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IN SITU TESTING FOR CONCRETE STRENGTH

V.M. MALHOTRA AND G.G. CARETTE

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IN SITU TESTING FOR CONCRETE STRENGTH

by

V.M. Malhotra* and G.G. Carette**

ABSTRACT

This paper describes test methods for estimating in situ strength of concrete. The methods discussed are surface hardness tests, rebound and penetration techniques, pullout and breakoff methods, pulse velocity techniques, combined methods approach and maturity concept.

The hardness, rebound, penetration, pulse velocity and maturity techniques do not directly measure the in situ strength but attempt to measure some other property of concrete from which an estimate of its compressive or flexural strength may be obtained. The pullout and breakoff methods do, however, directly measure some strength property. The accuracy of estimating compressive strength from in situ tests will depend on the type of test used and may vary from 10 to 25%.

Although such tests are relatively easy to perform, the analysis and interpretation of the data are not because concrete is a relatively complex material. It is emphasized that interpretation of test data must always be performed by specialists rather than by the technicians performing the tests.

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ESSAIS IN SITU CONCERNANT LA RESISTANCE DU BETON

par

V.M. Malhotra* et G.G. Carette**

RESUME

Ce rapport décrit certaines méthodes d'essai pour l'estimation de la résistance du béton in situ. Les méthodes discutées sont les essais de dureté de surface, les techniques de pénétration et de rebondissement, les méthodes d'extraction et de fracture en flexion et les techniques de vitesse d'impulsions. On y présente aussi un aperçu sur les méthodes combinées ainsi que celles relevant du concept de maturité.

Les techniques de dureté, rebondissement, pénétration, vitesse d'impulsions et maturité ne permettent pas une mesure directe de la résistance in situ, mais ont plutôt pour but la mesure d'une autre propriété du béton à partir de laquelle une estimation de sa résistance en compression ou en flexion peut être obtenue. Les méthodes d'extraction et de fracture à la flexion cependant permettent la mesure d'une propriété ayant directement trait à la résistance. L'exactitude selon laquelle la résistance à la compression peut être estimée à partir d'essais in situ dépend du type d'essai et peut varier entre 10 et 25%.

Bien que l'exécution de ces essais soit relativement simple, l'analyse et l'interprétation des résultats ne sont pas aussi faciles dû au fait que le béton est un matériau relativement complexe. On souligne donc que l'interprétation des données doit toujours être faite par des spécialistes plutôt que par les techniciens qui effectuent les essais.

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INTRODUCTION

In current concrete practice, the accepted methods of evaluating the quality of concrete in structures consist of simultaneously testing cast companion specimens in compression and flexure. The main disadvantages of this approach are: the delay in obtaining test results; the test specimens may not be truly representative of concrete in a structure because of different placing, compacting and curing conditions; the necessity of testing the specimens to failure; the lack of reproducibility in test results; and the high cost of testing. These, combined with the fact that structural units are considerably larger and more massive, cast further doubts as to the validity of such measurements. As a result, there have been a large number of attempts over the past 40 years to develop quick, inexpensive and reproducible methods for testing concrete in structures.

Because the direct determination of strength implies that the concrete specimens must be loaded to failure, it becomes abundantly clear that nondestructive methods of testing concrete cannot be expected to yield absolute values. These methods therefore attempt to measure some other property of concrete from which an estimate of its strength may be obtained. Such properties include its hardness, resistance to penetration by projectiles, and rebound number.

The following sections describe in some detail the surface hardness, rebound, penetration, pullout, breakoff and pulse velocity techniques. Also included is a brief description of the maturity concept. Although these tests are relatively simple to perform, the analysis and interpretation of the data are not because concrete is a complex material. Engineers are therefore cautioned that interpretation of the data must always be carried out by specialists in this field rather than by technicians performing the tests.

SURFACE HARDNESS METHODS

The known surface hardness methods are of the indentation type which consists 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.

The basic principles of various indentation devices have been outlined by Gaede and Vassitch (1,2). There is little apparent theoretical relationship between the strength of concrete and its hardness so measured. However, within limits, empirical correlations have been established between strength properties and the data obtained from hardness tests.

The three known methods employing the indentation principle are:

1. Williams testing pistol
2. Frank spring hammer
3. Einbeck pendulum hammer

Williams Testing Pistol

In 1936, Williams reported the development of a testing pistol weighing about 0.9 kg that uses a ball as an indentor (3). The diameter of the impression made by the ball is measured by a magnifying scale or by other means. The depth of indentation is only about 1.5 mm for concrete with compressive strengths as low as 7 MPa.

On the basis of several hundred tests, Williams established the following relationship: f_c is proportional to 1/Z, where f_c is compressive strength and Z is the curved surface area of indentation.

Because of the difficulty of measuring the curved surface area precisely, this method was not widely accepted.

Frank Spring Hammer

The Frank spring hammer consists of a spring-controlled mechanism housed in a tubular frame. The tip of a hammer can be fitted with balls of different diameters and impact is achieved by placing the hammer against the surface under test and manipulating the spring mechanism. Generally, about 20 impact readings are taken at short distances from one another, and the mean of these is considered as one test value. The diameter and depth of indentation are measured and these in turn are correlated with the compressive strength.

Einbeck Pendulum Hammer

This hammer consists of a horizontal leg, at the end of which is pivoted an arm with a pendulum head weighing about 2.3 kg. The indentation is made by holding the horizontal leg against the concrete surface under test, and allowing the pendulum head to strike the concrete. The diameter and depth of indentation are measured and these are then correlated with compressive strength.

This hammer can be used on vertical surfaces only and is therefore less versatile than the Frank spring hammer.

The surface hardness tests are simple to use and provide a large number of readings in a short time. According to Jones, the impact hammers have been adopted in a German standard (4,5,6). To interpret the data correctly, it is desirable to know the mix proportions, type of coarse aggregate used, age, and moisture condition of the concrete under test.

According to Weil and a RILEM (Réunion internationale des laboratoires d'essais et de recherches sur les matériaux et les constructions) working group, the strength of concrete under investigation can be predicted with an accuracy of 20 to 30% by test hammers (7,8). Williams has claimed somewhat better accuracy with the testing pistol (3).

REBOUND METHOD

In 1948, a Swiss engineer, Ernst Schmidt developed a test hammer for measuring the hardness of concrete by the rebound principle (9). As for indentation methods, there appears to be little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer. However, within limits, empirical correlations have been established between strength properties and the rebound number. Kolek has also attempted to establish a correlation between the hammer rebound number and the hardness as measured by the Brinnel method (10).

The Schmidt hammer consists of a spring-controlled hammer mass that slides on a plunger within a tubular housing. When the plunger is pressed against the surface of the concrete, it retracts against the force of the spring; when completely retracted, the spring is automatically released. The hammer impacts against the concrete and the spring-controlled mass rebounds, taking a rider with it along the guide scale. By pushing a button, the rider can be held in position to allow readings to be taken. While the hammer is still in its testing position, the sliding index is read to the nearest whole number. This reading is designated as the hammer rebound number.

The detailed procedure for calibrating the hammer has been described elsewhere (11,12). A typical relationship between compressive strength and rebound number for limestone aggregate concrete, obtained by Zoldners, is shown in Fig. 1 (13). In 1975, ASTM issued a tentative test method (C805-75T) for determining the rebound number of hardened concrete.

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 Schmidt rebound hammer are affected by:

1. smoothness of surface under test
2. size, shape and rigidity of the specimen
3. age of concrete
4. surface and internal moisture condition of the concrete
5. type of coarse aggregate
6. type of cement
7. type of mould
8. carbonation of concrete surface.

The above limitations are discussed in detail elsewhere (12,14,15,16).

According to Kolek and Malholtra, there is a general correlation between compressive strength of concrete and the hammer rebound number (10,12). However, there is wide disagreement among various research workers concerning accuracy of estimating strength from rebound readings. By consensus, the accuracy of estimation using test

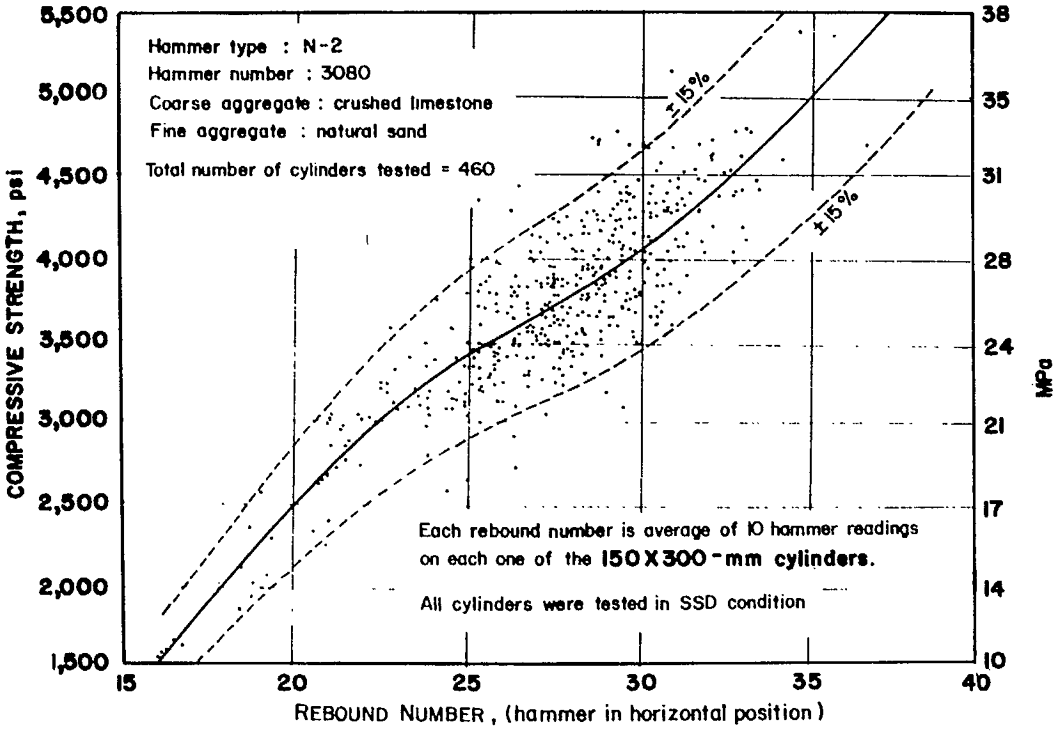

Fig. 1 - Relationship between compressive strength and rebound number for limestone aggregate concrete obtained with Type N-2 hammer; from reference 13

specimens cast, cured, and tested under laboratory conditions by a properly calibrated hammer lies between ±15 and ±20%. However, the probable accuracy of predicting concrete strength in a structure is ±25%. It cannot be overemphasized that the rebound hammer must not be regarded as a substitute for standard compression tests, but as a method for determining the uniformity of concrete in the structure and comparing one concrete with another.

PENETRATION TECHNIQUES

The evaluation of hardness by probing techniques was first reported by Voellmy in 1954 (17). Two techniques were reported: one, known as the Simbi hammer was used to perforate concrete, and the depth of borehole was correlated to the compressive strength of cubes; in the other, the probing of concrete was achieved by blasting with spit pins, and the depth of penetration by the pins was correlated with the compressive strength of concrete.

Apart from the data reported by Voellmy, there is little published work available on these tests, and they appear to have received little acceptance in Europe or elsewhere.

In 1966, a new technique known as the Windsor probe was introduced in the U.S.A. for in situ testing (18). Since its introduction, a number of organizations in both the U.S.A. and Canada have carried out studies with it. Arni has reported results of a detailed investigation on the evaluation of the Windsor probe, and Malhotra has reported results of his investigations on both 150 x 300-mm cylinders and 600 x 600 x 200-mm concrete slabs (19,20,21). In 1975, ASTM issued a tentative test method (C803-75T) for determining penetration resistance. At the present time, the only equipment known to be available and to meet the requirements of ASTM C803 is the Windsor probe.

The Windsor probe consists of a powder-activated gun or driver, hardened alloy probes, loaded cartridges, a depth gauge for measuring penetration of probes, and other related equipment (Fig. 2). The probes have a diameter of 6.3 mm, a length of 79.5 mm, and a frustoconical point on the front. The rear of the probe is threaded and screws into a probe driving head which is 12.6 mm in diameter and fits snugly into the bore of the driver.

The method of testing is relatively simple. The powder-activated driver fires a probe into the concrete using a single probe templet. The exposed length of the probe is measured by a calibrated depth gauge and is taken as a measure of the compressive strength.

A relationship between the exposed probe length and 28-day compressive strength of 150 x 300-mm cylinders is shown in Fig. 3. The relationships established by Arni, Malhotra, Law and Burt are shown in Fig. 4 (19,21,22).

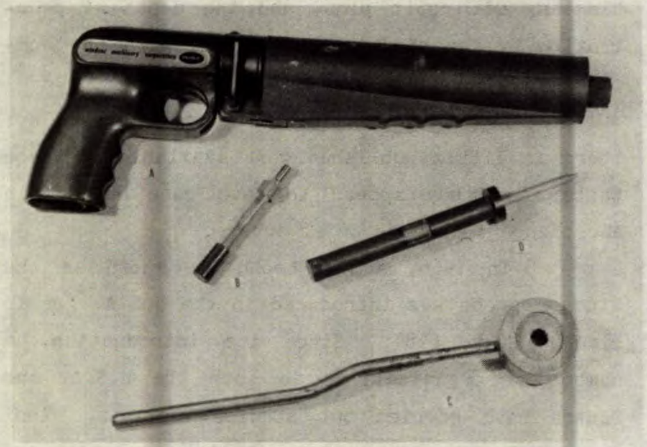

Fig. 2 - Windsor probe equipment. A. driver unit, B. probe for normal weight concrete, C. single probe templet, D. calibrated depth gauge; from reference 12

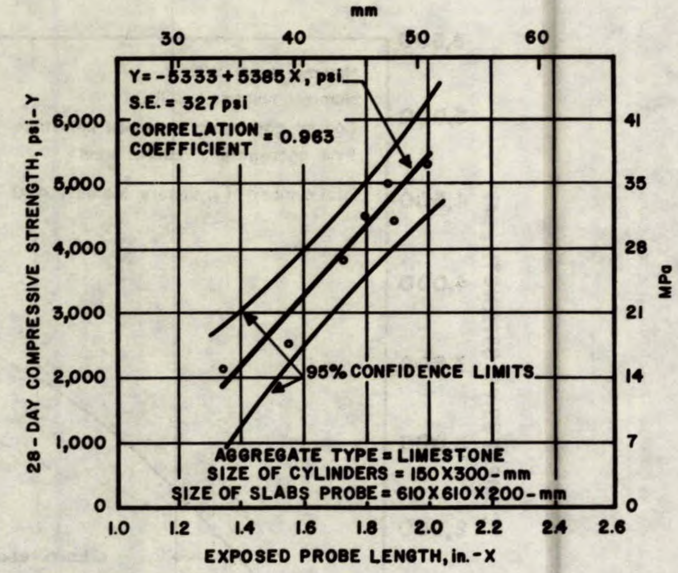

Fig. 3 - Relationship between exposed probe length and 28-day compressive strength; from reference 12

The Windsor probe is basically a hardness tester and provides an excellent means of determining the relative strength of concrete in the same structure or relative strengths in different structures, without extensive calibration with specific concretes. Because of the very nature of the test equipment, it cannot and should not be expected to yield absolute values of strength.

The Windsor probe is simple, rugged, and needs little maintenance except for occasional cleaning of the gun barrel. The system has a number of built-in safety features that prevent accidental discharge or escape of the projectile from the gun. However, wearing of safety glasses is required.

Penetration of the probe into the concrete is affected by the hardness of the aggregate as measured on Mohs' scale of hardness. In this scale, talc, the softest of all minerals, is given number 1 and diamond, the hardest of all known substances, is numbered 10. It is therefore desirable for each user of the Windsor probe to prepare his own calibration charts for the type of concrete under investigation; with change in source of aggregates, new calibration charts become mandatory.

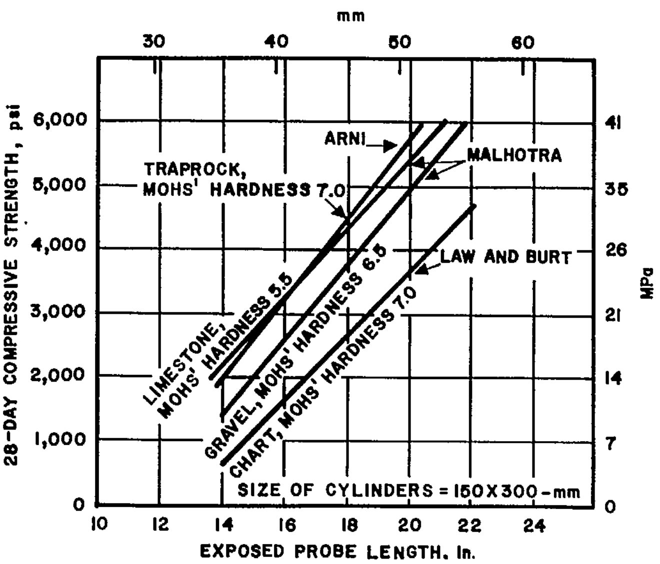

Fig. 4 - Relationship between exposed probe length and 28-day compressive strength as published by different investigators; from reference 12

The published data by Arni, Malhotra and Gaynor indicate that the variation in the probe test results is large compared with the variation in compressive strength on companion test specimens (19,21,23). This is expected because of the small areas under test. The within-batch standard deviation and coefficient of variation, as reported by various investigators, are shown in Table 1.

PULLOUT TESTS

A pullout test measures with a special dynamometer the force required to pull out from concrete a specially shaped steel rod whose enlarged end has been cast into the concrete (Fig. 5 and 6). Because of its shape, the steel rod is pulled out with a cone of concrete. The concrete is simultaneously in tension and in shear, the generating lines of the cone running at approximately 45° to the direction of pull. The pullout force is then related to compressive strength, the pullout strength being 10 to 30% of the compressive strength.

The pullout techniques, though in use in the U.S.S.R. since 1935, are relatively new elsewhere (24). In 1944, Tremper in the U.S.A. reported results of laboratory studies dealing with pullout tests covering strengths up to 35 MPa (25). In 1968, Tassios, in Greece, reported the development of a test in which a standard nail, 34 mm long and 4 mm in diameter, is driven into a concrete surface using a gun (26). Ten minutes after driving, the nail is extracted; the necessary pullout force is then measured on a manometer.

In 1975, Kierkegaard-Hansen summarized researches carried out over 13 years in Denmark in developing a pullout in which a disc embedded in the concrete is extracted through a cylindrical counter-pressure member (27). He named the technique Lok-Test because the Danish word for pulling out is "lokning."

In recent years, Richards in the U.S.A., has advocated these tests on structural concrete members (28). Gaynor, Malhotra, and Rutenbeck have reported data on the pullout tests proposed by Richards (29,30,31). In 1978, ASTM issued a tentative test method (C900-78T) for determining the pullout strength of concrete.

A relationship between the pullout strength and 28-day compressive strength of 150 x 300-mm cylinders is shown in Fig. 7. The results obtained by Malhotra, and Malhotra and Carette have been compared with those reported by Rutenbeck and are shown in Fig. 8 (30,31,32). Though these data cannot be compared directly because of using different materials and pullout assemblies, the correlations appear to be similar.

In his investigations, Kierkegaard-Hansen found that the relationship between the pullout force and compressive strength was linear but that the maximum size of the aggregate influenced the relationship (27). His correlation equations were as follows:

For 16-mm max. size aggregate:

Pullout force (KN) = 5.10 + 0.806 x compressive strength (MPa)

For 32-mm max. size aggregate:

Pullout force (KN) = 9.48 + 0.829 x compressive strength (MPa).

Table 1 - Within-batch standard deviation and coefficient of variation of probe measurements[a]

Investigation reported by	Type of aggregate used	Maximum aggregate size		Type of specimens tested	Total number of probes	Age of test days	Standard deviation		Coefficient of variation
		in.	mm				in.	mm	%
Arni	Gravel, limestone, trap rock	2	50	16 x 20 x 8-in. slab (410 x 510 x 200-mm)	136[b]	3, 7, and 28	0.143	3.62	6.8
		1	25	16 x 20 x 8-in. slab (410 x 510 x 200-mm)	189[b]	3, 7, and 28	0.105	2.66	5.5
Malhotra	Limestone	3/4	19	6 x 12-in. cylinders (152 x 305-mm)	20[c]	7 and 28	0.124	3.14	7.7
		3/4	19	24 x 24 x 8-in. slab (610 x 610 x 200-mm)	48[d]	7 and 29	0.054	1.37	3.4
	Gravel	3/4	19	6 x 6 x 66-in. prisms (150 x 150 x 1690-mm)	28[c]	35	0.062	1.57	3.4
		3/4	19	24 x 24 x 8-in. slab (610 x 610 x 200-mm)	48[d]	7 and 28	0.087	2.21	5.5
Gaynor	Quartz	1	25	6 x 23 x 48-in. walls (150 x 580 x 1210-mm)	384[e]	3 and 91	0.16	4.05	-
	Semi-lightweight (expanded shale as coarse aggregate)	1	25	6 x 23 x 48-in. walls (150 x 580 x 1210-mm)	256[f]	3 and 91	0.17	4.30	-

NOTE: Compressive strength of 6 x 12-in. (152 x 305-mm) cylinders ranged from 2000 to 6000 psi (13.8 to 41.3 MPa).

[a] From reference 12.

[b] 4 probes per test.

[c] 2 probes per test

[d] 3 probes per test

[e] 16 probes per test

[f] 9 probes per test

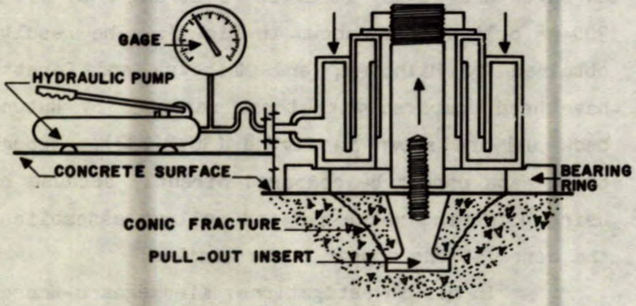

Fig. 5 - Apparatus for pullout test; adopted from ASTM C900-78T

Fig. 6 - Pullout test being performed at CANMET laboratories

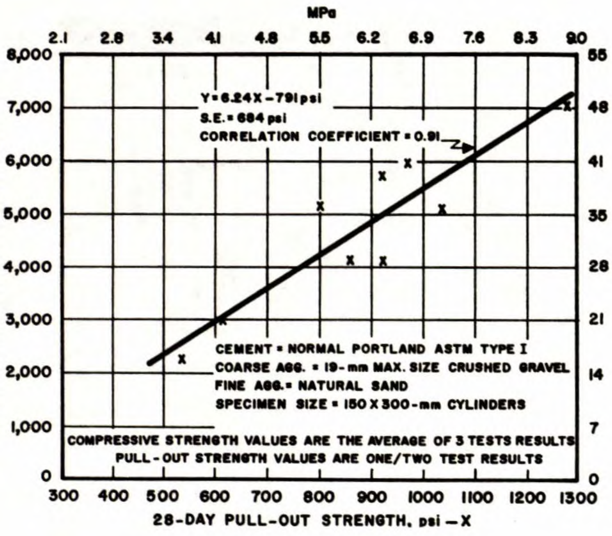

Fig. 7 - Relationship between pullout and 28-day compressive strength of 150 x 300-mm cylinders; from reference 32

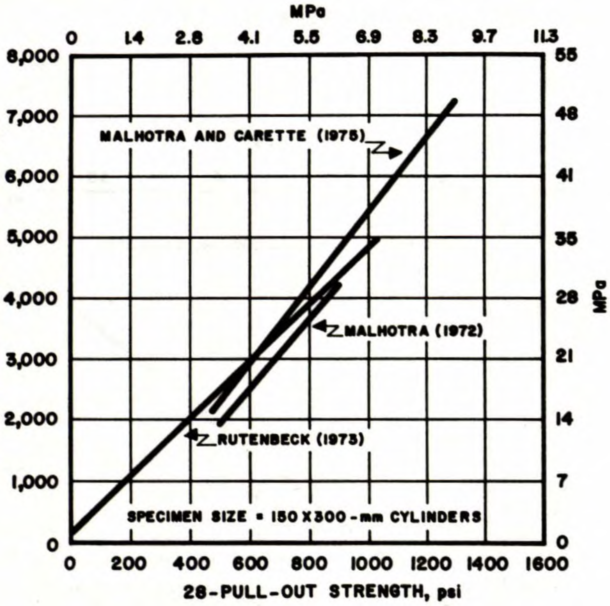

Fig. 8 - Relationship between pullout and 28-day compressive strength of 150 x 300-mm cylinders as obtained by different investigators; from reference 32

Recently, Lok-Test has been introduced in North America and has been used on some construction projects to determine the early strength of concrete for the purpose of stripping forms (33).

In principle, the Danish pullout test is identical to that used by Richards, Malhotra and others except that the equipment is more compact and sophisticated and hence, considerably more expensive (Fig. 9) (28,29,30,31,32).

The main advantages of the pullout tests are that they do measure the in situ strength of concrete. The technique is simple, and effective. The testing can be done in the field in a matter of minutes and the test results are reproducible.

The pullout strength is of the same order of magnitude as the direct shear strength, indicating that the strength value obtained in the pullout test is probably a measure of the direct shear strength.

The major disadvantage of a pullout test is that damage to the concrete surface must be repaired. However, if a pullout force of a given minimum strength is applied without failure, it may be assumed that a minimum strength has been reached for in situ concrete and the structural unit need not be stressed to failure. Another disadvantage is that the pullout tests being used

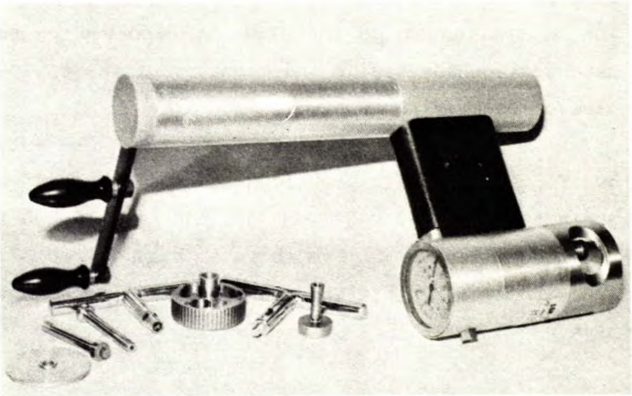

Fig. 9 - Lok-Test equipment; from reference 27

in North America have to be planned in advance and, unlike other in situ tests, cannot be performed at random after the concrete has hardened.

Investigations by Mailhot et al. and Chabouski and Bryden-Smith describe new pullout techniques that overcome the drawbacks associated with the methods discussed above (34,35). In these techniques, holes are drilled into hardened concrete and split-sleeve assemblies or wedge anchors are installed which are then pulled out causing internal cracking of the concrete. Mailhot et al. also discussed tests dealing with the pulling out of bolts set by means of an epoxy in holes drilled in hardened concrete.

INVESTIGATIONS BY MAILHOT ET AL.

Split-Sleeve Assembly Technique

This technique is based on the determination of the pullout force required to cause shear failure using a split sleeve assembly (Fig. 10). Although it also involves the application of a pullout force on a bolt, the mechanism of stressing and failure of the concrete is quite different from that obtained with the usual pullout tests. The testing arrangement is such that the pullout force is transmitted to the walls of the drilled hole in the form of a lateral force exerted by the ring of the sleeve, ultimately resulting in shear failure of the surrounding concrete. The effectiveness of the test is reported to be dependent on the design and geometry of the split-sleeve assembly.

Correlations obtained between the pull out force using this technique and the compressive strengths of 150 x 300-mm cylinders and 100 x 200-mm drilled cores are shown in Fig. 11 and 12. The within-test variation was found to be somewhat high.

Technique Involving Epoxy Grouted Bolts

This technique consists in pulling out a bolt set in hardened concrete with an epoxy. Like other pullout tests, it involves pulling out not only a bolt but a section of concrete; failure occurring along a shear-tension plane determined

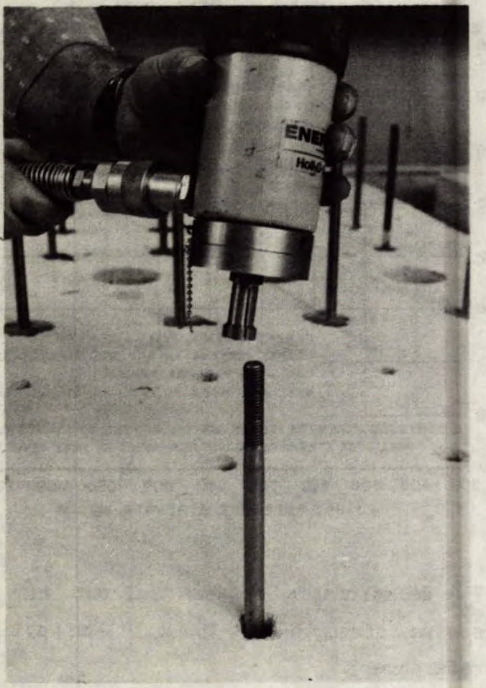

Fig. 10 - Equipment for split sleeve assembly technique; from reference 34

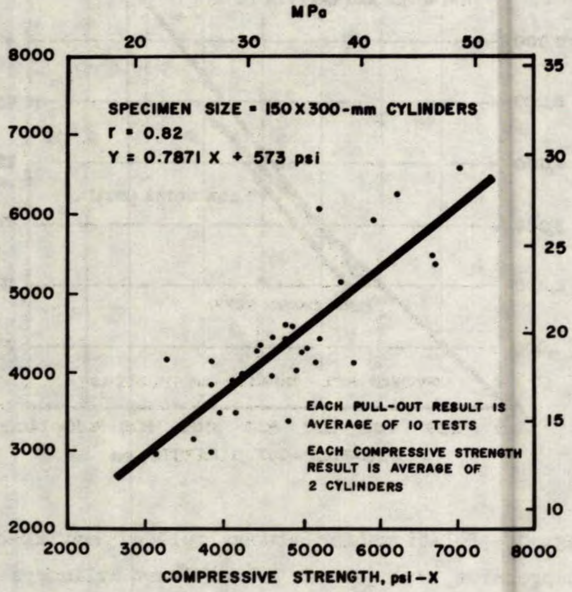

Fig. 11 - Relationship between pullout load and compressive strength of 150 x 300-mm cylinders using split sleeve pullout technique; from reference 34

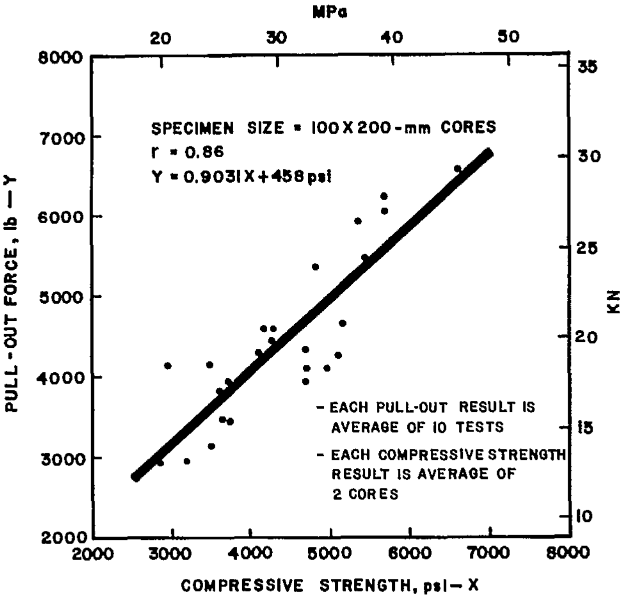

Fig. 12 - Relationship between pullout load and compressive strength of 100 x 200-mm cores using split sleeve pullout technique; from reference 34

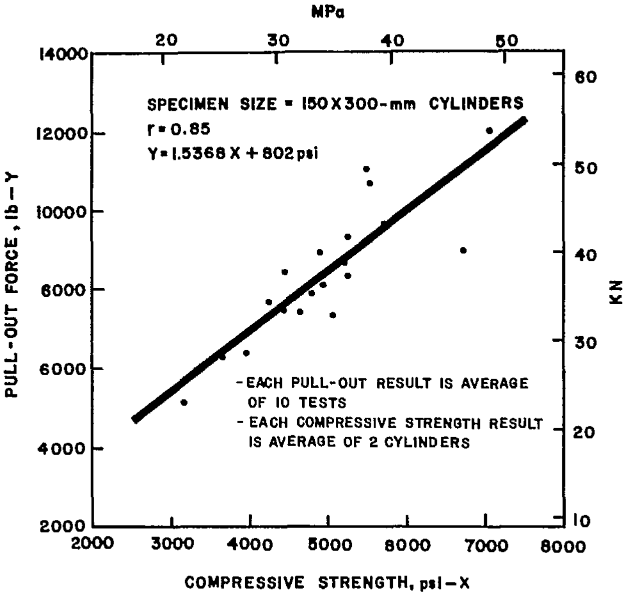

Fig. 13 - Relationship between pullout load and compressive strength of 150 x 300-mm cylinders using epoxy-grouted bolts; from reference 34

by the geometry of the arrangement. In this case, the success of the method depends on the proper selection of dimensions for the drilled holes as well as the use of a suitable type of epoxy. The relationships between results obtained with this technique and compressive strengths of 150 x 300-mm cylinders and 100 x 200-mm drilled cores are shown in Fig. 13 and 14. The within-test variations are again reported to be high, but it is believed they could be significantly reduced by standardizing test procedures.

INVESTIGATIONS BY CHABOUSKI AND BRYDEN-SMITH

The technique described by Chabouski and Bryden-Smith is very much similar to the split-sleeve assembly technique described by Mailhot et al., the only difference being that the former employed wedge anchors instead of split sleeves (Fig. 15).

Chabouski and Bryden-Smith, after developing the pullout technique at the Building Research Station (BRE), England, used the method to assess the strength of in situ high-alumina cement

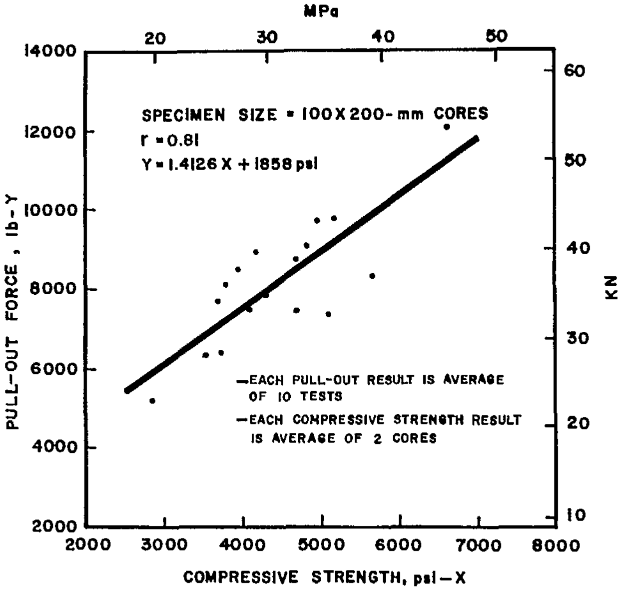

Fig. 14 - Relationship between pullout load and compressive strength of 100 x 200-mm cores using epoxy-grouted bolts; from reference 34

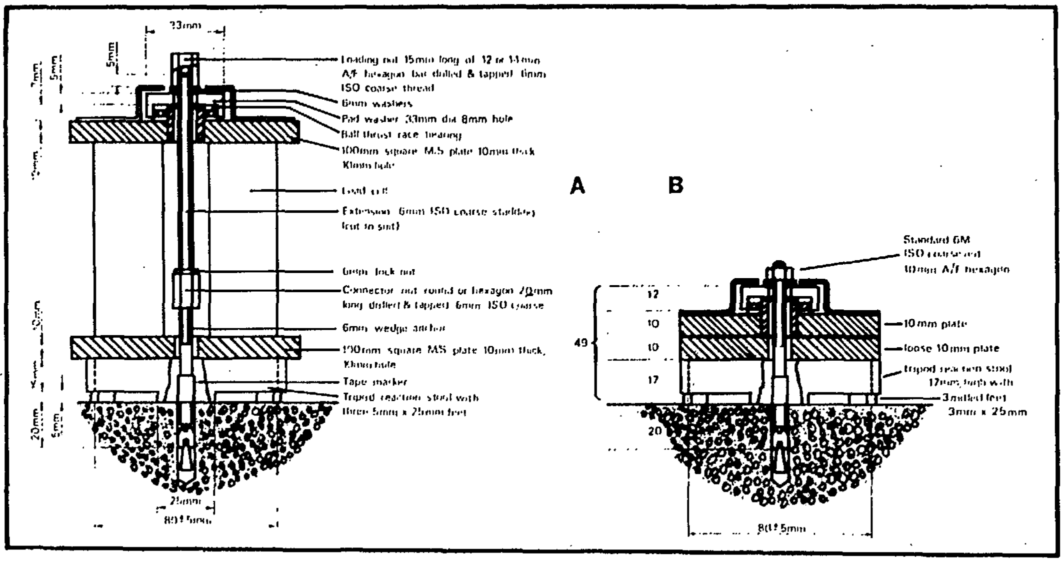

Fig. 15 - Equipment for "wedge anchor" pullout technique, A. assembly for use with load cell, B. assembly for use with torque meter; from reference 35

concrete and found it to be sufficiently accurate for use in engineering appraisals of such structures. Further research is in progress at BRE to examine the use of the method for a wide range of normal portland cement concretes. The authors have not offered any results on within-test variations but do recommend that usually six determinations be performed for each test, thereby implying high within-test variations.

BREAKOFF METHOD

This method consists of determining flexural strength in a plane parallel to and at 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 off at the bottom by applying a force to the top and at right angles to the axis of the core. The principle of the test is illustrated in Fig. 16 and a view of the testing equipment is shown in Fig. 17.

Data by Johansen indicate good correlations of breakoff strength with modulus of rupture and compressive strength (Fig. 18 and 19) (36).

According to Johansen, the test method is rapid and simple and the test results are not affected by the surface condition or by local temperature and shrinkage effects (36).

The test method appears promising for certain applications such as airport and highway pavements but suffers from the disadvantage that tests have to be preplanned and the within-test variation is high.

Limited investigations at CANMET have shown that difficulty is experienced in inserting tubes in concrete with slumps of less than 75 mm.

PULSE VELOCITY TECHNIQUES

This method was developed in Canada in 1945 by Leslie and Cheesman, and at about the same time in England by Jones (37,38). The Canadian studies, carried out in Toronto at the Hydro-Electric Power Commission of Ontario, were aimed at developing a nondestructive method to examine concrete in dams ranging in thickness up to 12 m.

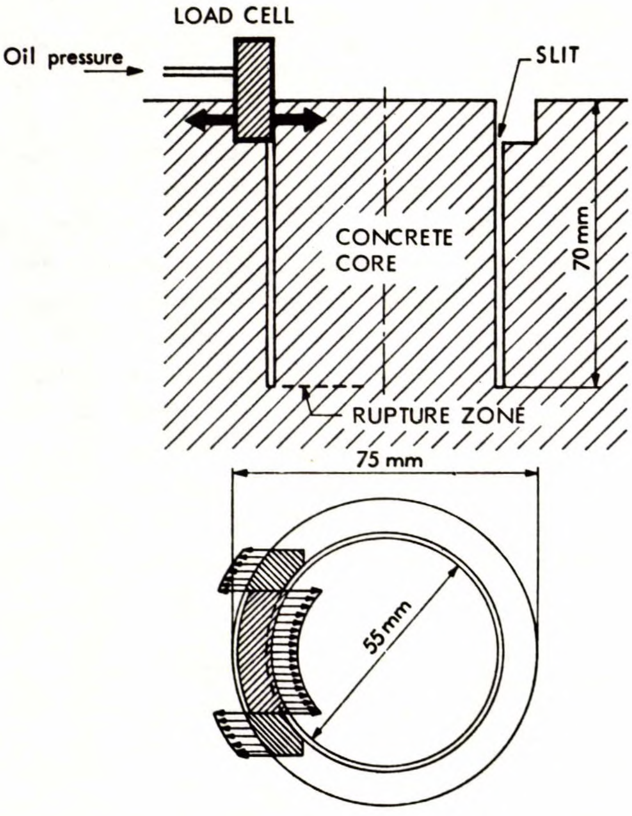

Fig. 16 - Principle of the breakoff method; from reference 36

These studies resulted in the development of an instrument known as Soniscope. Since then, a considerable amount of work has been reported on the use of this instrument both in Canada and in the United States (12,39).

The purpose of the research work carried out at the Road Research Laboratory, England, was to develop a technique for testing laboratory specimens. This led to the development of an instrument known as ultrasonic concrete tester. The development and use of this instrument has been reported in great detail by Jones and others (40,41,42).

To overcome some of the problems associated with the size of the above instruments, in the early 1970's portable digital types of pulse velocity instruments were developed both in Holland and England and these have given an added impetus to the use of pulse velocity techniques (Fig. 20) (43,44).

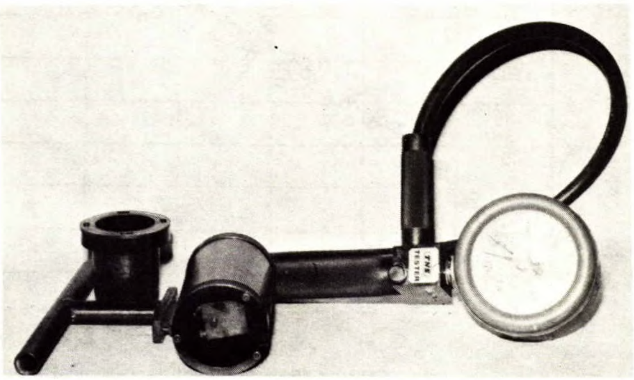

Fig. 17 - Testing equipment for breakoff method; from reference 36

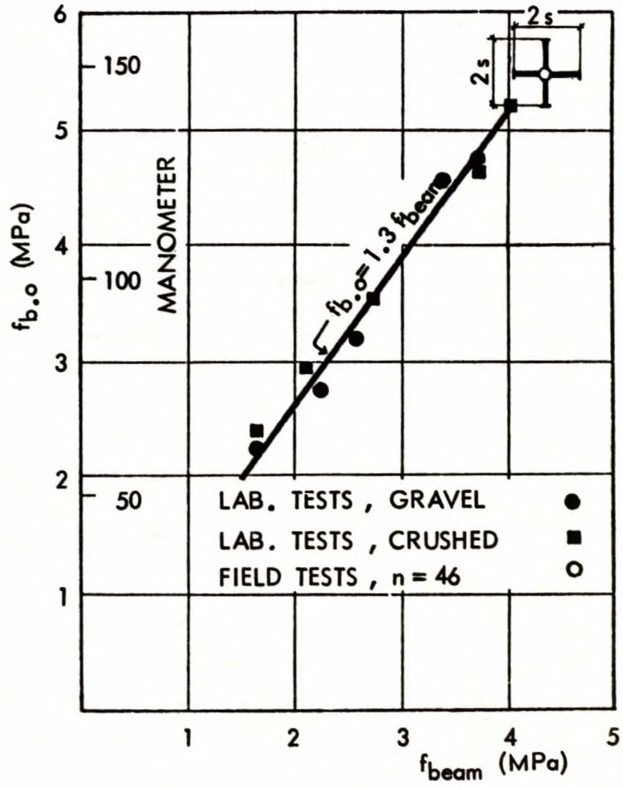

Fig. 18 - Relationship between breakoff strength ($f_{b.o.}$) and conventional modulus of rupture (f_{beam}); from reference 36

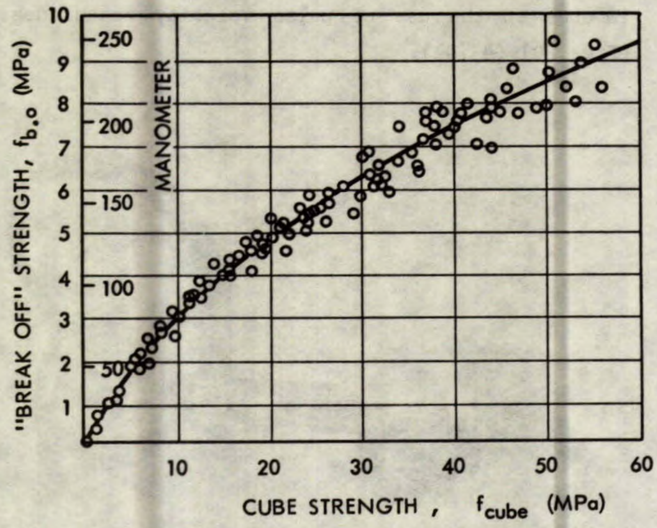

Fig. 19 - Correlation between the breakoff strength ($f_{b.o.}$) and the standard cube strength (f_{cube}); from reference 36

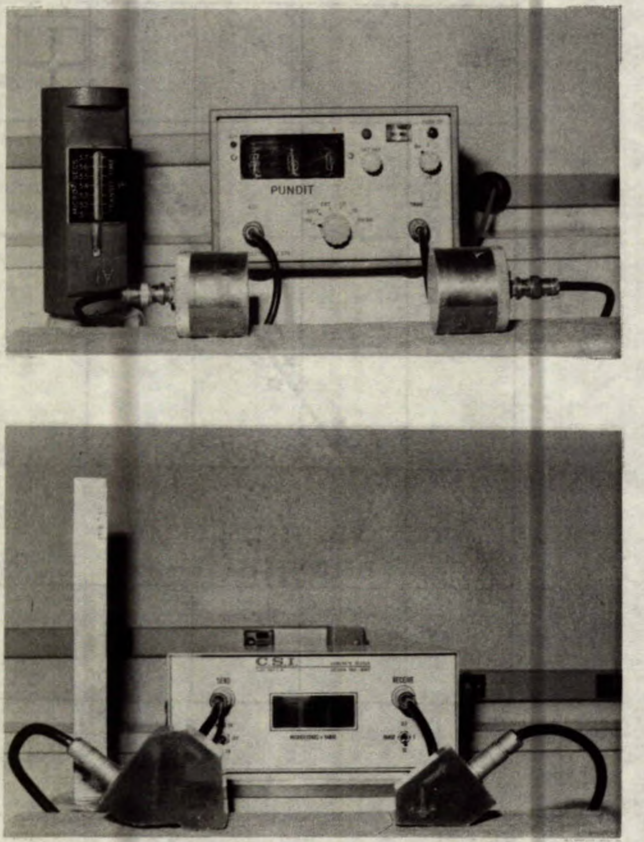

Fig. 20 - Portable ultrasonic concrete testers; top - PUNDIT (England), bottom - CSI (Holland)

BASIC PRINCIPLE

The ultrasonic pulse velocity method consists of measuring the time of travel of an ultrasonic wave passing through the concrete. An electrical impulse from a central unit is transmitted to a sending transducer where it excites a block of crystals. The transducer, through the block, emits an ultrasonic pulse which travels through the concrete to the receiving transducer. Here the ultrasonic pulse is converted back into an electrical impulse which is then displayed on the face of a cathode-ray oscilloscope. 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 propagation.

ESTIMATION OF STRENGTH OF CONCRETE

The pulse velocity technique is excellent for establishing uniformity of concrete, for measuring and detecting cracks and for measuring deterioration of concrete due to fire. However, less than satisfactory results have been reported when pulse velocity has been used to estimate in situ strength. The relationship between pulse velocity and strength is affected by a number of variables such as age of concrete, surface moisture condition, aggregate to cement ratio, type of aggregate and location of steel reinforcement. In spite of this, a number of researchers have used pulse velocity to estimate strength of concrete (40,41,45). In recent years, the combined use of pulse velocity and rebound number has been advocated to increase the accuracy of prediction of in situ strength (46,47).

Correlations between strength and pulse velocity enable the strength of structural concrete to be predicted within ±20% (12,40). To obtain this accuracy, allowance must be made for the type of cement, mix proportions and curing conditions.

At a recent ACI symposium, Anderson discussed the use of short-term nondestructive test measurements to predict long-term in situ strength of concrete (48). Based on carefully conducted laboratory investigations, Anderson selected pulse velocity as a predictor of compressive strength as the preferred method.

According to the author, although the prediction of 28- and 90-day compressive strength from 1- or 2-day pulse velocity measurements is feasible, the prediction depends on compositional factors such as air content and aggregate type. The author suggests that pulse velocity measurements could be used in conjunction with accelerated test methods for a comprehensive evaluation of in situ strength.

At the same symposium, Tomsett presented a fresh approach to using the pulse velocity data to estimate the in situ strength (49). According to the author, because the curing and compaction of actual structural concrete members are vastly different from those of control test cylinders or cubes, the correlations established between pulse velocity of control specimens and their compressive strength cannot be used to predict with great accuracy the structural strength of in situ concrete. To overcome this problem the author related the differences in pulse velocity through control specimens and in situ concrete to the ratio of strength of control specimens and cores taken from a structure. Nomograms were presented to simplify the use of this approach. Unfortunately, the author failed to provide sufficient field data to indicate that this new approach does give a better estimate of the in situ strength of concrete. The author hoped that a combination of pullout techniques and pulse velocity methods might provide a universally acceptable method for monitoring both relative and absolute quality of concrete in structures.

The following statement by Malhotra best sums up the relationship between the pulse velocity and the strength of concrete (12):

> "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 strengths of concrete is not recommended. Indeed, serious consideration should be given to the use of pulse velocity as a control test in its own right, and perennial attempts to correlate pulse velocity with strength parameters should be discouraged."

COMBINED METHODS

It has been shown in the preceding sections that compressive strength does correlate with various parameters obtained using in situ strength tests, but that some of these correlations leave much to be desired. This is particularly so for pulse velocity techniques and the rebound hammer. To predict the compressive strength of in situ concrete more accurately, a number of investigators, especially in Europe, have tried to apply more than one nondestructive method at the same time (46,47,50,51).

A survey by Jones and Făcăoaru in 1968 indicated that the most popular combination was the measurement of ultrasonic pulse velocity in conjunction with hardness measurements (52). For testing small specimens in the laboratory, damping constant as determined by resonance tests combined with ultrasonic pulse velocity or dynamic modulus of elasticity have been used (47,50,51).

From his experiences in Romania, Făcăoaru concludes that by the use of the ultrasonic pulse velocity-rebound hammer combination the following degree of accuracy can be obtained in predicting compressive strength (46):

(i) when composition of the concrete is known and test specimens or cores are available for the check of transformation, accuracy is within 10 to 15%;

(ii) when only the correct composition of the tested concrete is known, accuracy is within 15 to 20%;

(iii) when neither the composition is known nor test specimens or cores are available, accuracy is within 20 to 30%.

Both Samarin and Meynink, and Ulf Bellander have shown that the accuracy of predicting compressive strength is increased with the combined method compared with pulse velocity alone (53,54). However, the increase in accuracy is only marginal with the combined method compared with that of the rebound method alone.

According to Samarin and Meynink, when using the combined method, there is an increase in the multiple correlation coefficient of 0.03 above the correlation coefficient for rebound number and strength and 0.08 above the correlation coefficient for pulse velocity and strength (53).

Furthermore, as shown below, there is a decrease in the value of standard error of estimate as a percentage of the mean strength by 2% below that for correlation of rebound number and strength and 6% below that for correlation of pulse velocity and strength.

	Form of regression*	Correlation coefficient	$S/\bar{S}$, %
Combined method	$S = A_o^4 + A_1R + A_2V$	0.95	8.3
Rebound hammer	$S = A_o + A_1R$	0.92	10.1
Ultrasonic pulse velocity	$S = A_o + A_1V^4$	0.87	14.6

* S = Compressive strength
R = Rebound number
V = Pulse velocity
A_0, A_1, A_2 = Constants

Ulf Bellander performed comprehensive investigations to compare the accuracy of prediction for combined method techniques with those of pulse velocity and rebound hammer when used separately (54). As shown below, his data like that of others do show increased accuracy of prediction for the combined method.

	No. of tests	Regression equation	Correlation coefficient
Combined method	221	$S = 0.00082R^3 + 11.03V - 32.7$	0.93
Rebound hammer	221	$S = 0.00093R^3 + 13.1$	0.92
Ultrasonic pulse velocity	221	$\text{Log } S = 0.882V - 0.259$	0.63

The limited investigations carried out at CANMET have indicated that under controlled laboratory conditions, the improvement in predicting strength by the combined instead of by individual rebound or pulse velocity techniques, may be rather small. In these investigations, large concrete blocks measuring 600 x 600 x 300 mm covering a wide range of water cement ratios under continuous moist-curing conditions were tested at different ages between 7 and 90 days. Correlations between rebound number or pulse velocity measurements on the blocks and strength as determined on 100 x 200-mm cores drilled from the same blocks were reported as being very good with correlations coefficients being 0.92 and 0.93 for rebound and pulse velocity respectively. However, the correlation coefficient was not found to increase by more than 0.02 when the combined method was used as shown below:

	Form of regression	Correlation coefficient
Combined method	$\text{Log } S = A_o + A_1\log R + A_2V$	0.94
Rebound hammer	$S = A_o + A_1R$	0.92
Ultrasonic pulse velocity	$S = A_oe^{A_1V}$	0.93

Notwithstanding the data by Facăoăru and others, it is to be noted that the use of pulse velocity measurements contribute relatively little to the increased degree of accuracy (46,53,54). In addition, in heavily reinforced structural elements when location and depth of reinforcing steel are unknown, pulse velocity tests performed by inexperienced personnel may be of little value. Furthermore, Bellander concluded that the pullout test was somewhat more accurate than the combined methods discussed above (54).

Tomsett has suggested the use of the combined method approach employing pullout and pulse velocity tests, and Logothètis has proposed the combining of pullout, rebound hammer and pulse velocity tests for the prediction of in situ strength (49,55).

The use of more than two combined methods on the same structural concrete cannot be justified because of economy and time requirements and the possible marginal increase in the accuracy of predicting compressive strength.

MATURITY CONCEPT

It is well known that the compressive strength of moist-cured concrete increases with time. However, the increase in strength is governed by many factors other than curing time, the most important being the temperature of curing. The combined effect of time and temperature has been the subject of study by several investigators since 1904, but no hypothesis was formulated in early years. Then in the 1950's, the concept of maturity was advanced by McIntosh, Nurse, Saul, and others, and strength-maturity relationships were published (56,57,58,59,60). Maturity was defined as the product of time and temperature with a datum temperature of -10°C.

In 1956, Plowman examined relationships between concrete strength and its maturity, and attempted to establish a rational basis for datum temperature for use in maturity calculations (61). He defined the datum temperature for maturity as that at which the strength of concrete remains constant. As a result of his investigations, he concluded that the datum temperature was -12.2°C.

The maturity of in situ concrete can be estimated using thermocouples or by instruments called maturity meters. The strength of in situ concrete is then estimated using prior relationships established between maturity and compressive strength of test cylinders. One such relationship is shown in Fig. 21.

Swenson has used the maturity concept to estimate the strength gain of concrete in structures (62). In recent years, the maturity concept has been used to estimate the in situ strength of concrete during construction in a number of buildings in the Toronto area, the CN Tower being one (62,63,64). Hudson and Steel have used the maturity approach to predict potential strength of concrete on highway projects in West Virginia using the equation (65):

$$\text{Log } S_{28} = 2.9844 + 0.75 \text{ Log } S_e - 0.51 \text{ Log } m$$

where S_{28} = predicted 28-day compressive strength, psi

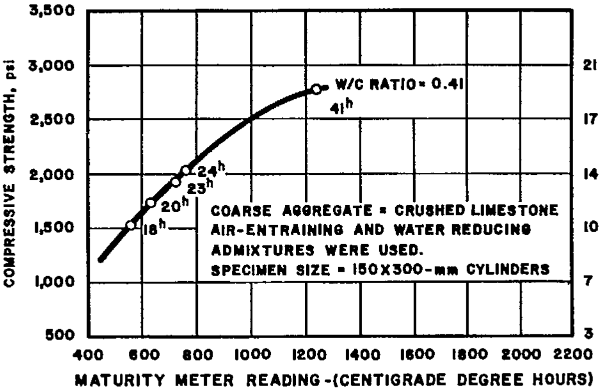

Fig. 21 - Typical relationship between maturity of concrete and its compressive strength; from reference 12

S_e = compressive strength (psi) of specimens tested at an early age and having a maturity m, and

m = degree hours of maturity at the time of test (°F.h).

Malhotra and others have attempted to relate compressive strengths obtained using accelerated-strength tests with the maturities for these tests (66,67).

The advantages of the use of the maturity concept are obvious; with proper use of in-place thermocouples, strength of concrete in structures can be successfully monitored. However, this concept has serious limitations and these must be recognized. It is generally agreed that the maturity concept is applicable only if:

(a) testing of concrete is confined within the range of maturity represented by about 3 to 28 days at normal temperatures;

(b) the initial temperature of concrete is between 15 and 30°C; this is a rather limited range;

(c) no loss of moisture by drying occurs during the curing period.

At a recent ACI conference, two papers discussed use of the maturity concept based on the Nurse-Saul maturity law. Naik described laboratory investigations using a maturity meter having solid-state parts and this appears to be the only difference between this instrument and its British counterpart (68). The author claimed that in situ compressive strength can be reliably predicted from a predetermined maturity-strength relationship. Ramakrishnan reported results of laboratory investigations dealing with linear multiple correlations involving maturity, pulse velocity and compressive strength (69). According to the author, the inclusion of water/cement ratio in the regression equations greatly improved the degree of accuracy of predicting in situ strength.

CONCLUSIONS

Slow but steady advances are being made in developing in situ strength testing procedures and a large measure of standardization has been achieved in these tests.

Most in situ tests discussed in this paper cannot and do not yield absolute values of compressive strength in a structure and must not be considered as a substitute for standard compression tests. The pullout and breakoff methods do measure strength but this is probably the shear strength of concrete from which an estimate of compressive strength may be made. However, the techniques discussed are satisfactory for determining relative strengths of concrete in different parts of the same structure or relative strengths in different structures.

When performed by skilled technicians and the results evaluated by experienced engineers, the in situ strength tests provide extremely useful data which otherwise cannot be obtained. When performed in conjunction with standard tests, they can reduce the cost of testing.

Unless laboratory correlations have been established between the strength parameters to be estimated and the results of in situ tests, the use of the latter to predict compressive or flexural strength of concrete is not recommended.

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