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In Situ/Nondestructive Testing of Concrete — A Global Review

By V.M. Malhotra

Synopsis: During the past 40 years in-situ/non-destructive testing of concrete has achieved increasing acceptance for the evaluation of existing concrete structures with regard to their uniformity, durability and other properties. This paper reviews critically the available in-situ/non-destructive tests for estimating concrete strength and for determining properties other than strength, and discusses their implications. The methods discussed for estimating concrete strength include surface hardness and penetration resistance tests, pullout, ultrasonic pulse velocity, break-off, combined methods, and maturity techniques. The tests reviewed for determining properties other than strength include magnetic, electrical, radioactive, pulse echo, radar, microwave absorption, acoustic emission, nuclear, infrared thermography, and permeability methods.

Some of the tests described are relatively easy to perform whereas others require sophisticated equipment and trained personnel, and there are others which are still in the development stage. Regardless of the type of test used, it is emphasized that interpretation of test data must be performed by specialists rather than by technicians performing the tests. Unless comprehensive laboratory correlations have been established between the strength parameters to be predicted and the results of in-situ/non-destructive tests, the use of the latter to predict compressive or flexural strength of concrete is discouraged.

Keywords: acoustic emission; break-off tests; calibrating; compressive strength; concretes; flexural strength; impact hammer tests; measuring instruments; nondestructive tests; penetration tests; pullout tests; radiography; reviews; ultrasonic tests.

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INTRODUCTION

In an overall quality assurance program, it must be assured that a finished concrete element is structurally adequate for the purposes for which it has been designed. According to the currently used specifications in major countries of the world, if the 28-day compressive strength of test cylinders or cubes indicates compliance with the specified strength, it is assumed that the concrete represented by the test specimens satisfies the design criteria. In concrete technology, the great emphasis on the determination of strength of concrete, which almost reaches fetish proportions in some instances, is easy to explain: a number of other properties of concrete such as its elastic behaviour and to some extent its service performance can be approximated, directly or indirectly, from its strength characteristics. The strength tests, regardless of the type, are excellent for determining the criteria of quality during manufacture and delivery but they leave a lot to be desired. The main disadvantages of this approach are: the delay in obtaining test results, the fact that the test specimens may not be truly representative of concrete in a structure because of different placing, consolidation and curing conditions, the necessity of testing the specimens to failure and the lack of reproducibility in the test results. These combined with the fact that structural concrete elements are considerably larger and more massive in size, cast doubt whether the 150 x 300-mm cylinders do really represent strength of concrete in a structure. As a result, to ensure designers and owners about quality of concrete in a structure, there have been a large number of attempts over the last 40 years to develop methods for in-situ and non-destructive testing of concrete.

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As the direct determination of strength implies that concrete specimens must be loaded to failure, it becomes abundantly clear that in-situ/non-destructive methods of testing concrete cannot be expected to yield absolute values of strength. The currently available in-situ methods can be broadly classified into two categories: the first category consists of those methods which attempt to measure some property of concrete from which an estimate of its strength, its durability, and its elastic parameters are obtained. Some such properties of concrete are its hardness, its rebound number, its resistance to penetration and its ability to allow ultrasonic pulses to propagate through it. The second category consists of those methods which can determine position and size of reinforcement, areas of poor consolidation, voids, cracks, honeycombing and moisture content of in-place concrete.

This paper gives a global review of the above test methods and discusses their implications. The paper is concluded by a list of pertinent references.

TEST METHODS FOR ESTIMATING STRENGTH OF CONCRETE

Two types of test methods are available for estimating compressive or flexural strength of concrete. The first type includes those methods which do not measure strength directly but measure some other property of concrete from which an estimate of strength can be made; these include surface hardness, penetration resistance, ultrasonic pulse velocity and maturity methods. The second type of test methods are those which measure some strength property from which an estimate is then made of the compressive or flexural strength of concrete; these include various types of pullout methods and break-off techniques. All of the above methods are described briefly below.

Surface Hardness Methods

The surface hardness methods consist essentially of impacting the concrete surface in a standard manner, using a given mass activated by a given energy and measuring the size of indentation or rebound. The most commonly used method is the rebound hammer. Although the rebound hammer provides a quick, inexpensive means of checking uniformity, it has many serious limitations and these must be recognized. For example, the results of the rebound hammer are affected by smoothness, carbonation, and moisture condition of concrete surface, size and age of concrete specimens, and type of coarse aggregate.

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Penetration Resistance Techniques

The techniques to determine penetration resistance of concrete consist essentially of powder activated devices, the currently available system being known as the Windsor probe. In this system a powder activated driver is used to fire a hardened alloy probe into the concrete; the exposed length of the probe is a measure of the penetration resistance of concrete. This method is excellent for measuring strength development of concrete at early ages in order to determine stripping times for formwork and for determining the relative strengths of concrete in different parts of the same structure or relative strengths in different structures. The test results are affected by the hardness of the aggregate used.

Pullout Tests

Briefly, a pullout test consists of pulling out from concrete a specially shaped steel insert whose enlarged end has been cast into the concrete. The pullout force required is measured using a dynamometer. Because of its shape, the steel insert is pulled out with a cone of concrete. The concrete is in shear/tension with generating lines of the cone running at approximately 45° to the direction of the pull. The pullout strength is of the order of 20 percent of compressive strength. Like the penetration resistance technique, the pullout test is an excellent means of determining the strength development of concrete at early ages.

The major drawbacks of the pullout tests are that these have to be planned in advance and, unlike most other in-situ tests, cannot be performed at random after the concrete has hardened. To overcome the above drawbacks, new techniques are being developed in which holes are drilled into hardened concrete, into which either normal pullout inserts or split-sleeve assemblies/wedge anchors are installed which are then pulled out; in the former case a cone of concrete is pulled out and in the latter case internal cracking of concrete is caused. Investigations have also been reported dealing with the pulling out of bolts set by means of epoxy in holes drilled in hardened concrete.

Break-Off Method

This method consists of determining flexural strength in a plane parallel to and a certain distance from the concrete surface. For this purpose, tubular disposable forms are inserted in the fresh concrete. When testing, the inserts are removed and the concrete core is broken

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off at the bottom by applying a force to the top and at right angles to the axis of the core.

The test method is rapid and simple, and the test results are not affected by the surface condition of concrete. However, the method suffers from the disadvantage that tests have to be pre-planned, difficulty is experienced in inserting tubes in concrete with slumps of less than 75 mm, and the test cannot be used for concretes incorporating aggregate larger than 19 mm in size. Portable equipment is available commercially.

Ultrasonic Pulse Velocity Method

The ultrasonic pulse velocity method consists of measuring the time of travel of an ultrasonic wave passing through the concrete. The time of travel between the initial onset and reception of the pulse is measured electronically. The path length between transducers divided by the time of travel gives the average velocity of wave propogation.

The pulse velocity technique is excellent for establishing uniformity of concrete, and has often been used for estimating in-situ strength. However the relationships between pulse velocity and strength are affected by a number of variables such as age of concrete, moisture conditions, aggregate to cement ratio, type of aggregate and location of steel reinforcement.

Maturity Concept

The basic principle of the maturity concept is that the strength varies as the function of both time and temperature. The maturity of in-situ concrete can be monitored by thermocouples or by instruments called maturity meters. Two commonly used maturity functions to estimate the strength of concrete are the Nurse-Saul and the Arrhenius, the former being suitable when concrete is cured between 10 and 30°C and the latter being applicable over a larger temperature range. Disposable maturity meters of Danish origin are a refreshing development.

GENERAL COMMENTS ON TEST METHODS FOR ESTIMATING STRENGTH OF CONCRETE

It cannot be overstressed that rebound and penetration resistance tests are not substitutes for standard compression tests. Estimation of strength of concrete by these methods within an accuracy of ±15 to ±20 percent may be possible only for specimens cast,

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cured and tested under identical conditions to those from which the calibration curves are established.

Inasmuch as a large number of variables affect the relations between the strength parameters of concrete and its pulse velocity, the use of the latter to predict the compressive and/or flexural strength of concrete is not recommended.

The pullout tests, measure tensile/shear strength of concrete and the break-off tests approximate flexural strength of concrete. From the above strength values, estimates of concrete compressive strength may be made. Once again prior laboratory correlations are a prerequisite.

Variability

The within-batch variability of in-situ test results is generally high, the only exception being the pulse velocity techniques. The within-test coefficient of variation for the pulse velocity tests performed in a laboratory is generally of the order of 2 percent whereas for commercially available pullout and penetration resistance tests this value varies between 6 and 10 percent. Other methods such as surface hardness show higher variability. Caution should be exercised to ensure that for the results to be valid, a minimum number of tests are specified for a particular test method to be used.

Use of Calibration Charts Provided by Manufacturers of Equipment

Usually manufacturers of in-situ tests provide correlation charts with their equipment and recommend their use for estimating strength properties of concrete. These charts do not appear to be satisfactory because their development is based on the use of certain types and sizes of aggregates, test specimens, and test conditions. It is therefore essential for users of in-situ tests to prepare their own calibration charts for the type of concrete under investigation. With changes in source of materials new calibration charts become mandatory.

Surface moisture condition of specimens under test affects significantly the in-situ test results. This is especially so for the rebound test method. It is desirable to ensure that the surface of the structural concrete under test is uniformily moist. Needless to say that the use of in-situ tests on frozen concrete is not recommended.

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Use of Multiple Methods

In Europe in general and in Romania in particular, the use of more than one in-situ/non-destructive testing technique to improve the accuracy of prediction of strength parameters of concrete has gained some credibility. RILEM* is processing a document giving details of a combined method involving pulse-velocity and rebound hammer. Some researchers have suggested the use of pullout and pulse velocity techniques, while others have suggested the use of other combined methods. The proponents of this approach claim that the use of two methods, each measuring a different property, can overcome the limitations associated with the use of one method. Some case histories have been published supporting this claim; data disputing this claim are available also.

The use of more than one method may provide useful information in some instances but its general use is not advocated because of economy and time requirements, and the possible marginal increase in the accuracy of predicting compressive strength.

Certification of Testing Personnel

One of the serious problems associated with the use of in-situ/non-destructive testing methods for estimating strength of concrete in the field is the lack of trained support personnel. Unlike the metals field where there are well structured facilities available for the certification of non-destructive testing technologists**, no such system exists for certification of concrete personnel. Properly trained and certified technicians can advance considerably the use of in-situ/non-destructive testing methods by giving designers and engineers confidence in the accuracy of test data.

Standardization

A number of leading organizations such as ASTM, BSI, DIN and ISO have issued or are in the process of issuing standards on the use of in-situ/non-destructive testing methods. The ASTM provides the most comprehensive coverage with standards on rebound method, pulse velocity, penetration resistance and pullout tests. There is a fair degree of common ground in the standards of the above

*The International Union of Testing and Research Laboratories for Materials and Structures.
**In Canada, CANMET routinely certifies such personnel.

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organizations, but occasionally there is a difference in approach. It is suggested that the various organizations writing standards should form joint committees to review the currently available standards to develop a more common approach. The ASTM may be best suited to do so.

Specifications

Canadian and U.S.A. specifications have no provisions for the acceptance of concrete on the basis of in-situ/non-destructive methods. The British and European specifications are no different. The development of well documented detailed field test data by testing organizations is a prerequisite before the specification writing authorities would allow the acceptance of concrete on the basis of the above tests. It is imperative that such data be developed. The organizations best suited to develop such information are Portland Cement Association and Bureau of Standards in the U.S.A., and the Building Research Station and the Cement and Concrete Association in the U.K.

Differences Between North America and European Practices

In North America, in-situ tests have been used primarily to determine development of strength of in-place concrete to provide data for safe form removal times. Also, the in-situ tests are used to assess quality of concrete when the 28-day strength tests fail to meet the specified design criteria. The writer knows of no region of North America where government or private laboratories are engaged on a routine basis to develop data-banks on correlations between the results of in-situ tests and the 28-day compressive strength of concrete with a view to using this data for predicting the latter. On the contrary, in a number of countries in Europe, the in-situ tests are used primarily to predict the 28-day compressive strength of concrete. As a back up, a number of laboratories in Europe and especially in eastern Europe have developed correlation data between parameters of in-situ tests and the 28-day compressive strength of concrete covering a wide range of local aggregates, cements and mix proportions. One such example is the INCERC* in Romania.

The origins of this difference in approach are rooted in history but are probably due to the fact that, in relative terms, the European specifications until recently have been more strength oriented as compared with North American specifications where both strength and durability criteria are specified.

*Institutul de Cercetari in Constructii Si Economia Constructilor

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Safety Aspects

Of all the in-situ/non-destructive testing methods the penetration resistance and pullout tests seem to be the most suitable for monitoring early-age strength development of concrete and this fact can be used to develop correlation data for determining safe form stripping times. In the case of the penetration resistance test, data should be developed that would indicate that if probes fail to penetrate into concrete a predetermined distance, the concrete has reached sufficient maturity, and that forms could be removed safely. In the case of pullout tests, the pullout assemblies need not be torn out of concrete; instead if a predetermined pullout force has been reached on the gauge, the test can be terminated and forms can be removed safely.

Cost Effectiveness

In-situ/non-destructive testing methods provide an effective way of obtaining a considerable amount of preliminary test data at relatively little cost. Both rebound and pulse velocity methods can be used to monitor structural elements to delineate zones of weaker concrete that can then be subjected to core testing if necessary. Core testing and loading tests should only be performed as a last resort, and only after the structural elements under investigation have been fully evaluated using in-situ/non-destructive testing methods.

Research Needs

In-situ/non-destructive testing methods for estimating strength of concrete have reached a standstill as to new developments. Very little research and development work is in progress in this area in North America and Europe. There seems to be no major break-through on the horizon. The only promising aspect appears to be that international standardization organizations either have, or are in the process of, writing standards for known available tests. There are perhaps two possible types of research needs, the immediate ones and the long-term ones. The immediate research needs consist of refining penetration resistance, pullout and maturity tests; for example the inserts for the commercially available pullout tests are too small and too close to the surface and the within-test variability is too high. These problems need solutions. The development of multi-channel digitized maturity meters would encourage use of the maturity technique. The long-term research needs are for more fundamental work in the properties of materials to help develop tests based directly upon these properties.

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TEST METHODS FOR DETERMINING PROPERTIES OTHER THAN STRENGTH

In a number of instances in concrete technology, strength is not the most critical parameter to be investigated; instead information is needed to determine position and size of reinforcement, to assess moisture content, to delineate cracks and discontinuities, and to locate areas of poor consolidation, voids and honeycombing in concrete. Over the years attempts have been made to develop methods to assist in resolving some of the above problems. These methods vary from simple magnetic devices to highly sophisticated infrared thermography; some of these have reached maturity while others are still in an experimental stage. These methods are described briefly below.

Magnetic Methods

A number of portable battery-operated magnetic devices that can measure the depth of reinforcement in concrete and detect the position of reinforcement bars are available commercially. The devices manufactured in the U.K. and in Holland are known as cover meters and a French device is called a pachometer.

Cover meters and pachometers are magnetic devices and are based on the principle that the presence of steel affects the field of an electromagnet. In a typical cover meter or pachometer, the probe unit consists of a highly permeable U-shaped magnetic core on which two coils are mounted. An alternating current is passed through one of these coils and the current induced in the other coil is measured. The induced current depends upon the mutual inductance of the coils and upon the nearness of the steel reinforcing bars. A moving coil meter measures the induced current. British Standard (BS 4408, Part 1) gives guidance for the use of these devices. Cover meters and pachometers give satisfactory results if structural members are lightly reinforced. In heavily reinforced sections, the effect of secondary reinforcement cannot be eliminated and the satisfactory determination of the cover to steel becomes difficult. The performance of the magnetic devices is adversely affected at temperatures below 0°C.

Electrical Methods

Electrical methods are gaining increasing acceptance as a tool for evaluation of in-place concrete to determine reinforcement corrosion and thickness of concrete pavements. They also offer potential for determining moisture content of and moisture penetration through hardened concrete.

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