Guide for the Evaluation of Shotcrete

Reported by ACI Committee 506

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Evaluation of in-place shotcrete requires experience, education, and engineering judgement. This document serves as a guide for engineers, inspectors, contractors, and others involved in accepting, rejecting, or evaluating in-place dry or wet mix shotcrete.

Keywords: brooming; construction practices: cracking (fracturing): defects; dry mix; finishing in situ testing inspection; lenses; nozzleman; overspray; permeability; quality; sags; sand pockets screeding; shotcrete; trowel cutting; visual appearance voids; wet mix.

CONTENTS

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning, executing, or inspecting construction and in preparing specifications. References to these documents shall not be made in the Project Documents. If items found in these documents are desired to be part of the Project Documents, they should be phrased in mandatory language and incorporated into the Project Documents.

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CHAPTER 1-INTRODUCTION

1.1-The purpose of this report is to present procedures that can be used to evaluate the quality and properties of in-place shotcrete.

1.2-Considerable literature is available on testing fresh concrete, concrete specimens, and in-place concrete. Procedures for the production and testing of concrete are covered by ACI and ASTM Standards. The development of in-place (nondestructive) test procedures for evaluating concrete structures has progressed to the point where the use of such procedures has become common.

1.3-Procedures for in-place evaluation of shotcrete have not been well developed or widely used This may be due to the lack of understanding of the difference between shotcrete and concrete. The most important factor in producing quality shotcrete construction is the skill of the nozzleman. While ACI 506.2 requires preconstruction testing to verify a nozzleman's ability, such testing is not always done. Additionally, inspectors who are knowledgeable in shotcreting are not ordinarily available to monitor shotcrete quality. Thus, if properly skilled nozzlemen are not used, defects such as improper encasement of reinforcing steel, voids behind steel, excessive cracking caused by shrinkage, sand pockets, and defects caused by inclusions of overspray and rebound can occur.

CHAPTER 2-STRENGTH

2.1-General

Strength is widely used to evaluate shotcrete quality. Although both compressive and flexural strength can be obtained, the compressive strength is most commonly used. Many of the sampling and testing methods for shotcrete are similar to those used for concrete and can be broadly categorized as destructive and nondestructive determinations. Because it is generally not possible to mold standard test specimens for shotcrete, the sampling and testing of shotcrete are usually performed on in-place hardened material or on test panels as described in ACI 506.2 and ASTM C 1140, which cover preparing and testing specimens from shotcrete test panels.

2.2-Destructive testing

Under this category, samples obtained from hardened shotcrete by drilling cores, sawing cubes, or prisms are tested to failure. Core samples are most frequently used. In addition to providing specimens for strength tests, drilled cores offer an excellent opportunity to visually examine the shotcrete, at depth, for consolidation, embedment of reinforcement, contact with substrate, sand streaks, and other faults, as discussed below.

2.1.1 *Obtaining core samples*-Obtaining core samples from the actual structure is not always possible and in situations where core samples can be obtained, the integrity of the structure may be damaged to varying degrees depending on the size, number, and location of the core samples. ASTM C 42 describes the testing procedure and explains how the results should be corrected for height-to-diameter ratio. The nominal core diameter should not be less than 2 in. (50 mm) with 3 in. (75 mm) being the preferred diameter for shotcrete. ASTM C 823 states when and how cores should be taken, and the required moisture condition of the cores at the time of test. It is recommended that interpretation of results be made by an engineer experienced in shotcrete technology. The following factors should be considered:

2.2.1.1 *Damage to samples*-Minor chipping of the perimeter of core ends during drilling is not significant. Cracks may invalidate the test result. Sharp diamond drill bits on watercooled drills rigidly fixed to the structure normally produce suitable samples.

2.2.1.2 *Density*-Each 1 percent of void volume in shotcrete will reduce the strength approximately 5 percent (Neville 1986). If undercompaction is significant, considerable voids will be present and the extent to which it is typical of the shotcrete in the structure in question should be determined

2.2.1.3 *Presence of reinforcing bars*-It is highly desirable that cores do not contain reinforcing bars. However, there is no established standard to account for the effect of reinforcement on the strength of the specimen. Examination of the core failure pattern will help determine if the bar has significantly affected strength. Embedded reinforcement can be located using a magnetic detector.

2.2.1.4 *Evidence of alkali-aggregate reaction, freeze-thaw damage, sulphate or other chemical attack*-If there is doubt as to what factors have caused apparent damage, the advice of a petrographer should be sought.

2.2.2 *Testing drilled cores*-Normally, cores are drilled from the structure after the shotcrete has hardened and are tested in order to evaluate the quality of in-place shotcrete, particularly in terms of uniaxial compressive strength. Although the strength test itself is fairly simple, the details of the procedure should be carefully established and followed. Numerous factors can affect the strength which, in turn, can influence judgment of the overall quality of shotcrete. Some of the factors are the diameter of the core, its height-to-diameter ratio, direction of coring in relation to the placing of shotcrete and the location in the structure, curing and moisture conditions of cores prior to testing, and maximum size aggregate and presence of reinforcing steel in the core.

2.2.3 *Cubes and prisms*-Such specimens may be sawed from test panels but they are difficult to obtain from shotcrete that is bonded to the substrate. It has been reported that the variation between tests on sawed cubes is less than that for drilled cores from the same shotcrete (Rutenbeck, 1976).

2.3-Nondestructive testing

2.3.1 *Rebound and indentation tests*

2.3.1.1 The rebound method and the indentation method both measure relative hardness of surface layers, which is generally related to strength. Both methods are well known and are used. However, the methods are empirical in nature and several precautions must be taken to obtain significant results. The methods give only an estimate of the strength of shotcrete, and then only the shotcrete near the surface.

2.3.1.2 Hardness methods in combination with other nondestructive methods have been used to make strength predictions. It is desirable to take advantage of the potential offered by the hardness methods because of the relatively low cost of these methods.

2.3.1.3 The Schmidt Rebound Hammer is the most commonly used apparatus for measuring the hardness of concrete by the rebound principle (Malhotra, 1976). ASTM C 805 describes the test procedure. Although this rebound hammer provides a quick, inexpensive means of checking uniformity, it has many limitations which must be recognized. The results of the rebound hammer are affected by the texture, degree of carbonation, and moisture condition of the shotcrete surface, thickness and age of the shotcrete structure, and type of coarse aggregate. Estimation of strength of shotcrete within an accuracy of **±15** to **±20** percent may be possible (ACI 228.1R). Each hammer is furnished with a calibration chart supplied by the manufacturer. However, each hammer varies in performance and needs calibration for use on shotcrete of a specific type and composition. This test cannot be regarded as a substitute for compressive strength testing of cores; however, it may be used to locate nonuniform areas within a shotcrete structure or to compare the relative strength of one shotcrete with another. It is suggested that Schmidt Rebound Hammers for use on shotcrete be calibrated against shotcretes from the same materials but with a range of strengths.

2.3.2 *Penetration test*-This method is described in ASTM C 803. A driver, usually powder-activated, delivers a known amount of energy to a steel pin. The penetration resistance of the concrete is determined in place by measuring the exposed length of the probes, which have been driven into the concrete. This method measures the surface hardness of concrete and relates to the strength property at a depth greater than indicated by the rebound hammer method

2.3.3 *Pull-out test*-In the pull-out test, ASTM C 900, a dynamometer is used to measure the force required to pull out a specially shaped steel insert with an enlarged end which has been cast into the shotcrete. A cone of shotcrete is pulled out with the insert, and the shotcrete is simultaneously in tension and in shear. The pull-out force can be correlated with shotcrete compressive strength. The cost is relatively low and the testing can be quickly done in the field There may be some damage to the shotcrete surface which will require patching. However, the test need not be done to failure of shotcrete; if a pull-out force of a given minimum value is applied and the shotcrete has not failed, then the shotcrete can be assumed to have attained the compressive strength specified. The equipment is simple to operate and the tests are reproducible. It should be recognized that pull-out tests do not measure strength in the interior of shotcrete. They have been used effectively for monitoring strength development at early ages. This method presents some difficulties when used with shotcrete, since the techniques used by the nozzleman to embed the insert will, of necessity, be different than those employed in applying the shotcrete to the surrounding areas. Therefore, the test results may not be representative of the bulk of the shotcrete.

2.3.4 *Other tests*-Some relatively new in-place pull-out tests have been developed for testing the in-place strength of concrete or shotcrete. In one test method, a suitably shaped hole is drilled into concrete using an underreaming tool, and an expandable insert is installed in the hole. The insert is then pulled out in the same manner as in the pull-out test and the data are analyzed similarly. This method has the advantage over pull-out test C 900 in that sampling can be random and not dependent on the nozzleman's skill in shooting around an insert.

CHAPTER 3-VOIDS AND BOND

3.1-General

This section discusses the techniques, tools, and tests currently available to detect lack of bond to underlying surfaces and voids in shotcrete.

3.2-Sounding

The most frequently used technique for locating subsurface voids is sounding. Sounding can be accomplished by using a hammer or a "chain drag" method may be used for horizontal surfaces.

3.2.1 *Hammer*- Sounding surveys may be conducted by striking the finished surface with a hammer. The operator listens to the ring or sound that the shotcrete imparts. A sharp ringing sound is indicative of sound shotcrete. A "drummy" or hollow sound is indicative of lack of bond between layers of shotcrete or between the shotcrete and the substrate. Large voids can also be detected with a hammer. The "drummy" sounding areas are marked and data transferred to field records. Before using this method, several hammer weights should be tried to determine the best one for the wall thickness and the materials to reveal the "drummy" sounds. Often 1- to 5-lb (0.5 to 2.3 kg) hammers are used; heavier hammers being used for thicker shotcrete.

3.2.2 *Chain drag* -Horizontal areas can be sounded by dragging a metal chain across the shotcrete. Voids and delaminations will be indicated by a change in the sound emanating from the shotcrete. This method is described in ASTM D 4580; areas indicating voids and delaminations can be recorded as described in 3.11.

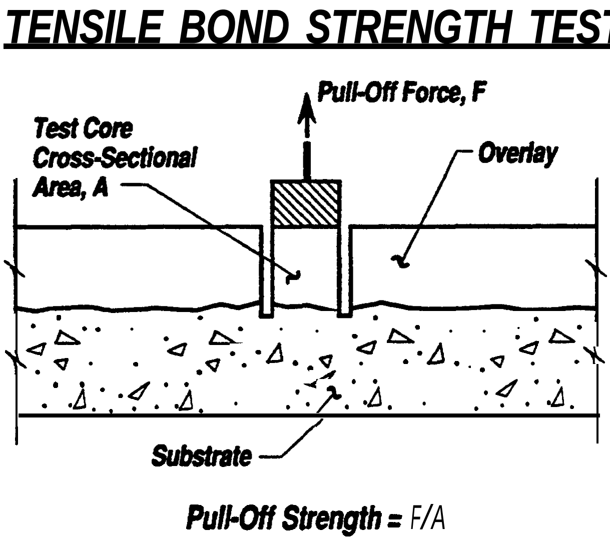

Fig. 3.2-Direct tension (tensile bond) - test set-up

3.3-Direct tension (tensile bond)

To perform tensile bond tests, a core drill, usually 2 in. (50 mm) in diameter, is used to drill through the shotcrete layer into the substrate or underlying layer. A steel disk is attached to the top of the core with an epoxy resin. The test setup is shown in Fig. 3.2. During testing, a tensile load is applied to the plate through a loading rod and hydraulic ram. Measured failure loads divided by core area are reported as bond strength. This method gives numerical tensile bond strengths between shotcrete layers or between shotcrete and the substrate when failure occurs at the bond line. If failure occurs in the shotcrete or the substrate, the bond strength is known to exceed the cohesive strength of the system. The data should be examined by the engineer to determine acceptability. Extreme care in drilling must be exercised to obtain representative results. Any eccentricity in the core barrel or wavy or stepped core surfaces can cause tensile loads which are not parallel to the axis of the core and result in lower indicated strengths.

3.4-Sonic and radar methods

Techniques that have been developed for testing concrete can also be used to provide information on the integrity of shotcrete. These nondestructive methods are based on the effects of internal defects, such as delaminations and voids, on wave propagation through the test object.

In general, these methods involve the introduction of an energy pulse into the test object at an exposed surface. If the pulse is mechanical, such as by impact, the methods are referred to as *sonic* methods. If the pulse is electromagnetic, the method is known as *radar*. In either case, the pulse propagates through the object and interacts with interfaces between dissimilar materials, such as those between shotcrete and air or shotcrete and steel. By monitoring the signal produced by the reflected portion of the pulse or the portion that passes through the object, a trained operator can interpret the received signal and decide whether the test object is solid or contains internal defects. Because these are indirect methods, survey results should be verified at selected locations by means of cores.

3.4.1 *Sonic methods*-Methods based on the propagation of sound waves, or mechanical stress waves, through a material are sensitive to changes in density and elastic stiffness (Sansalone and Carino, 1991). Therefore, sonic methods have proven useful for inspection of concrete structures. Depending on the technique that is used, sonic methods can be used to provide information on the uniformity of the concrete (or shotcrete) in the structure or to locate hidden defects. The sonic techniques can be divided into transmission and echo methods.

3.4.1.1 *Transmission method*-In the transmission method, a transmitting transducer is used to introduce a pulse of vibrational energy into a member. The pulse propagates through the member and is received by another transducer located directly opposite the transmitter. The test instrument includes a timing circuit to measure the time it takes for the pulse to travel from the transmitter to the receiver. The measured distance between the transducers is divided by the travel time to obtain the *pulse velocity* through the member (Naik and Malhotra, 1991). Since the transducers emit a pulse with characteristic frequencies greater than 20 kHz, the technique is commonly called the *ultrasonic pulse velocity* (UPV) method. The travel time is dependent on the elastic properties and density of the material along the travel path. The presence of defective material, such as due to inadequate consolidation, voids, or microcracking, increases the travel time and results in a lower apparent pulse velocity (see Fig. 3.4.1.1). If there is a large void or delamination and the transducers are far from the edge of the void, the pulse does not arrive at the receiver, and travel time cannot be measured.

Procedures for performing UPV tests are given in ASTM C 597, and information on using the method to estimate in-place strength is provided in ACI 228.1R. For the latter application, the user must be aware of the interfering factors affecting the UPV that may result in wrong strength estimates. In performing UPV tests, a gel or grease is used to ensure effective coupling of the transducers to the surfaces of the member. Ineffective coupling results in an increase in the apparent travel time.

The preferred testing configuration is to have the transducers located directly opposite each other as shown in Fig. 3.4.1.1. This direct orientation ensures the highest signal amplitude and the most reliable travel time measurement. However, it is possible to place the transducers on two perpendicular surfaces, and make measurements by the *semidirect* method (see Fig. 3.4.1.1). In this case, the signal amplitude will be affected by test geometry, and the timing circuit may not measure the correct travel

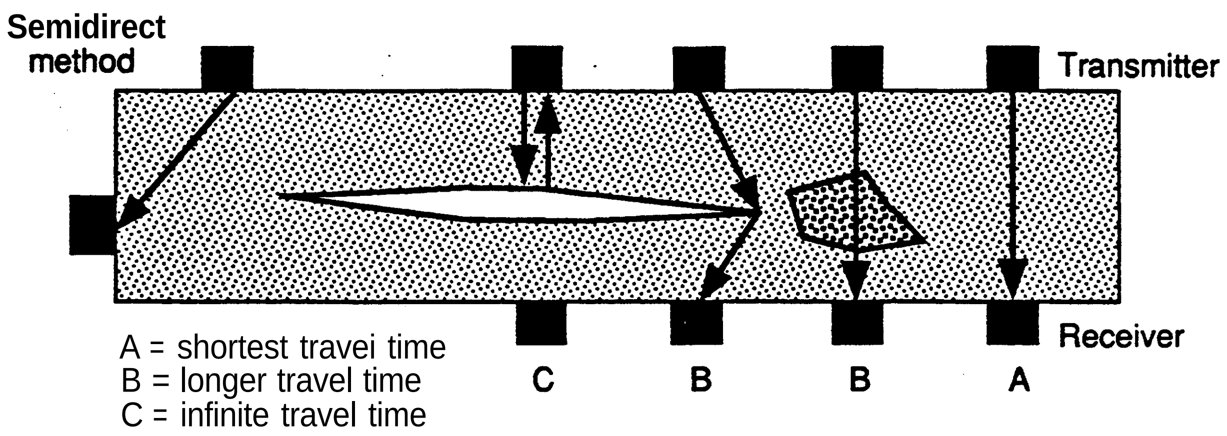

Fig. 3.4.1.1-Ultrasonicpulse velocity method showing different situations

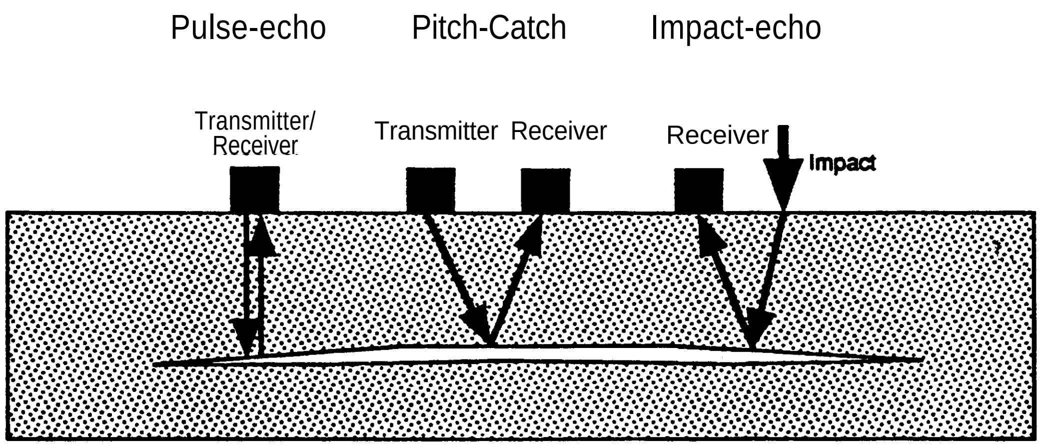

Fig. 3.4.1.2-Echo methods

time. Hence, this method should only be used by experienced operators, and it may be advantageous to use an oscilloscope to monitor the received signal to confirm the travel time indicated by the instrument. The use of the surface method, in which the transducers are located on the same surface, is not recommended for routine testing because there is uncertainty about what is actually measured.

The UPV method is a relatively simple and rapid test method that can establish the uniformity of the shotcrete in a member. Its' major disadvantages are the need for access to two sides of the member and lack of information of the location of an apparent anomaly with respect to the depth of the member. These deficiencies can be overcome by using the sonic echo methods.

3.4.1.2 *Echo methods*-The sonic echo methods are, in principle, similar to the sonar technique for measuring the distance to an underwater target. A stress pulse is applied to a free surface of the test object, and the pulse propagates into the object as different type of stress waves (Sansalone and Carino, 1991). When the waves are incident on an interface between dissimilar materials, portions of the waves are reflected back to the test surface. The arrival of the reflected waves causes surface motion which is measured by an appropriate transducer. If the wave speed through the material is known and the round-trip travel time is measured, the distance from the surface to the reflecting interface can be determined. Depending on how the stress pulse is generated and how the reflected waves are monitored, different names are used for these echo methods (see Fig. 3.4.1.2).

The amplitude of the reflection at an interface is governed by the difference in the *acoustic impedances* of the materials. The acoustic impedance is the product of the wave speed and density. At a concrete-air interface, there is nearly complete reflection of the incident stress wave and this accounts for the success of the echo methods in detecting the presence of voids and cracks. Even if the void is filled with water, there is still a sufficient difference in acoustic impedance to cause strong reflections.

In the testing of metals, a single transducer is used to emit the stress pulse and to measure the surface motion caused by the arrival of the reflected wave. In this case, the technique is known as *pulse-echo,* and it requires a pulse with a duration that is a small fraction of the round-trip travel time. This is necessary to ensure that the transducer stops vibrating as a transmitter in time to act as a receiver. As a result, a pulse-echo transducer has to emit a short pulse of high frequency waves (generally greater than 500 kHz). Such high-frequency waves would be quickly attenuated in concrete, due to reflection and scattering by the air voids and paste aggregate interfaces. Therefore a high frequency, pulse-echo system is not available for testing concrete or shotcrete structures.

Some success has been achieved by using two transducers on the test surface in the *pitch-catch* configuration as shown in Fig. 3.4.1.2. The damped, transmitting transducer sends out a pulse of stress waves with frequencies in the range of 100 to 200 kHz and a receiving transducer monitors the arrival of the reflected waves An oscilloscope is used to measure the round-trip travel time. As summarized by Sansalone and Carino (1991) various researchers have developed pitch-catch devices for laboratory and field use. However, for one reason or another, they have not been developed into commercial test systems. One of the major limitations of prototype pitch-catch systems has been their limited penetration, which is on the order of 10 to 12 in. (250 to 300 mm).

Some of the limitations of the pitch-catch method have been overcome by the *impact-echo* method. A short duration stress pulse is generated by mechanical impact on an exposed surface, and the resulting surface motion is measured by a sensitive, high fidelity displacement transducer. The distance between the impact point and receiver should be between 0.2 to 0.5 of the depth of the reflecting interface. Contrary to the other echo methods, signal analysis does not involve measurement of the round-trip travel time. Instead, the impact-echo method relies on the principle that the stress wave produced by the impact undergoes multiple reflections between the internal reflector (or the opposite side of the test object) and the test surface. Thus, the stress pulse arrives at the top surface at a frequency that is dependent on the wave speed and depth to the reflector. The signal analysis technique determines the wave arrival frequency. This is accomplished by transforming the digitally recorded, time-domain waveform from the receiver into the frequency domain using a technique called the *fast Fourier transform*. The result of the transformation is an *amplitude spectrum* which gives the amplitudes of the principal frequency components in the waveform. For slab-like structures, such as walls and slabs-on-grade, the amplitude spectrum is dominated by a single peak at a frequency corresponding to the inverse of the round-trip travel time. Frequency analysis simplifies the interpretation of impact-echo signals.

For a successful impact-echo testing, it is necessary to match the duration of the impact with the depth of the defect that is to be measured. The underlying principles have been explained elsewhere (Carino, Sansalone, and Hsu, 1986, Sansalone, Lin, Pratt, and Cheng, 1991). As a guide, the duration of the impact should be less than the round-trip travel time of the stress wave. For example, if it is to be determined whether a delamination exists at the interface of a 0.10 m thick layer of shotcrete, and if the wave speed is 4000 m/s, the duration of the impact should be less than (2 x 0.10 m)/(4000 m/s) = 0.00005 s, or 50 microseconds. Based on the theory of elastic impact, it can be shown that an impact of this duration can be achieved by using a 10 mm sphere as the impact source. Thus impact-echo testing of relatively thin shotcrete layers requires using small impactors.

The basis of the impact-echo method has been documented in a series of analytical and experimental studies, which were initiated at the National Institute of Standards and Technology (formerly the National Bureau of Standards) and have continued at Cornell University. It has been shown that, in addition to measuring member thickness, the technique can locate delaminations, voids, and honeycombing in plain and reinforced concrete (Sansalone and Carino, 1988a, 1988b). These defects are fairly easy to locate within slab-like members. It has also been shown that in order to be able to detect reflections from an interface, the ratio of the acoustic impedances of the materials has to be less than about 0.6 or more than about 1.7.* Subsequent work at Cornell University lead to the development of a prototype test system (Pratt and Sansalone, 1992) that has been commercialized, and extended the application of the method to prismatic members. The interpretation of tests of prismatic members is inherently more complex due to the modes of vibration that originate from reflections by the sides of the members. Nevertheless, with proper training, a user can locate defects within beams and columns.

Another variation of the echo methods is to monitor the time history of the impact by means of an instrumented hammer. The output of the receiver and load cell are converted to the frequency domain and a characteristic *transfer function* for the structure is determined. The transfer function contains information about the integrity of the structure. This approach, known as the *impulse-response* method, has been used for detecting voids beneath pavements and integrity testing of deep foundations.

3.4.2 *Ground penetrating radar*-Radar is the electromagnetic equivalent of the pulse-echo method A transmitter sends out a pulse of electromagnetic radiation and a receiver senses the arrival of the reflected portion of the pulse. Measurement of the round-trip travel time and knowledge of the propagation speed allows determination of the distance to the reflector. Originally developed for military purposes, its early civilian uses were for geologic investigations and for locating buried objects in soils. In the 1970s, radar was used for detecting voids beneath concrete pavements; and, in the 1980s, attention focused on using it to locate delaminations in bridge decks. The technique is known by various names such as *short-puke radar*, *impulse radar*, and *ground penetrating radar*.

* Lin, J.M., and Sansalone, M., "Impact-Echo Response of Hollow Cylindrical Concrete Structures Surrounded by Soil or Rock: Numerical Studies," manuscript submitted to *ASTM Geotechnical Testing Journal*.

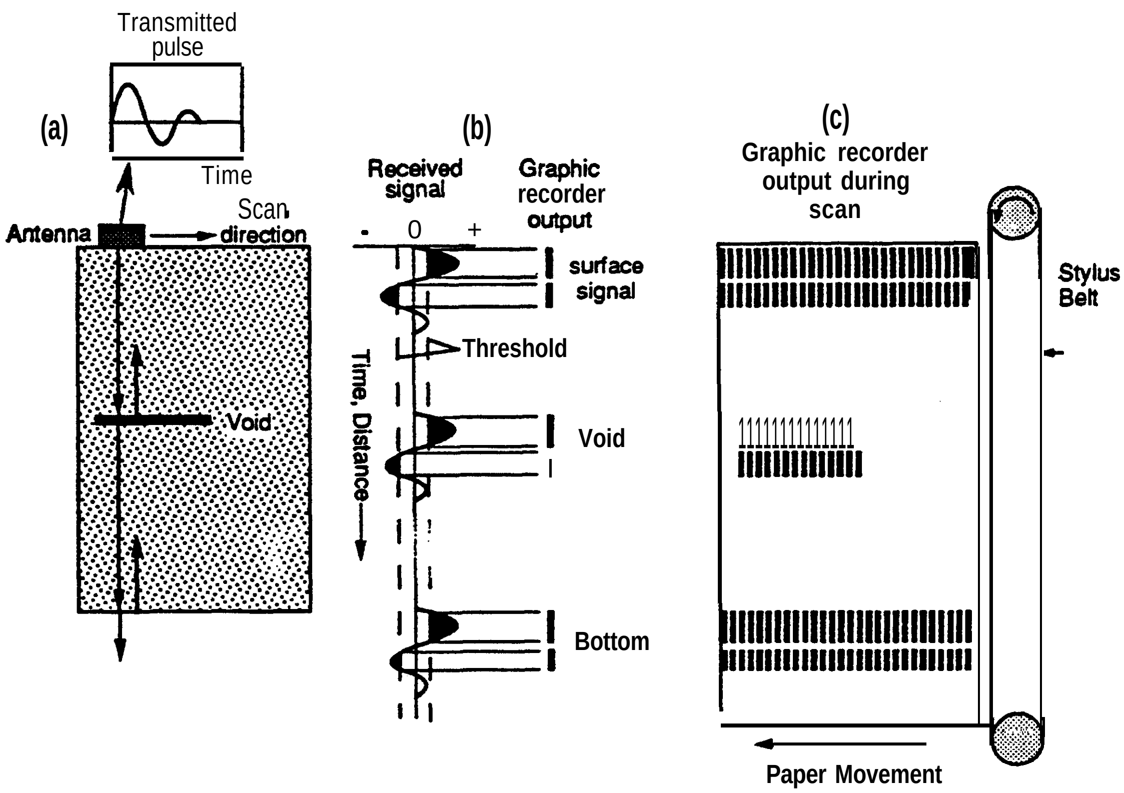

Fig. 3.4.2-Ground penetrating radar: (a) reflections of pulse at interfaces; (b) idealized waveform from receiving antenna and threshold platting by graphic recorder; (c) schematic of output from graphic recorder during scan over slab with a void

From an electromagnetic viewpoint, materials can be classified as conductors, such as metals, and insulators or *dielectrics.* Electromagnetic waves in the short radio and microwave range (on the order of 1 GHz) of the electromagnetic spectrum will propagate through dielectric materials and will be reflected by embedded conductors. The electromagnetic properties of insulators are characterized by their *dielectric constants.* The dielectric constant of air is, by definition, equal to 1 and for water it is 80. Concrete may have a dielectric constant between 6 and 11, depending primarily on moisture content, a gravel subbase may have a value between 5 and 9, and rock may have a value between 6 to 12 (ASTM D 4748). The propagation speed of electromagnetic waves in air equals the speed of light, or about 3×10^8 m/s. The propagation speed in a dielectric equals the speed in air divided by the square root of the dielectric constant.

A pulse of electromagnetic waves will propagate through a dielectric and a portion of the pulse is reflected if there is an interface between materials of different dielectric constants. Whereas a stress wave is totally reflected at a shotcrete-air interface, only a fraction of the electromagnetic pulse is reflected. Thus, signals due to the arrival of reflections from cracks and voids have low amplitude. In a simulation study, Maser and Roddis (1990) found that a 3 mm air gap in concrete produced little noticeable effect in the received waveform. However, the addition of moisture to the simulated crack resulted in stronger reflections which could be noticed in the waveforms. The presence of reinforcing bars, or other embedded metals, results in total reflection of the incident portion of the pulse. The strong reflections from embedded metal objects may mask the weak reflections from shotcrete-air interfaces that may be present.

The duration of the electromagnetic pulse controls the penetrating ability and resolution of the radar. A longer duration pulse can penetrate further, but it has poorer resolution (resolution refers to the ability to distinguish between small or closely spaced reflectors). The high resolution antenna commonly used for inspection of concrete pavements and bridge decks has a pulse length of about 1 nanosecond (ns), which corresponds to a propagation distance of about 120 mm in shotcrete with a dielectric constant of 6. To be able to measure depths accurately, the pulse length must be less than the round trip distance. Therefore, the minimum depth that could be measured accurately by a 1-ns pulse is 60 mm.

Various techniques have been used to assist in interpreting the large amount of data recorded during a radar scan. A common method of presenting the results of a radar scan is using a graphic recorder. Such a device operates on the principle of threshold plotting as illustrated in Fig. 3.4.2. When the signal amplitude exceeds a user-defined threshold value, the stylus of the graphic recorder draws a line on the paper. The length of the line corresponds to the time interval during which the threshold value is exceeded. Thus, the time-domain waveform is transformed into a series of dashes as shown in Fig. 3.4.2(b). As the paper feeds through the recorder and the antenna is scanned across the surface, the dashes result in a series of horizontal bands on the paper, and the position of the bands is related to the depth of the reflector. If the antenna is scanned across a slab containing a void, the output of the graphic recorder will be similar to that shown in Fig. 3.4.2(c). In effect, the output represents a cross-sectional view of the structure.

3.5-Infrared thermography

The technique known as *infrared thermography* is based on the following principle. If there is heat flow into or out of an object, the presence of a defect with a different thermal conductivity than the surrounding material affects the heat flow. As a result, the surface temperature will not be uniform. By measuring the surface temperature, the presence of the defect can be inferred The variation in surface temperature is measured by the use of another physical principle, namely, a surface emits radiation at a rate that depends on its temperature. Within the vicinity of room temperature, the radiation is in the infrared range of the electromagnetic spectrum. Therefore, a calibrated infrared scanner, which is similar to a video camera, can be used to obtain a "picture" of the variation in surface temperature. Infrared scanners are capable of detecting temperature differences as low as 0.1 deg C, but the detectors have to be cooled by liquid nitrogen to attain such sensitivity.

Infrared thermography has been used successfully to locate delaminations in concrete bridge decks and it can be used for shotcrete as well. To apply this technique, there needs to be heat flow into or out of the test object. This can be achieved by artificial heating or by using the natural effects of solar heating and night-time cooling (ASTM D 4788). For example, during solar heating, the presence of a delamination would block the flow of heat into the structure, and the area above the delamination would become warmer. Thus, portions of the structure identified as *hot spots* by the infrared scanner would be potential locations of subsurface anomalies.

Even with proper heat flow conditions, not all delaminations are detectable by infrared thermography. Analytical studies by Maser and Roddis (1990) examined the factors affecting the differences in the surface temperature of a solid concrete slab, and a slab with a delamination. It was found that the maximum differential surface temperature decreased as the depth of the delamination increased, and as the width decreased. Also, a water-filled delamination resulted in nearly identical surface temperatures as in a solid slab.

3.6-Radiography

Radiography uses high-energy forms of electromagnetic radiation (X-rays and gamma rays) to determine the internal condition of a portion of a structural member, or locate embedded reinforcement. Radioactive isotopes, such as cobalt-60, cesium-137 and iridium-192, can be used to provide gamma rays, and portable devices have been developed to generate X-rays. The radiation source is placed on one side of the test object, and special photographic film is placed on the opposite side. As the penetrating radiation passes through the material, a portion is absorbed or scattered. The amount of absorption and scattering increases as the density of the material increases, and hence, the intensity of the radiation that strikes the film decreases with increasing density of the material between the source and the film. Thus, reinforcing bars show up as light areas on the exposed film, while cracks and voids show up as dark areas. However, narrow cracks for which the crack plane is perpendicular to the direction of the radiation, such as delaminations, are difficult to detect.

Radiographic equipment is bulky because of the shielding required for safety reasons. Long exposure times are required for thick members, and the test site has to be evacuated except for the licensed testing personnel. For these reasons, radiography is not used routinely unless it is the only method that will be able to provide the needed information.

CHAPTER 4-DENSITY

4.1-General

4.1.1 The nature of shotcrete application may result in variations in homogeneity of the structure, which do not commonly occur in conventional concrete. Such variations include: sand lenses or streaks, porous zones, and segregation of stone in the case of coarse aggregate dry process shotcrete. Further information on the nature of shotcrete is available in ACI 506R.

4.1.2 One type of variation in the composition of shotcrete is normal and desirable. As shotcrete is first applied to a surface, there is no layer of mortar in which the coarser particles can embed, they, therefore, rebound. This process leaves a cement-rich bonding layer at the inter face of the substrate and the shotcrete. As shooting continues, a layer of mortar will be built up thick enough to retain the coarser particles.

4.1.3 Typical shotcrete structures, including those judged to be substandard, are illustrated in ACI 506R, *Guide to Shotcrete,* and in Figs. 4.1, 4.2, and 4.3.

4.2-Density

4.2.1 Other factors being equal, the in-place density of shotcrete is a major factor in determining its quality and durability. Strength and service life will be decreased as a function of void content or porosity. The in-place density can be easily determined by the procedures of ASTM C 642* using cored samples. The test results are sensitive

* The absorption of the aggregates themselves will affect test results. Limits quoted are for relatively low absorption aggregates, generally less than 2 percent. Higher limits will be required for more absorptive aggregates.

Fig. 4.1-Serious sandpocket developd because of carelessness of nozzlemen. Use of the No. 6 bar made proper encasement more difficult but with careful and skilled nozzling, the work could have been properly accomplished Note the fine crack above the bar and also mending down from the bottom of the sandpocket. When cracking develops above the line of a bar, a continuous sandpocket may be suspected behind the bar. The sandpocket reduces the section area, encouraging cracking

to size of sample, so it is suggested that comparative or specification compliance tests be conducted on samples of similar size. Cubes of 3 in. (75 mm) dimension or cores of 4 in. (100 mm) diameter have been found to be satisfactory for density measurements.

4.2.2 For specification purposes, water absorption values, particularly the boiled absorption determined by ASTM C 642, have been found useful. A typical boiled absorption value of good quality shotcrete would be less than 8 percent.*

4.2.3 The quality of in-place shotcrete from the same mixture can be compared by density determinations.

4.2.4 Because of variations, it is recommended that density tests be determined by averaging a minimum of three individual tests, each on a different sample.

CHAPTER 5-PERMEABILITY

5.l-General

Permeability of shotcrete is recognized as a critical component of durability and protection of reinforcing

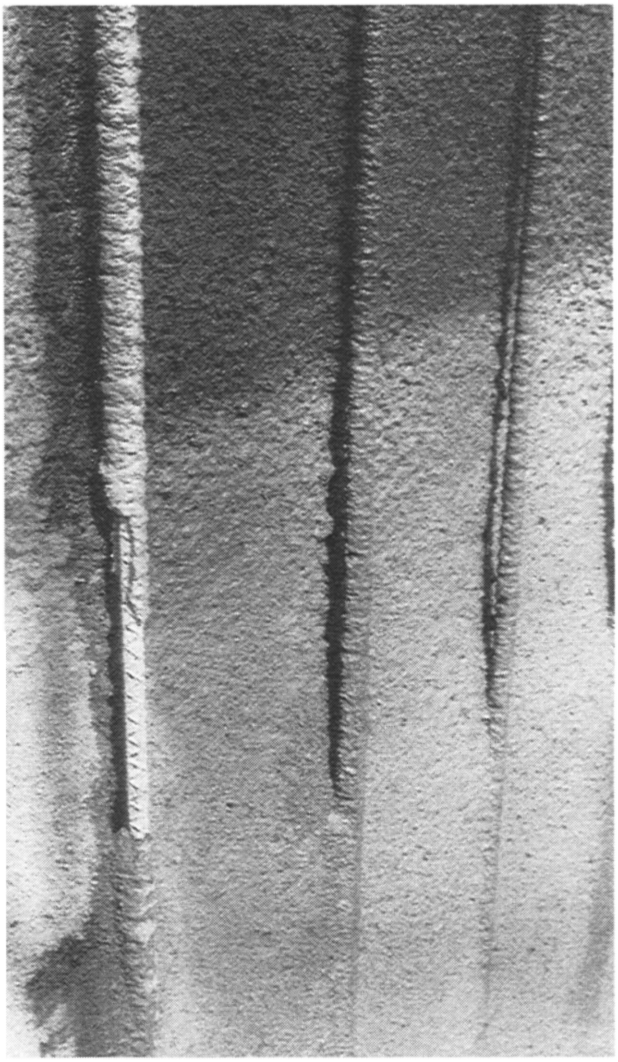

Fig. 4.2-Overspray on vertical reinforcing bars. Note the hardened overspray chipped off the bar at the lower left ***of*** *the picture. Glossy texture of shotcrete surface indicates correct water content. For adequate bond of any additional shotcrete, the glazed surface must be removed by brooming or screeding at or before initial set*

steel. Reported results are difficult to compare because there is no standard test procedure for permeability.

5.2-Permeability tests

5.2.1 *Laboratory permeability under hydrostatic pressure*

5.2.1.1 In these tests, a core or cylindrical sample of concrete is sealed into a chamber and hydrostatic pressure is applied to the top surface. Measurements are made of the time for a specific volume of water to pass through the sample as uniaxia1 flow. Calculations of permeability are made from Darcy's Equation.

5.2.1.2 The U.S. Corps of Engineers, Canada Center for Mineral and Energy Technology, and the International Standards Organization have each developed a test

*The absorption of the aggregates themselves will affect test results. Limits quoted are for relatively low absorption aggregates, generally less than 2 percent, Higher limits will be required for more absorptive aggregates.

Fig. 4.3 void behind bar caused by failure to remove overspray

procedure. Present experience suggests that they are difficult to perform on high quality (low permeability) concrete or shotcrete because they need high pressures and/or long test times.

5.2.2 *Chloride permeability*-There is a special rapid chloride permeability test, ASTM C 1202, that measures the rate of chloride ion flow through cores with the driving force of a voltage differential. Values for shotcrete need to be correlated with degrees of permeability.

5.2.3 *In situ permeability*

5.2.3.1 There are devices which drive gas or water into a hole drilled in shotcrete and measure the volume of material injected over time. Proprietary devices have been developed in Denmark, England (for example, the FIGG Test), and Japan.

5.2.3.2 There is little experience or published work on the permeability testing of shotcrete. Specifications for concrete permeability levels are not extensively used.

5.2.3.3 At this time, it is not appropriate to recommend permeability limits for shotcrete.

CHAPTER 6-EVAULATION OF FRESHLY MIXED SHOTCRETE

6.1-General

As with conventional concrete, tests performed on the freshly mixed material can be used to control quality.

6.2-Tests applicable for wet process shotcrete

The following test procedures can be employed to determine the properties of wet process shotcrete.

6.2.1 *Time of setting*

ASTM C 1117 — Tie of Setting of Shotcrete Mixtures by Penetration Resistance

ASTM C 403 — Time of Setting of Concrete Mixtures by Penetration Resistance

6.2.2 *Workability*

ASTM C 143— Slump of Hydraulic Cement Concrete

ASTM C 360— Ball Penetration in Fresh Portland Cement Concrete

6.2.3 *Air content*-Since wet process shotcrete is pumped, injected with air, and impinged on a surface, air content should be determined after shooting.

ASTM C 138 — Air Content (Gravimetric) Unit Weight and Yield of Concrete

ASTM C 231- Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C 173— Air Content of Freshly Mixed Concrete by the Volumetric Method

6.2.4 *Sampling*

ASTM C 172 — Sampling Freshly Mixed Concrete

6.2.5 *Test specimen fabrication*

ASTM C 1140 — Preparing and Testing Specimens from Shotcrete Test Panels

ASTM C 192 — Making and Curing Concrete Test Specimens in the Laboratory

6.3-Tests applicable for dry mix process shotcrete

Since dry-mix process shotcrete is a nonplastic mixture, standard test methods for freshly mixed concrete cannot be used. The following test method has been used by various researchers.

6.2.1 *Tie of setting*

ASTM C 1117 — Time of Setting of Shotcrete Mixtures by Penetration Resistance

6.2.2 *Test specimen fabrication*

ASTM C 1140— Preparing and Testing Specimens from Shotcrete Test Panels

CHAPTER 7-DETERMINATION OF SHOTCRETE MIXTURE PROPORTIONS

7.1-General

The procedure described in 7.3 may be used to determine the in-place proportions of cementing material and oven dry aggregate for shotcrete. Because rebound is low in the wet-mix shotcrete process, the in-place proportions should not vary significantly from the as-batched mixture proportions. In the dry-mix shotcrete process, however, the rebound tends to contain a higher proportion of aggregate compared with cementitious material. Therefore, the in-place cementitious materials content will tend to be higher than in the as-batched shotcrete.

7.2-Sampling

7.2.1 *Normal setting shotcrete*-Within 15 min of application of the shotcrete, remove three samples totaling at least 2,000 g. The full depth of the shotcrete should be obtained Place the samples in a nonabsorbent pan. When it is necessary to carry the sample a distance to the laboratory, it should be covered

7.2.2 *Accelerated shotcrete*-Immediately after application of the shotcrete, and before initial set, remove three samples totaling at least 2,000 g. The full depth of the shotcrete should be obtained. Immediately mix each sample with acetone of known mass; 1,000 g would be sufficient. Cover samples to prevent evaporation of the acetone. The test procedure in 7.3 should then be continued, compensating for the weight of acetone in each weighing and calculation.

7.3-Test procedure

The following steps, except for the oven drying, should be completed within 30 min after the sample has been obtained.

7.3.1 Mix the sample thoroughly, breaking up all large pieces.

7.3.2 Weigh approximately 1,000 g of sample. Place the test sample in a container and add sufficient water to cover it. Agitate the contents of the container vigorously and immediately pour the wash water over a nest of two sieves arranged with a No. 16 (1.25 mm) sieve on top and a No. 200 (80 **µm)** sieve on the bottom. Agitate with sufficient vigor to effect the complete separation from the coarse particles of all particles finer than the No. 200 (80 **µm)** sieve and bring the fine material into suspension in order that it will be removed by decantation of the wash water. Avoid the decantation of the coarse particles of the sample. Repeat the operation until the wash water is clear. Return all material retained on the nested sieves to the washed sample. Dry the washed aggregate to constant weight at a temperature of 110 25 deg C, and weigh the mass to the nearest 0.1 percent.

7.3.3 Determine the total moisture content of at least a (separate) 500 g sample by ASTM C 566 using a hot plate and anhydrous denatured alcohol to accelerate the drying.

7.3.4 *Calculations*

A = *Initial* weight of shotcrete sample in grams (sample weight = approximately 1,000 g)

ℓ = Loss in weight on washing and drying Sample A in grams

B = initial weight of shotcrete sample for moisture content determination in grams (sample weight = approximately 500 g)

C = Oven dry weight of shotcrete sample for moisture content determination

p = Total moisture content in Sample B, percent

m = Loss in weight on drying Sample B in grams

α = Average weighted aggregate absorption, percent, of combined aggregates (determined separately by ASTM C 127 and ASTM C 128)

Cementitious content: Oven-dry aggregate, ratio by weight =

$$1 : \frac{(100 + \alpha)(A - \ell)}{100\left(\ell - \frac{(Ap)}{100 + p}\right)}$$

where

$$p = \frac{m \times 100}{C}$$

7.3.5 *Examples*

- Weight of 1,000.0 g fresh shotcrete Sample A plus No. 200 mesh (80 um) sieve = 1,350 g
- Weight of sample plus No. 200 mesh (80 urn) sieve after washing and drying = 1,050 g

ℓ = difference 300 g

- Weight of fresh concrete Sample B plus pan = 1,000 g
- Weight of oven dried Sample C plus pan = 967 g
- m = difference = 33 g
- Weight of pan = 400 g
- Percent average weighted absorption, a = 1.0 percent

Percent total moisture in shotcrete Sample B

$$= p = \frac{m \times 100}{C}$$

$$= \frac{33 \times 100}{967-400} = 5.8 \text{ percent}$$

Cementitious Content: Oven Dry Aggregate Ratio in Sample A

$$= 1 : \frac{(100 + \alpha)(A - \ell)}{100\left(\ell - \frac{(Ap)}{100 + p}\right)}$$

$$= 1 : \frac{(100 + 1.0)(1{,}000 - 300.0)}{100\left(300 - \frac{(1{,}000 \times 5.8)}{(100 + 5.8)}\right)}$$

= 1: 2.88 by weight

Note: This is the approximate ratio of cementitious material to aggregate since the aggregate may have contained material passing No. 200 sieve.

CHAPTER 8-REFERENCES

8.1-Specified references

The documents of the various standards-producing organizations referred to in this document are listed with their serial designation.

American Concrete Institute

228.1R In-Place Methods for Determination of Strength of Concrete

506R Guide to Shotcrete
506.2 Specification for Materials, Proportioning, and Application of Shotcrete

ASTM
C 42 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 127 Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate
C 128 Standard Test Method for Specific Gravity and Absorption of Fine Aggregate
C 138 Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
C 143 Standard Test Method for Slump of Hydraulic Cement Concrete
C 172 Standard Practice for Sampling Freshly Mixed Concrete
C 173 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C360 Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C 403 Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C566 Standard Test Method for Total Moisture Content of Aggregate by Drying
C 597 Standard Test Method for Pulse Velocity Through Concrete
C642 Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete
C803 Standard Test Method for Penetration Resistance of Hardened Concrete
C 805 Standard Test Method for Rebound Number of Hardened Concrete
C823 Standard Practice for Examination and Sampling of Hardened Concrete in Constructions
C 900 Standard Test Method for Pullout Strength of Hardened Concrete
C1117 Standard Test Method for Tiie of Setting of Shotcrete Mixtures by Penetration Resistance
C 1140 Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels
C1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist chloride Ion Penetration
D 4580 Standard Practice for Measuring Delaminations in Concrete Bridge by Sounding
D 4748 Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar
D 4788 Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography

The previously listed publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219

ASTM
1916 Race Street
Philadelphia, PA 19103

8.2-Cited references

Carino, NJ., SansaIone, M., and Hsu, N.N., "Flaw Detection in Concrete by Frequency Spectrum Analysis of Impact-Echo Waveforms," *International Advances in Nondestructive Testing,* 12th ed., W. J. McGonnagle, Ed., Gordon & Breach Science Publishers, New York, 1986, pp. 117-146.

MaIhotra, M., "Testing Hardened Concrete: Nondestructive Methods," ACI *Monograph* No.9, 1976.

Maser, K.R., and Roddis, W.M.K., "Principles of Thermography and Radar for Bridge Deck Assessment," ASCE *Journal of Transportation Engineering,* V. 116, No. 5, Sept.-Oct. 1990, pp. 583-601.

Naik, T.R., and MaIhotra, V.M., "The ultrasonic Pulse Velocity Method," Chapter 7 in *Handbook on Nondestructive Testing of Concrete,* V.M. MaIhotra, and NJ. Carino, Eds., CRC Press, Boca Raton, FL, 1991, pp. 169-188.

Neville, AM., "Properties of Concrete," I. Pitman, London, John Wiley & Sons, New York, 1986.

Pratt, D., and Sansalone, M., "Impact-Echo Signal Interpretation Using Artificial Intelligence," *ACI Materials Journal,* V. 89, No. **2,** Mar.-Apr. 1992, pp. 178-187.

Rutenbeck, T., "Shotcrete Strength Testing — Comparing Results of Various Specimens, Shotcrete for Underground Support," ACI SP-54, Oct. 1976.

Sansalone, M., and Carino, NJ., "Stress Wave Propagation Methods," Chapter 12 in CRC *Handbook on Nondestructive Testing in Concrete,* CRC Press, Boca Raton, FL, 1991.

Sansalone, M., and Carino, NJ., "Laboratory and Field Study of the Impact-Echo Method for Flaw Detection in Concrete," in *Nondestructive Testing of Concrete,* ACI-SP 112, American Concrete Institute, Detroit, 1988b, pp. l-20.

Sansalone, M., Lin, Y., Pratt, D., and Cheng, C., "Advancements and New Applications in Impact-Echo Testing," *Proceedings,* ACI International Conference on Evaluation and Rehabilitation of Concrete Structures and Innovations in Design, Hong Kong, V.M. MaIhotra, Ed, ACI SP-128, 1991, pp. 135-150.

This report was submitted to letter ballot **of the committee and was approved according to Institute balloting procedures.**