ADVANCES IN NONDESTRUCTIVE TESTING OF CONCRETE

Shu-t'ien Li, V. Ramakrishnan, and J. E. Russell,
South Dakota School of Mines and Technology

This paper reviews recent advances in the following nondestructive methods of testing concrete: ultrasonic, resonance, radioactive, electrical, initial surface absorption, chemical analysis, and hardness. A brief review is given of the research work in progress at the South Dakota School of Mines and Technology. There is a great potential in the concrete industry for nondestructive methods of testing concrete. Two major fields where those methods could prove to be superior to traditional methods are quality control in the construction of structural members, both precast and cast-in-place, and monitoring strength development to determine acceptable times for the removal of form work or transfer of prestressing force to concrete.

•THE PURPOSE of this paper is to review some of the recent advances in nondestructive testing methods as applied to concrete technology. Advances in both field and basic laboratory research methods are discussed. Special attention is given to advances and trends that, in the authors' opinions, will dominate the field in the future. An attempt is made to present a modern, balanced, realistic picture of nondestructive testing of concrete. References are used freely to indicate the sources from which the authors' opinions have been derived. References include those that present information on nondestructive testing of concrete (1, 2, 3, 4) and those that review the state of the art of nondestructive testing of concrete (5, 6, 7).

Nondestructive methods have been of considerable value in the testing of concrete. They are most useful in the testing of concrete structures in situ. In the laboratory, their special usefulness lies in the repetitive testing of the same specimen when the influence of time is evaluated. These are the two aspects of testing to which the nondestructive methods are better suited than the destructive methods.

It is, however, essential to keep the limitations of nondestructive testing methods in view and to exercise due caution in interpreting the results of these methods. All methods, including surface hardness methods, resonance methods, pulse velocity methods, and radioactive methods have been found to have their own limitations in application. Those methods cannot, at the present, replace the destructive test for the purposes of assessing the strength of concrete. Hence, in all cases, it is recommended that the data obtained be interpreted by taking into account all other available information under test, including the strength data from destructive testing, if any. Nondestructive methods of testing concrete may be used with greater confidence when the objective is only a comparative qualitative assessment or a change from a known quantitative state or standard.

Some of the recent trends in the studies concerning nondestructive methods appear to be determination of damping properties of concrete; resonance vibration of circular plates for determining the elastic properties of concrete (8); utilization of more than one observation in the statistical correlation of the strength of concrete (9), such as pulse velocity and damping constant (10) or these two along with rebound hammer observations (8); and a differentiation between the sharpness and flatness of the onset of the pulse. The use of more than one method to solve a particular problem is certainly logical in view of the inherent complexity of concrete. It is expected that this trend will continue.

The attempts are toward either developing new procedures of estimating the strength and other properties of concrete or using the existing methods for getting more reliable and dependable information of the quality of concrete. Although every such attempt adds to the usefulness of nondestructive methods, investigations should also be directed toward development of altogether new methods and new instruments that can overcome many of the limitations of the existing methods.

"In all but the methods employing radioactive isotopes," states Jones (3), "the experimental techniques have now reached a stage when no major development is likely to occur for many years and, in most cases, commercial apparatus is readily available." It is, therefore, to be inferred that instrumentation of hardness, resonance, and pulse velocity methods do not constitute a potential field for a major breakthrough, and some other properties must be effectively used in the development of new nondestructive methods for testing concrete.

ULTRASONIC TESTING OF CONCRETE

The ultrasonic testing of concrete is mainly based on straightforward measurements of longitudinal pulse velocity; the pulse is produced by an electroacoustical transducer, which is held in contact with one surface of the concrete member under test and received by a similar transducer in contact with the other surface. There are several ways in which the behavior of ultrasonic pulses in concrete can be used to obtain useful information, particularly with regard to elastic stiffness and strength. Generally the elastic modulus of concrete increases with density and so does the velocity of ultrasonic pulses. It is for this reason that pulse velocity varies from point to point in a piece of concrete because density and elastic modulus are by no means constant throughout the concrete. However, between pulse velocity and static modulus there is a simple empirical correlation that holds good over quite a wide range of different concrete compositions (11). Both elastic modulus and pulse velocity are related to strength or quality of concrete.

Most of the experimental work carried out to evaluate the results of ultrasonic testing of concrete has been based on a comparison between pulse velocity and the standard crushing test. The statistical confidence of this correlation is not so high as concrete engineers would like. The reason is that the correlation is influenced by a number of factors such as cement content, aggregate type, age of concrete, and curing temperature. Those factors would have to be taken into account if a reasonable prediction of crushing strength has to be made from pulse velocity measurements.

Ultrasonic testing is also used for locating flaws, voids, or other defects in concrete (12); the technique is based on the negligible transmission of ultrasonic energy across a concrete-air interface. Ultrasonics is also used for defectoscopy investigations for location of weaknesses and damaged units and for analysis when failure has occurred. It is cheaper than drilling test cores (6). A combination of surface pulse propagation and longitudinal thickness resonance techniques (6) or pulse reflection has been developed to provide estimates of thickness of a concrete slab.

There are many applications of ultrasonic testing to field problems during the construction and acceptance phase and the evaluation of damaged concrete structures (2, 13). During the construction phase, ultrasonic testing can be used to determine consolidation and filling of deep forms. Voids may be detected in the filling of deep forms. Inadequate consolidation will result in reduced velocity readings. Detecting and correcting potential problems immediately in the field result in significant long-term economics.

Ultrasonic testing of concrete at an early age in the field can be used to determine setting characteristics and evaluate the action of accelerators and retarders. Furthermore, ultrasonic testing as early as 10 hours can provide an estimate of 7- and 28-day compressive strengths. Because the strength of concrete depends on many factors, all nondestructive methods for estimating it should be used with caution. Calibration data should be prepared for each particular mix and aggregate used. Care should be taken if any parameters having an effect on concrete strength change after the calibration is complete. Galan (10) states that "estimating concrete strength, especially in a water saturated condition, by pulse velocity alone is unreliable and in most cases impractical." Galan advocates measuring both the pulse velocity and the damping constant of the ultrasonic impulse in order to assess both elastic and inelastic properties of concrete.

Ultrasonic testing has been used successfully in prestressing and precasting operations where quality control is generally better than that in the field. The added variables of cast-in-place operations require more care on the part of the operator running the ultrasonic tests.

The pulse velocity of concrete may be used as an acceptance criterion in its own right. High-quality concrete has a pulse velocity markedly greater than that of poor-quality concrete.

In older and potentially damaged structures, the integrity of the concrete can be assessed by ultrasonic means. In this case, cores may be cut from representative parts of the structure to provide calibration data. Ultrasonic testing may also be used to predict accumulating damage under fatigue conditions as well as damage resulting from fires, earthquakes, and overloads.

Measurements of concrete pavement thickness may be made by using pulse velocity measurement in conjunction with resonance testing as discussed by Muenow (14). Other techniques for measuring pavement thickness by using the transmission of mechanical energy as a base are discussed by Howkins (4).

Assessment of Ultrasonic Testing of Reinforced Concrete Beams

A recent investigation (15) examined the validity of pulse velocity measurements in comparison with compressive strength tests when the structural quality of reinforced concrete beams is judged. It has been shown that pulse velocity measurements are more successful than crushing tests of companion specimens in assessing the flexural strength of beams. Although most of the investigation has been concerned with beam failure in bending, part of the program considered the prediction of shear failure from ultrasonic tests. It has also been shown that ultrasonic tests can clearly identify regions of low-strength concrete in reinforced concrete beams, and the influence of these weak zones can be predicted with reasonable accuracy. Evidence has been presented to show that the flexural stiffness of beams is closely related to ultrasonic pulse velocity in the concrete.

Pulse Velocity Technique as Applied to Small Concrete Specimens Under Repeated Compressive Loads

An ultrasonic pulse velocity technique has been applied by Raju (16) for the study of microcracks formed in high-strength concrete in a state of uniaxial compression under static and repeated loads. The tests were conducted on prismatic concrete specimens. They have revealed significant differences in the magnitude of pulse velocity decrease under static- and repeated-load systems. The progressive nature of the failure in concrete under repeated loads was studied by the parameter percentage decrease in pulse velocity in relation to the percentage of fatigue life. An empirical relation between the parameters was established from the test data, which could be used to predict the remaining fatigue life of a partially fatigued specimen.

The ultrasonic pulse velocity technique first introduced by Long, Kurtz, and Sandenaw (17) is essentially a nondestructive method of testing the quality of concrete by transmitting a vibrational pulse to travel a known distance through concrete. This technique has a definite advantage over the resonant frequency technique in that it could be used on any element irrespective of size and shape. This factor becomes important for testing the quality of concrete that forms part of a built-in structure.

Many investigators (18, 19) have used the longitudinal wave velocity method for detecting the formation of cracks inside concrete specimens; of these, Jones has conducted the most comprehensive study of microcracking under short-term static loads. The purpose of Raju's investigation was to extend the use of this well-established technique to repeated load situations, the data from which could be helpful in understanding the mechanism of fatigue failure in concrete.

The pulse velocity studies have demonstrated that sonic techniques can be advantageously used for detecting the development and growth of cracks under repeated loads, as shown by the progressive changes in the pulse velocity. The technique has a considerable advantage because of the ease of setup and use in the laboratory or field; and the method permits an assessment of the condition of concrete along the entire path length, in contrast to the strain measurements that are made only on the surface. The use of pulse velocity and fatigue life relations determined from tests on small specimens, such as those used to predict the remaining fatigue life of larger structural members, should be made with caution. More tests are needed to study the effect of size on changes in pulse velocity in relation to fatigue life.

Significant differences were observed in the magnitude of decrease in pulse velocity between static and fatigue tests. The average decrease of pulse velocity in fatigue tests was found to be nearly 3 times that observed in static tests. The reasons for this considerable difference were investigated by conducting separate static and fatigue tests on similar concrete prisms with their surfaces ground so as to expose the aggregate matrix interface clearly. The crack data resulting from the microscopic studies during the tests were grouped into bond, matrix, and aggregate cracks. One study indicated that the major proportion in both static and fatigue tests was bond cracks, varying from 55 percent of the total length in static to 75 percent in fatigue tests. However, their orientation appears to have an almost identical distribution in each type of test with the greater part of their length nearly parallel to the direction of compressive stress.

The large magnitude of bond cracks accounts for the large decrease in the pulse velocity observed in fatigue tests. The constant stress amplitude used in fatigue tests favors the growth of a large number of local bond failures; in static tests only a few well-defined cracks form and grow. The large decreases in pulse velocity and modulus of elasticity of the specimens that fail under repeated loads indicate that the basic fracture mechanics concepts are qualitatively true for concrete in a state of uniaxial compressive stress.

Under repeated loads, the progressive nature of the failure provides excellent possibilities for using the pulse velocity technique with brittle materials. More research in the field of size effect in relation to changes in pulse velocity will help to make the ultrasonic pulse velocity method valuable in assessing the remaining fatigue life of a partially fatigued structural member in the field so that replacement or strengthening can be effected whenever necessary.

Raju has drawn the following conclusions from his investigation:

1. A significant decrease in the pulse velocity occurs in the lateral and longitudinal directions for concrete specimens subjected to repeated compressive loads of intensity 65 to 85 percent of the static ultimate strength;
2. The magnitude of decrease in the pulse velocity in the lateral direction under repeated compressive loads is nearly 3 times greater than that under static loads; and
3. The pulse velocity decreases with fatigue life at an increasing rate, and an empirical relation established between the parameters can be used to estimate the remaining fatigue life of a partially fatigued specimen.

Improvement in Instrumentation

One of the major difficulties in the popular use of nondestructive test methods, particularly the pulse velocity method, is the complicated and expensive instrumentation. However, new digital instruments that could revolutionize ultrasonic testing of concrete have been developed (20, 21) and are easy to operate, quick, cheap, and more accurate than currently available instruments.

The traditional equipment uses a cathode-ray tube to display the onset of the pulse and its position relative to timing marks superimposed on the same display. The use of this type of equipment requires patience and skill that are often difficult to maintain under arduous conditions usually prevalent on construction sites or in precast concrete factories. An instrument recently developed by Elvery and Vale (21) has no cathode-ray tube but gives a direct digital display of the time of transmission of an ultrasonic pulse passing from a transmitting to a receiving transducer; and it is compact (10.5 by 4.3 by 6.2 in.) and portable, demands less operator skill, and enables testing to be done more rapidly. This has a range of 1 to 1,000 μS and an accuracy of ±1 count.

RESONANCE TESTS

For the measurement of the elastic moduli of concrete, resonance techniques have become part of concrete testing technology. In this country and in many other countries, including Russia, India, Japan, Poland, and Czechoslovakia, this test has been included in the standards. Resonance methods are also specified in this country as a means of determining resistance to frost, and they have been used in other countries to determine resistance to attack by sulfate or sewage.

The main disadvantage of this method is that it is restricted to specimens of shapes for which it is possible to derive the frequency equations. Resonance techniques are rarely applicable to structural concrete for which ultrasonic methods are more suitable for in situ testing.

RADIOACTIVITY METHODS

Radioactivity methods are being increasingly used for the identification of defects that develop in concrete during construction and are hidden from the eye. When a beam of X-ray or gamma radiation passes through concrete, more radiation is absorbed by the denser parts than by the less dense parts of concrete. Gamma rays differ from X-rays only in their origin. The two main techniques used are radiography and radiometry. In both cases, gamma radiation is preferred because it is more portable than X-rays, is easier to use on sites, can penetrate thicker sections of concrete, and is cheaper than X-rays.

Radiography

Gamma radiography is now an established technique. The observation is made by the interaction of the emergent radiation with a suitable photographic film. Voids in the concrete will produce more intensity, and the steel in reinforced concrete will attenuate the radiation more than the concrete and consequently produce less interaction with the film. In a recent paper (22) Forrester reviewed the principles, techniques, and limitations of gamma radiography of concrete. The main use of radiography to date has been to detect voids in concrete and voids in the grouting of post-tensioned concrete, to locate steel in reinforced concrete, to determine the quality of mortar joints in precast prestressed units, to detect variable compaction in concrete of thickness up to 2 ft, and to measure the extent of corrosion. Gamma radiography is now being used increasingly in Great Britain where a British Standard Specification is being proposed for its use (22).

Radiometry

In radiometry, variations in the gamma intensity are detected by radiation detectors, such as Geiger or scintillation counters, and measured by associated electronic apparatus. There is an approximately linear relationship between attenuation of gamma radiation and density of concrete, and that provides a basis for measurement of the density of concrete.

Radiometry is used in Russia and East Germany for measuring density and its variation in precast concrete units (6). It is especially suitable for testing large numbers of precast units of a given shape and is used at the Road Research Laboratory in England for measuring density variations in cores cut from pavements (23). The core is rotated through a gamma-ray beam, and the count variation is detected by a rate meter. The change in count rate versus the depth in the core is automatically plotted on a chart record.

Instruments used for the in situ determination of density of concrete are either the backscattering type or the transmission type. The backscatter method is used to detect voids in concrete under steel plating where the use of ultrasonic reflection would cause confusion. The transmission type has been employed in the study of density variations with depth in columns and deep beams (24).

Microwave Absorption

Microwave absorption provides one way of measuring the moisture content in various materials including concrete. The method is based on the much higher absorption of microwaves by moisture than by the material in which the water is dispersed (7).

Radioisotope X-Ray Methods for Field Analysis of Wet Concrete Quality

One of the most outstanding problems today in concrete technology is that of quality control of concrete. Criteria of quality are based on the strength of the concrete, and currently that can only be measured after the concrete sets and cures. It may then be too late and very expensive to rectify mistakes. The strength of concrete is related to the cement and water contents, the bulk density, and the degree of air entrainment of the wet mix. Ideally, on-site measurement of these parameters should be made within the short time available between delivery and pouring. Unsatisfactory concrete could then be rejected on the spot and costly mistakes avoided.

Nucleonic density and moisture gages have been available for some time, and their application to concrete analysis and other construction materials is increasing every year. These instruments are capable of rapid nondestructive measurement and, if properly employed, give adequate accuracy of concrete bulk density and water content. Other non-nuclear methods are also available for measuring air entrainment and concrete consistency. No other suitably rapid method has yet been developed, however, for on-site measurement of the cement content of the mix, except for the pioneering work of Berry and Furuta (22) on a radioisotope X-ray methodology and conceptual instrument design for field analysis of wet concrete quality.

Their work has shown that the technique of low-energy gamma-ray scattering offers much promise for the analysis of cement in wet concrete mix. A practical arrangement of source and detector and a choice of radiation energy that afford good sensitivity while being insensitive to the coarse particle size distribution have been obtained. The measurement is relatively insensitive to moisture content per se but does depend on the sample bulk density and chemical nature of the aggregate. For a known aggregate, an accuracy of ±0.3 sack/cu yd is possible provided the density is determined to about ±1 lb/cu ft. A theoretical treatment of the problem has been shown to give a satisfactory explanation of the experimental observations. The theory also suggests that a practical self-contained instrument can be developed to yield the cement content independently of bulk density, water content, and aggregate type. To correct for the latter requires a sample of the raw aggregate for normalization purposes. The conceptual design of a portable instrument suitable for field assay was obtained.

Berry and Furuta recommend that future study should include the optimization of gage parameters, for example, the source-detector spacing and scattering geometry of the 2 radiation beams, because it is very important that both beams effectively see the same sample. Further experimental work on actual concrete mixes is also necessary to establish the effectiveness of the matrix correction technique and to develop a simple calibration procedure for variable aggregate type. It is envisaged that following a short period of proof testing in the laboratory the instrument will undergo further tests in the field by highway engineers.

COVER METERS

Position of Reinforcement

The depth of cover and condition of the steel can be determined by nondestructive test of in-place concrete. Gamma radiography is used to ascertain the position and condition of reinforcement in concrete. There are simpler magnetic devices for measuring the depth of the reinforcement near the surface. Cover meters, as they are called, are both portable and relatively cheap. One British cover meter (6) operates by measuring the reluctance of a magnetic circuit incorporated in a search unit; it consists of 2 coils mounted on a U-shaped core. An alternating current is passed through one of the coils, and the current induced in the other is measured; this depends on the mutual inductance of the coils and hence on the distance of the search unit from the reinforcement. A similar cover meter has also been developed in Holland.

Neutron Meter for Moisture Measurements

The use of a neutron meter is as feasible in moisture measurement in unsaturated and saturated zones of concrete as in soils (25). It is a nuclear technique using isotopes and radiation technology, primarily with the aid of commercial instruments. There is a slow but steady increase in its application, even though field calibration remains a rather difficult problem. A real need exists for research and development to increase the reliability of the meters in field use (26). The variation of moisture content with depth in columns and deep forms has been studied by using this method (24).

ELECTRICAL METHODS

Moisture Content

When the moisture content of concrete changes, its dielectrical properties are changed. By measuring these changes by electrical methods, one can determine the moisture content. An instrument that measures the changes of capacitance by using fixed electrode geometries is being used in France to measure the moisture of plaster walls to ascertain when they can be painted (6).

Electrical resistance probes have been used in tracing moisture permeation through concrete (28). Concrete specimens were subjected to a constant head of water while electrical resistance measurements were made periodically by means of embedded pairs of electrodes. The presence of moisture lowered the local resistance and consequently indicated the depth of penetration. Results showed that oven-dried specimens were fully permeated within a few days, but then, during a period of 120 days, hardening and reduction of permeability occurred.

Electrical Measurements of Corrosion of Reinforcing Steel

The extent of corrosion of reinforcing steel in bridges exposed to a variety of climatic conditions can be assessed by electrical measurements (29). The measuring technique consists of using a copper sulfate half-cell and voltmeter.

Laboratory results of the use of this equipment were previously reported by the California Division of Highways. That agency also reported on the results of using this equipment on bridges in California. The Federal Highway Administration has made electrical measurements of corrosion on reinforcing steel in bridge decks exposed to a number of different climatic conditions both in the South and as far north as South Dakota.

Pavement Thickness by Electrical Resistivity Measurements

Several methods of nondestructively measuring the thickness of concrete pavement are discussed by Howkins (4). One method not mentioned is the electrical resistivity method that is being studied at the South Dakota School of Mines and Technology. This method was originally proposed by Moore (30) and is an adaptation of the resistivity method commonly used in geophysical exploration. Resistivity measurements are relatively easy to make, and the equipment is relatively inexpensive. These factors both favor the use of electrical resistivity to determine pavement thickness. The primary difficulty lies in the interpretation of the field readings. Several methods of interpretation have been proposed for geophysical exploration and are currently being evaluated for use on concrete pavement. Results from field tests are encouraging; however, no report will be made until the limitations of the method are more clearly defined.

The electrical resistivity of concrete varies from that of an electrolyte before setting to that of a semiconductor after aging. It has been reported that the electrical resistivity of concrete varies exponentially with temperature. The higher the temperature is, the lower the resistivity is. Furthermore, the resistivity of concrete is highly dependent on the moisture content of the material. Fortunately, all of the resistivity methods for determining the thickness of concrete pavement depend only on the ratio of the resistivities of the layers involved in the pavement system.

The temperature and moisture dependence of the electrical resistivity does pose the problem of interpreting the data in the presence of temperature gradients or moisture gradients or both through the depth of the pavement. All resistivity methods assume that the resistivity of each layer is constant or varies only slightly with depth. These potential problems are now under consideration.

Cumulative Damage in Aggregates by Electrical Resistivity Measurements

The electrical resistivity of rocks has been used as an indicator of accumulating damage (31). In dry rock, it was hypothesized that, as damage accumulated in the microstructure, more cracks opened and the electrical resistivity increased. The experimental data tend to confirm this hypothesis. Other investigators have shown that the resistivity of saturated rock tends to decrease as failure is approached. Here the cracks that open apparently fill with water, which conducts better than the rock. Because concrete may be thought of as a synthetic rock, it is anticipated that the same behavior may be observed. A program to study the variation of electrical resistivity with accumulating damage in concrete is expected to begin presently.

INITIAL SURFACE ABSORPTION METHOD

Levitt (32) has discussed the apparatus and techniques used for the measurement of permeability and absorption, and he has also shown how one can interpret the results obtained in terms of resistance to frost and chemical attack, color change, and lime bloom efflorescence. As a nondestructive test, the method has value as an alternative to the present destructive absorption test as far as durability is concerned.

CHEMICAL ANALYTICAL METHODS

A chemical analytical method of rapid analysis of fresh concrete, in which the composition of a sample can be determined in 10 to 15 min, is reported by Brown and Kelly (33). It is claimed that it is possible to determine with adequate accuracy the cement content, the water content, and the content of chloride added deliberately or adventitiously. In addition, water-cement and aggregate-cement ratios and the dosage of calcium chloride on the weight of cement can be determined by calculation. A full description of the development work and of an extended on-site trial has been reported (34). The possibility of the use of chemical analytical methods as a means of predicting the strength development characteristics of portland cement and predicting the strength of hardened concrete is under investigation.

HARDNESS METHODS

In a recent paper (35), Kolek argued that it is not only possible but also desirable to take advantage of the potential offered by the hardness methods and thereby to improve the general quality control, which prevails in concrete construction today, at relatively little extra cost. There are basically 2 methods: the rebound method and the indentation method. Both are well known and are used internationally. However, both methods are of an empirical nature, and several precautions must be taken to obtain meaningful results. The methods give only a rough idea of the quality of concrete. Hardness methods in combination with other nondestructive methods have been used with success, and the accuracy of a strength prediction has been improved in such cases. The successful practical use of the combination of rebound index and pulse velocity measurements in Romania has been reported by Facaoaru (36).

ACOUSTIC-EMISSION OR STRESS-WAVE-EMISSION TECHNIQUES

For nearly a decade acoustic-emission or stress-wave-emission techniques have been used to study the rate of cracking and the presence and growth of fatigue cracks in metals. Recently Green (37) extended the use of those techniques to detect the failure and progress of failure in cylindrical concrete specimens and a model prestressed concrete pressure vessel. His findings have shown that variations in the stress-wave-emission data can determine impending failure and previous structural loading extremes. He also found a limited correlation between stress-wave emission and modulus of concrete.

Low-level acoustic emission is the characteristic and irreversible sound emitted when a material is plastically deformed. These waves propagate from their source as elastic stress waves and are detected as minute perturbations by sensors positioned on the surface of the test specimens. The variations in the time of stress-wave arrival at each sensor location are used to locate the origin of the wave. Sound is also emitted when a crack grows. This is acoustic emission. The intensity of sound emitted by a crack is a function of its size. When the crack reaches a critical size, the material will fail. The detection technique involves periodic proofing to loads greater than working load while simultaneously monitoring for acoustic emission. The detected stress-wave emissions are amplified, selectively filtered, conditioned, and then channeled to either a magnetic tape recorder or a specially developed digital computer (or both) for recording and analysis.

Acoustic emission during successive loading can be employed to nondestructively evaluate prior loading levels and to locate the origin of cracking, the zone of maximum specimen deterioration, and the prestressing steel failures. The deviation from elastic response of the material can also be detected from the acoustic-emission data.

BASIC MATERIALS RESEARCH

Microstructure Studies

Nondestructive and semi-nondestructive methods are being used in studying the microstructure of concrete. These studies will eventually lead to a better understanding of the phenomenological macroscopic behavior and to improved concrete and better design criteria. Bhargava (24) reports that radiography, penetrant (colored) dyes, acoustic emission, ultrasonic pulse velocity, surface observation by optical microscope, and the photoelastic method have all been used in various studies of the microstructure of concrete. An understanding of the initiation and growth of cracks in concrete structures under load is essential to the understanding and control of fracture. The analysis of accumulating damage and fatigue life awaits more basic research on the microstructure of concrete.

POTENTIALITIES OF NONDESTRUCTIVE TESTING

There is a great potential in the concrete industry for nondestructive methods of testing concrete. Of all the nondestructive testing techniques available, the ultrasonic method is potentially the most useful for assessing concrete quality in engineering structures (11). Although it has been successfully used in the role of a troubleshooter when faulty workmanship has been discovered or is suspected in concrete construction, its full potentialities have hardly been exploited yet. In particular there are at least 2 major fields of use in which it could prove to be superior to traditional methods: quality control in the construction of structural members, both precast and cast-in-place, and monitoring strength development to determine acceptable times for the removal of formwork or the transfer of prestressing force to the concrete. In regard to the quality control, ultrasonic testing provides an opportunity to test the actual concrete in the structure, and test zones can be chosen for their critical importance in having to resist the highest stresses.

Progress is being made in the nondestructive methods of testing concrete both in the field and in basic materials research on the microstructure. Nuclear methods are showing great progress and are receiving increasingly wider acceptance. Nevertheless, one of the greatest problems in nondestructive testing of concrete is education. Most engineers working with concrete in the field have been trained in civil engineering and do not have the background to work with ultrasonic, electrical, and nuclear equipment. The universities have an obligation to provide engineers with the basic background in applied physics necessary for evaluating, selecting, and using this type of equipment and for comprehending its limitations.

REFERENCES

1. Malhotra, V. M. Nondestructive Methods for Testing Concrete. Department of Energy, Mines and Resources, Ottawa, Mines Branch Monograph 815, 1968.
2. Whitehurst, E. A. Evaluation of Concrete Properties From Sonic Tests. American Concrete Institute, Monograph 2, 1966.
3. Jones, R. Non-Destructive Testing of Concrete. Cambridge Univ. Press, 1962.
4. Howkins, S. D. Measurement of Pavement Thickness by Rapid and Nondestructive Methods. NCHRP Rept. 52, 1968, 82 pp.
5. Li, S. T., and Russell, J. E. The State of the Art of Nondestructive Evaluation in Concrete Technology. Proc., 7th Symposium on Nondestructive Evaluation of Components and Materials in Aerospace, Weapon Systems and Nuclear Applications, South Texas Section of American Society for Nondestructive Testing, Inc., and Southwest Research Institute, 1969, pp. 306-314.
6. Jones, R. A Review of the Nondestructive Testing of Concrete. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
7. Browne, L. J. I. Nondestructive Testing of Concrete: A Survey. Nondestructive Testing, Feb. 1968, pp. 159-164.
8. Jones, R. Chairman's Report on the Activities of the RILEM Working Group on the Non-Destructive Testing of Concrete. RILEM Bulletin, No. 27, June 1965, pp. 121-125.
9. Brunarski, L. Simultaneous Use of Different Non-Destructive Test Methods for Checking Concrete Quality. Wissensch. Z., No. 12, 1963, pp. 191-197.
10. Galan, A. Estimate of Concrete Strength by Ultrasonic Pulse Velocity and Damping Constant. ACI Jour., Proc. Vol. 64, No. 10, Oct. 1967, pp. 678-684.
11. Elvery, R. H. A New Look at the Ultrasonic Testing of Concrete. Technical Bulletin, Dawe Instruments, Ltd., London, Vol. 13, No. 2, June 1970.
12. Krautkramer, J., and Krautkramer, H., eds. Ultrasonic Testing of Materials, 2nd revised German Ed. Springer-Verlag, Inc., New York, English translation, 1969, 521 pp.
13. Muenow, R. A. Nondestructive Testing of Structural Members. Public Works, Nov. 1966, pp. 62-65.
14. Muenow, R. A Sonic Method to Determine Pavement Thickness. Jour. of PCA Res. and Dev. Laboratories, Vol. 5, No. 3, Sept. 1963, pp. 8-21.
15. Elvery, R. H., and Din, N. M. Ultrasonic Inspection of Reinforced Concrete Flexural Members. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
16. Raju, N. K. Small Concrete Specimens Under Repeated Compressive Loads by Pulse Velocity Techniques. Jour. of Materials, Vol. 5, No. 2, June 1970, pp. 262-272.
17. Long, B. G., Kurtz, H. J., and Sandenaw, T. A. An Instrument and a Technique for Field Determination of the Modulus of Elasticity and Flexural Strength of Concrete Pavements. ACI Jour., Proc. Vol. 41, 1945, pp. 217-231.
18. Leslie, J. R., and Cheesman, W. J. An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures. ACI Jour., Proc. Vol. 46, 1949, pp. 17-36.
19. Cawkell, A. E. Investigation of Quality of Thick Concrete by Ultrasonic Pulse Propagation. Magazine of Concrete Research, Vol. 10, No. 28, March 1958, pp. 23-26.
20. Reiding, F. J. A Portable Concrete Tester. Institute TNO for Building Materials and Building Structures, Delft, Holland, Report B1-68-63/1 H1.8, Aug. 1968.
21. Elvery, R. H., and Vale, D. W. Pundit, A Digital Display Ultrasonic Instrument for Concrete Testing. RILEM Working Party on Nondestructive Testing of Concrete, Wexham Springs, England, June 23-26, 1970.

22. Forrester, J. A. Gamma Radiography of Concrete. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
23. Harland, D. C. A Radioactive Method for Measuring Variations in Density in Concrete Cores, Cubes and Beams. Magazine of Concrete Research, Vol. 18, No. 55, June 1966, pp. 95-101.
24. Bhargava, J. Nuclear and Radiographic Methods for the Study of Concrete. Royal Institute of Technology, Stockholm 1969, 102 pp.; NTIS, Springfield, Va., PB 189 911.
25. Gardner, R. P., and Roberts, K. F. Density and Moisture Content Measurements by Nuclear Methods. NCHRP Rept. 43, 1967, 38 pp.
26. Evaluation of Commercial Nuclear Gauges. Physical Research Section, South Dakota Department of Highways, Pierre, 1969.
27. Berry, P. F., and Furuta, T. Radioisotope X-Ray Methods for Field Analysis of Wet Concrete Quality—Phase I: Methodology and Conceptual Instrument Design. NTIS, Springfield, Va., Government Document Stock No. ORO-3842-1, April 1970, 66 pp.
28. Bracs, G., Balint, E., and Orchard, D. F. Use of Electrical Resistance Probes in Tracing Moisture Permeation Through Concrete. ACI Jour., Aug. 1970, pp. 642-646.
29. Communication from H. A. Lindberg, Office of Engineering and Operations, Federal Highway Administration, to Shu-t'ien Li, July 14, 1970.
30. Moore, R. W. Earth-Resistivity Tests Applied as a Rapid, Nondestructive Procedure for Determining Thickness of Concrete Pavements. Highway Research Record 218, 1966, pp. 49-55.
31. Russell, J. E., and Hoskins, E. R. Correlation of Electrical Resistivity of Dry Rock With Cumulative Damage. Proc., 11th Symposium on Rock Mechanics, Univ. of California, Berkeley, June 1960.
32. Levitt, M. Nondestructive Testing of Concrete by the Surface Absorption Method. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
33. Brown, B. R., and Kelly, R. T. Practical Applications of Nondestructive Testing Techniques for Concrete. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
34. Kelly, R. T., and Vail, J. M. Rapid Analysis of Fresh Concrete. Concrete, Vol. 2, 1968, pp. 140-145.
35. Kolek, J. Nondestructive Testing of Concrete by Hardness Methods. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
36. Facaoaru, I. Nondestructive Testing of Concrete in Romania. Proc., Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, British National Committee for Nondestructive Testing, London, June 11-12, 1969.
37. Green, A. T. Stress Wave Emission and Fracture of Prestressed Concrete Reactor Vessel Materials. 2nd Interamerican Conf. on Materials Technology, Mexico City, Aug. 24-27, 1970; Materials Technology, ASME, New York, Vol. 1, Aug. 1970, pp. 635-649.