direction of wave front propagation -- is a helpful concept for understanding subsequent wave interactions with the solid. Two rays, OA and OB, are shown in Fig. 1(a). At any point on the P-wave front the particle displacement is parallel to the ray, and on the S-wave front the displacement is perpendicular to the ray.

As shown in Fig. 2, the magnitudes of particle displacements (or stresses) within the plate are not uniform along the wave fronts. The figure is based on theoretical calculations for a point source [3], which were verified experimentally using small diameter transducers [4]. For P-waves, displacements are highest along rays with low radiating angles (θ), while for S-waves the displacements are greatest at intermediate radiating angles. Along any given ray, beam spreading causes the particle displacements to vary as the inverse of the wave travel distance [2].

Wave Reflection

When a wave front reaches an interface with a dissimilar material a portion of the wave energy passes into the second material (refraction) and the remainder is reflected. The wave-front reflection at the interface is much like the reflection of light by a mirror, and for this reason the term "specular reflection" is used. If the second material is air, it can be assumed that all of the energy is reflected [1]. The shape of the reflected wave front can be determined by considering the reflection of individual rays, which obey Snell's law [2]. In Fig. 1(b), incident rays OA and OB are reflected as rays AC and BD, and it is seen that the reflected rays behave as though they were radiating from virtual point O'. Thus, the reflected wave fronts PP and SS are also spherical. Reflection is complicated by the phenomenon of mode conversion whereby, for example, an incident P-wave results in a reflected P-wave and also a reflected S-wave. Similarly, an incident S-wave can result in reflected S- and P-waves. The reflection angles of the mode-converted rays are governed by Snell's law, and the resulting wave fronts are elliptical rather than spherical [2].

The amplitudes of the reflected rays depend on the reflection coefficients for the interface. Figures 3 and 4 show the reflection coefficients for incident P- and incident S-rays. These figures were developed from formulas in Ref. [2] for a concrete-air interface (Poisson's ratio equal to 0.2). Each figure is composed of three graphs: the graph in the upper left gives the reflection coefficient for the ray with the same mode as the incident ray; the graph in the lower right gives the reflection coefficient for the mode-converted ray; and the graph in the upper right gives the angular relationship (Snell's law) between the incident ray and the mode-converted ray. The drawings in the lower left give illustrative examples. The reflection coefficients assume that the incident rays have an amplitude (stress or displacement) equal to unity. To determine relative amplitudes along the reflected wave fronts one must consider the combined effects of total ray path length, the directivity patterns (Fig. 2) and the reflection coefficients.

When the reflected wave fronts return to the top surface, reflection and mode-conversion occur, and the wave fronts travel back toward the bottom surface. Thus, the initial impulse results in wave fronts travelling back and forth through the plate thickness. A transducer located on the top surface of the plate will respond to these multiple reflections. An understanding of the expected transducer response can be gained by considering the different rays that can travel from the impact point to the transducer location. Figure 5 shows some examples. The first ray to arrive is the surface wave or the reflected P-wave, depending on the transducer location and plate thickness. This is followed first by rays from mode-converted SP- and PS-waves and then by a ray from the reflected S-wave. Following these singly-reflected rays is a series of other rays having undergone multiple reflections and mode conversions. The amplitude of each arriving ray is reduced by the reflection coefficients and the total ray path length. In a finite plate, an added complication is the arrival of surface waves reflected from the boundaries of the top surface. The reflected surface waves interfere with the reflected P- and S-waves, and complicate the interpretation of the transducer output.

Diffraction

Previously it has been assumed that the wave fronts are reflected from the top and bottom plate surfaces. This analysis is also applicable to reflections from large, smooth and planar cracks within a plate. However, at the sharp edges of an embedded crack an additional phenomenon, known as diffraction, occurs. A ray intersecting the crack edge (e.g., ray OA in Fig. 6(a)) produces a reflected spherical wave [5]. Figure 6(b) illustrates the wave fronts present in the vicinity of a sharp edge for the case of an incident P-wave. An S-wave would result in a similar condition but at a later time. Mode conversion is also possible. Note that diffraction permits the stress wave to penetrate the "shadow zone" below the crack. Researchers have been able to record photographic images of diffraction effects using photoelasticity [6,7], which confirm the conditions depicted in Fig. 6(b). Similar to the initial wave front emitted from the source, the amplitude of a diffracted wave varies with direction and is, according to theoretical calculations, an order of magnitude less than specularly reflected waves [8]. Nevertheless, diffracted waves are important as they enable detection of cracks which are unfavorably oriented for detection by specularly reflected waves[9].

Attenuation

In addition to beam spreading and reflection at concrete-air interfaces, internal friction and scattering, collectively called attenuation, cause further reduction in amplitude [2]. Internal friction occurs at the atomic level and results in energy loss in the form of heat. Scattering is due to discontinuities within the concrete that reflect a portion of the incident energy. Losses due to scattering are strongly dependent on the wavelength of the propagating wave and the size of the discontinuities. More scattering results when the wavelength is about the same size or smaller than the discontinuities. Concrete inherently contains many defects in the form of air voids, microcracks and paste-aggregate interfaces. While most of these defects are not necessarily harmful to the performance of the concrete, they will reduce the penetrating ability of high frequency waves. Thus, the high frequency (megahertz range) transducers used for inspecting metals will not work in concrete. Measurement of attenuation is a difficult matter and the only known published data on concrete are for refractory concretes [10]. Obtaining data on the effects of various factors, such as aggregate size and cement paste porosity, on the attenuation chracteristics of concrete are needed areas of research.

EXPERIMENTAL WORK

The objective of the initial investigation was to study the applicability of using mechanical impact to create stress pulses for locating internal defects in hardened concrete. A large concrete slab (2 m by 4.5 m by 0.5 m) was cast in which were embedded disks of various diameters. The disks were made from 25-mm thick rigid polyurethane insulation board. Figure 7 shows the slab form with the disks in position prior to concrete placement. The concrete was made with 13-mm nominal maximum size crushed stone aggregate. The air content was 5 %, the unit weight of fresh concrete was 2.22 Mg/m^3, and the 28-day cylinder compressive strength was 25.9 MPa.

The receiving transducer was developed at NBS for acoustic emission testing and it has been shown to respond quite faithfully to the vertical displacement of the surface to which it is coupled [11]. The active piezoelectric element is in the shape of a small cone with a 1.5-mm diameter contact area, thus making the transducer behave as a point receiver. As the transducer was designed for use on a polished metal surface, grinding of the concrete surface was required for proper coupling. In addition, a sheet of aluminum foil had to be placed on the concrete in order to complete the transducer circuit. The foil was coupled acoustically to the concrete using water soluble jelly. For comparison with the NBS transducer, two commercial transducers were used in some of the tests.

The data acquisition system included a four-channel processing digital oscilloscope operating at a 500-kHz sampling rate.

RESULTS AND DISCUSSION

The following aspects were studied:

- o The type of impact source
- o The distance between the impact point and the receiver
- o The type of receiving transducer
- o The depth of the reflecting interface
- o The location of the receiver in relation to the boundary of the reflecting interface

A schematic of the experimental setup is shown in Fig. 8. "H" is the distance between the impact point and the receiving transducer, and "T" is the distance from the top surface to the reflector. The reflector is either the interface between concrete and a 0.50-m diameter disk or the bottom surface of the slab.