NBSIR 75-729

Nondestructive Tests to Determine Concrete Strength - A Status Report

James R. Clifton

Materials and Composites Section
Structures, Materials and Safety Division
Center for Building Technology, IAT

July 1975

Final

Prepared for
Building Safety Section
Structures, Materials and Safety Division
Center for Building Technology, IAT
National Bureau of Standards
Washington, D. C. 20234

NBSIR 75–729

NONDESTRUCTIVE TESTS TO DETERMINE CONCRETE STRENGTH – A STATUS REPORT

James R. Clifton

Materials and Composites Section
Structures, Materials and Safety Division
Center for Building Technology, IAT

July 1975

Final

Prepared for
Building Safety Section
Structures, Materials and Safety Division
Center for Building Technology, IAT
National Bureau of Standards
Washington, D. C. 20234

U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, *Secretary*
John K. Tabor, *Under Secretary*
Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

TABLE OF CONTENTS

NONDESTRUCTIVE TESTS TO DETERMINE CONCRETE STRENGTH - A STATUS REPORT

by
James R. Clifton

ABSTRACT

Individual and combined nondestructive test methods have been critically reviewed as potential methods to determine safe formwork removal times. The techniques reviewed are the Windsor probe, the Schmidt Rebound Hammer, pull-out measurements, push-out cylinders, ultrasonic pulse velocity measurements, and the maturity and equivalent age concepts. The individual methods, themselves, do not give good estimates of the in situ strengths of concretes and it is recommended that future research emphasize combined methods.

A proposed research program which emphasizes combined nondestructive test methods has been developed.

Key Words: Compressive strength; concrete; flexural strength; formwork removal; nondestructive testing; surface hardness.

1. INTRODUCTION

This report is based on a critical literature review of nondestructive test methods for estimating the early-age strength of in situ concrete. The estimation of the strength of concretes at early ages is important in deciding when the formwork can be safely removed. The premature removal of forms has resulted not only in numerous collapses [1, 2], but also in the often unreported sagging of partially cured concrete and in the development of hairline cracks which subsequently lead to serious maintenance problems [1].

Nondestructive testing of mature concrete has been the subject of symposia [3-6], review articles [7-10] and several books [11-13]. However, the current review discloses that relatively little attention has been given to nondestructive methods for estimating the early-age strengths of concretes.

Many of the test methods classified as being nondestructive do cause sufficient damage to the concrete that minor repairs are necessary. These methods are nondestructive in that the specimen being tested is not severely damaged or destroyed.

The nondestructive test methods covered in this report are those applicable to the estimation, of either the in situ strength of concrete or the quality of concrete. Therefore, radioactive, x-ray, and electrical nondestructive test methods are not included. This report is also restricted, with the exception of the push-out test method (Section 2.4), to tests which can be performed on site (if the proper calibration tables or charts have been previously prepared). Both individual and combined nondestructive test methods are discussed.

2. NONDESTRUCTIVE TEST METHODS

The individual nondestructive test methods of this section are evaluated on the basis of their apparent reliability, accuracy, ease of use, and information obtained. Their applicability to the determination of formwork removal times is considered as well as their advantages and limitations. Recommendations on needed research are also given.

2.1 Probing Methods

The probing methods used to measure the surface hardness of concrete are based on depth of penetration of probes in the concrete. The probe results are converted into compressive strengths by a correlation graph which is a construction of depth of penetration versus experimentally measured compressive strengths. Based on this correlation chart the in situ compressive strength of concrete can be estimated.

The first hardness measurements of concrete by probing techniques were reported by Voellmy [14], in 1954. He used two techniques: (1) a special hammer device was used to perforate concrete and afterwards the depth of the bore hole was measured; and (2) the depth of penetration of pins which were blasted into the concrete was measured. Neither technique gained wide acceptance. In the middle 1960's the Windsor Probe was developed by the Port of New York Authority, New York, and the Windsor Machinery Company, Connecticut. Cantor presented [15] the results of the investigations performed by the Port of New York Authority. The Windsor Probe technique is becoming an acceptable nondestructive test technique, as evidenced by the amount of recent investigations performed [16-21] to assess its reliability. The Nondestructive Testing Subcommittee of ASTM Committee C-9 is currently drafting specifications giving guidelines for the usage of the probe method.

2.1.1 Description of the Windsor Probe

The Windsor Probe device consists of a special driving gun into which is inserted a high-strength metal probe that is driven into the concrete by the firing of a powder charge (figure 1). Different probe shapes are available, as shown in figure 2. The length of the probe extending from the surface of the concrete can be measured using a device supplied by the manufacturer (figure 3).

The manufacturer supplies a set of 5 calibration curves, each curve corresponding to a specific Mohns' hardness for the coarse aggregate used in the concrete, by which probe measurements can be converted to strength measurements. However, several investigations have observed [17, 19-22] that use of the manufacturer's calibration curves often results in grossly incorrect estimates of the compressive strength of concretes. These investigations recommend that the Windsor Probe should be calibrated by the individual user, and should be recalibrated whenever the type of aggregate is changed.

Methods for calibrating the Windsor Probe are given by Malhotra [9] and by Keeton and Hernandez [23].

2.1.2 Windsor Probe for Compressive Strength Determinations

The relationship between the depth of penetration of the probe and the compressive strength appears to be only empirical as the penetration of the probe produces a complex mixture of tensile, shear, frictional, and compressive forces [19]. The estimation of compressive strengths with the Windsor Probe, therefore, must be made using a correlation diagram, with appropriate confidence limits.

The published results [17-21] reviewed by the author, indicate that the variations in the probe test results are large. Cantor [15] measured a standard deviation of about 1550 psi (10.7 MN/m^2), a coefficient of variation of about 35 percent and a range in predicted compressive strength of 5600 psi (38.6 MN/m^2), in a program based on 625 probe tests of a single concrete. These values are about ten-fold higher than those obtained by him with compression measurements of standard cylinders and drilled cores.

Arni [19-20] constructed a plot of probe measurements versus compressive strength (measured using 6" x 12" (.15 x .30 m) standard cylinders) and calculated the regression line and 95 percent confidence limits (based on 99 probes fired into the top of slabs made with 1 inch (.025 m) aggregate). This plot is shown in figure 4, where $\bar{P}$ is the average probe value, $\hat{S}$ is the average compressive strength and the subscripts l and u represent the lower and upper 95 percent confidence limits. The final 95 percent confidence limit band for the strength resulting from the combined compressive strength and probe confidence levels, is from S_1, 3290 psi (22.6 Mn/m^2) to S_u, 5650 psi (39.9 MN/m^2), or a range of 2360 psi (6.2 MN/m^2). Arni also statistically analyzed the data based on being able to detect a difference of 200 psi (.138 MN/m^2) from the true strength with a Type I (α) error of 0.10 and a Type II (β) error of 0.10. (This means that the average of a group of tests would exhibit a significant difference from an assumed true strength one time in 10 when the actual strength difference is 200 psi (1.38 MN/m^2) or less and 9 times in 10 when the difference is actually 200 psi (1.38 MN/m^2) or greater). He determined that about 85 probes would be required to detect the average strength within 200 psi (1.38 MN/m^2).

Large variabilities in probe test results were also observed by Malhotra [21] and by Gaynor [18]. Gaynor [18] suggested that the penetration of a probe into concrete is affected by both the strength of the concrete and other properties which have relatively little effect on concrete strength, such as aggregate strength, elasticity, and porosity. He concluded that the basic heterogeneity of concrete (with hardened cement paste, mortar matrix, and coarse aggregate phases) appears to limit the accuracy of the probe system.

Arni [19-20] and Malhotra [9] have reported that for the same concrete mix, depth of penetration of the probes decreased with increasing age of the concrete, reflecting an increased hardness of the concrete. However, these studies were too brief to give any definitive results.

2.1.3 Advantages and Limitations

The Windsor Probe equipment is simple, durable, requires little maintenance, and can be used by laymen in the field with little training. Care must be exercised, however, because a projectile is fired and safety glasses should be worn.

The Windsor Probe primarily measures hardness and does not yield precise measurements of the in situ strength of concrete. The probe test, however, is useful in assessing the quality and relative strengths of concrete.

The Windsor Probe test does damage the concrete, leaving a hole of about 5/16 in. (0.008 m) in diameter for the depth of the probe and, also, may cause minor cracking; necessitating minor repairs.

2.1.4 Research Required

The reliability of using the Windsor Probe to monitor the early-age strength development of concretes with different types of aggregates should be investigated.

2.1.5 Concluding Remarks

Based on the results reviewed in this report, it can be concluded that although Windsor Probe measurements show a correlation with compressive strength, this test does not provide a precise determination of strength. This method is best used to check the relative quality of concrete in place.

Possibly, the Windsor Probe method can be used in combination with another nondestructive test to monitor the strength development of concrete and to determine when the formwork can be safely removed.

2.2 Rebound Method

The rebound method is similar to the probe method in that both measure surface hardness. The rebound method is based on the rebound theories of Shore [23]. He developed the Shore Soleroscope method in which the height of rebound of a steel hammer dropped on metal test specimens is measured. The only commercially available instrument based on the rebound principle for testing concrete is the Schmidt Rebound Hammer [24-26].

The Schmidt Rebound Hammer has gained wide acceptance by researchers and is one of the most universally used nondestructive test methods for determining the in situ quality of concrete and for deciding when forms may be removed. Provisional standards have been drafted in Poland [27] and Rumania [28] for the Schmidt Rebound Hammer. The British Standards Institution has issued a Building Standards 4408 which covers nondestructive test methods for concrete, and includes the rebound hammer method in part 4 of the Standard

[29]. The Nondestructive Subcommittee of ASTM Committee C-9 is currently drafting specifications giving guidelines for the use of the rebound hammer method.

2.2.1 Description of Hammer Method of Testing

The Schmidt Rebound Hammer consists of a steel plunger and a tension spring in a tubular frame (figure 5). When the head of the hammer is pushed against the surface of the concrete, the steel plunger is retracted against the force of the spring. When the head is completely retracted, the spring is automatically released, the plunger is driven against the concrete and it rebounds. The rebound distance is indicated by a pointer on a scale that is graduated from 0 to 100, and the rebound readings are termed R-values. The determination of the R-values is outlined in the manual supplied by the manufacturer.

Each hammer is furnished with a calibration chart supplied by the manufacturer, showing the relationship between compressive strength of the concrete and rebound readings based on data from tests conducted by the Swiss Federal Materials Testing and Experimental Institute. Each hammer, however, varies slightly in performance and should be calibrated by the individual user. A method of calibrating the Schmidt hammer has been described by Malhotra [13].

2.2.2 Schmidt Rebound Hammer for the Determinations of Compressive Strength

Numerous investigators [30-33] have shown that there is a correlation between compressive strength of concrete and the hammer rebound number. There is, however, extensive disagreement (ex. references 34 and 35) concerning the accuracy of the strength estimates from rebound measurements. Mitchel and Hoagland [36], found that the coefficient of variation for compressive strength, determined on the basis of rebound measurements, for a wide variety of specimens from the same concrete averaged 18.8 percent and exceeded 30 percent in some cases.

In a detailed investigation, Arni [19-20] constructed a diagram of rebound number versus compressive strength, showing the regression curve and the 95 percent confidence limits (figure 6). The regression line was based on 16 plotted points, each representing 20 rebound measurements and the average compressive strengths of three 6 x 12 inch (.15 x .30 m) cylinders. Arni has thoroughly discussed the usage and statistical significance of this diagram. Briefly, $\overline{R}$ is the average rebound number and R_l and R_u are the rebound numbers representing the lower and upper 95 percent confidence limits. Similarly, $\hat{S}$ is the average compressive strength and S_l and S_u are the lower and upper 95 percent confidence limits. On figure 6, the horizontal lines from R_l and R_u intersect the confidence limits for points on the line at $S_1 = 4010$ psi (27.2 MN/m^2), and at $S_m = 5070$ psi (34.9 MN/m^2), for a range of 1060 psi (7.30 MN/m^2). This analysis indicates that to detect a difference of 200 psi (1.38 MN/m^2) from the true strength with a Type I (α) error of 0.10 and a Type II (β) error of 0.10, about 200 rebound measurements would be required.

The use of the Schmidt Rebound Hammer for testing either low-strength concretes or concretes at early ages is not recommended [36] because rebound numbers are often too low for accurate reading and the test hammer can damage the surface of the concrete. Arni [19-20] measured the rebound numbers of the concretes at ages 3, 7, 14, and 28 days and observed increased rebound values as the concretes aged.

2.2.3 Flexural Strength and Modulus of Elasticity

Several investigators [35, 37] have attempted to establish correlations between the flexural strength of concrete and the hammer rebound number. Relationships similar to those obtained for compressive strengths were obtained, except that the statistical variations were even greater.

Mitchel and Hoagland [36] attempted to correlate hammer rebound with the modulus of elasticity of the concrete specimens. They concluded that no valid correlations could be made. Peterson and Stoll [30] and Klieger [31] have developed empirical relations between the dynamic modulus of elasticity and hammer rebound.

2.2.4 Advantages and Limitations of the Schmidt Rebound Hammer

The Schmidt Rebound Hammer is a simple and quick method for the nondestructive in situ testing of concrete. The equipment is inexpensive, costing less than $1000, and can be operated by field personnel with a limited amount of instruction.

The Schmidt Rebound Hammer, however, has recognized limitations. The rebound measurements on in situ concrete are affected by [9, 35, 38]:

(1) Smoothness of the concrete surface

(2) Surface and internal moisture content of the surface

(3) Type of coarse aggregate

(4) Size, shape and regidity of specimen, ex. a thin wall or beam

(5) Carbonation of the concrete surface.

The Schmidt Rebound Hammer is largely an empirical test [10], and several precautions must be taken to obtain meaningful results [39]. It can be concluded that the rebound method does not provide a good estimation of the strength of concrete.

2.2.5 Research Required

The reliability of using the Schmidt Rebound Hammer to monitor the early-age strength development of concretes with different types of aggregates should be investigated. The extent of damage to early age concrete should also be determined.

2.2.6 Concluding Remarks

The Schmidt Rebound Hammer is a useful device to determine the relative quality of in-place concrete, but does not give a precise determination of strength.

Possibly the Schmidt Rebound Hammer can be used in combination with another nondestructive test to determine when formwork can be safely removed. It has been suggested [32] that the rebound hammer be used in conjunction with some accelerated cure method to make strength estimates.

2.3 Pull-Out

The pull-out test measures the force required to pull out a steel rod, having an enlarged end which has been cast in the concrete (figure 7). The concrete is subject to both tensile and shear stresses by the pull out forces, and a cone of concrete is removed at failure. These forces are usually related to the compressive strength of the concrete, with the ratio of pull out strength to compressive strength being in the range of 0.1 to 0.3 [13].

An early investigation of the pull-out concept was performed in Russia in 1934 [40], in a study on low-strength concrete. A type of pull-out testing apparatus, which used a nail as the steel rod, was developed by T. Yoshida at the Tokyo Imperial University in 1942 [41]; his work was the basis for the manufacturing of a nail tester by the Maruto Testing Machine Company of Tokyo, Japan. The potential value of the pull-out concept was realized by Tremper [42] who, in 1944, concluded that "pull-out tests can be reproduced within limits that are nearly as close as for compression tests." Thereafter, the pull-out concept received little attention until the recent issuance of several patents [44-45]. Richards [46] has been particularly active in advocating the pull-out test method to determine the in situ strength of concrete. Malhotra [47] has investigated the pull-out test using concretes with a wide range of compressive strengths, and his conclusions were similar to those of Tremper.

The Nondestructive Testing Subcommittee of ASTM Committee C-9 is currently drafting specifications giving guidelines to the usage of the pull-out method.

2.3.1 Test Method and Field Use

The pull-out assembly described by Malhotra [47] (similar to the device in figure 7) consists of a steel shaft of 0.75 inches (0.0019 m) in diameter and 4.25 inches (0.11 m) long, with the cast-in-place enlarged end being a washer, 2.25 inches (0.057 m) diameter and .125 inches (.0028 m) thick, held in position with a steel nut. The embedded depth of the steel shaft is normally about 2 inches (.05 m). The steel shaft and the embedded head are pulled out of the hardened concrete with a manually operated hollow tension ram exerting pressure through the steel reaction ring (inside diameter of 5.0 in (.13 m) and 0.5 in (.013 m) thick). The apex angle of the pulled out specimen of concrete is usually fixed in the range of 65 to 70° by adjusting the geometry of the pull-out apparatus. Richards in collaboration with the American Instrument Company has developed an efficient semiautomatic pull-out system which uses a hydraulic ram.

The pull-out assembly is usually cast-in-place during pouring of the fresh concrete and therefore these tests must be planned in advance. Alternatively, hardened concrete can be drilled to receive the pull-out assembly. This necessitates drilling through the bottom or backside of a concrete slab to the proper depth and width to permit the insertion of the enlarged head; a smaller hole, sufficient to permit insertion of the steel shaft, is drilled through the remaining portion of the concrete slab; then the apparatus is inserted through the bottom or backside; and the test carried out.

2.3.2 Review of Recent Studies

The few reports on pull-out studies found in this review were principally directed toward determining the extent of correlation between compressive and pull-out strength measurements. Malhotra has reported [47] that the ratio of pull-out strength to compressive strength varies directly with the compressive strength of concrete. At 3 days this ratio was found to range from 0.18 for concrete with compressive strength of 4800 psi (32.9 MN/m^2) to 0.46 for concrete with the strength of 1150 psi (7.9 MN/m^2). He measured the pull-out strengths of concretes at ages of 3, 28 and 91 days, but did not attempt to make a correlation between pull-out strengths and compressive strengths as a function of age. Interestingly, Malhotra found that the 28 day standard deviation and coefficient of variation of strength from pull-out tests were small, ranging from 15 to 45 psi (0.10 to 0.31 MN/m^2) and from 2.3 to 5.0 percent, respectively. The corresponding values from compressive strength testing of standard cylinders were 4 to 120 psi (0.03 to 0.182 MN/m^2) and 0.2 to 3.0 percent, except for one mix for which the values were 682 psi (4.7 MN/m^2) and 11.4 percent.

Richards has probably performed the most extensive investigation of the pull-out test method, the results of which, however, have not been published[1/]. He has measured the pull-out strength of lightweight insulating concrete between the age of 29 hours to 28 days and of shotcrete placed during the metro subway construction in Washington, D.C. These measurements suggest that the pull-out strength of hardening concrete increases with age. In another series of test, he determined that the ratio of pull-out strength to compressive strength of cores averaged 0.25 for concretes of compressive strengths in the range of 1000 to 5000 psi (6.9 to 34.5 MN/m^2) and that this ratio was not age dependent. Richards has also observed that in some cases the coefficients of variation of the pull-out measurements are less than those of standard compressive strength measurements.

Based on a nail extraction method, Tassios and Demiris have reported [48] that the pull-out strengths increase with increased compressive strength and that this correlation is better than the correlation between rebound hammer and compressive strength measurements.

Gaynor of the National Ready Mix Concrete Association is currently comparing the pull-out strengths of mature concretes with rebound values and probe depths.

1/ These results of Richards are based on his private records.

2.3.3 Advantages and Limitations

The major advantage of the pull-out technique is that it is the only nondestructive method which directly measured the in situ strength of concrete without the necessity of removing specimens (the measure strength is a combination of tensile and shear strengths). In the limited amount of tests which have been performed, acceptable correlations between the pull-out strengths and the compressive strengths of concrete were obtained.

The equipment is simple to assemble and to operate, inexpensive, and the testing can be accomplished in a few minutes.

The major disadvantage of the pull-out tests is that a cone of concrete is usually pulled out, necessitating minor repairs. However, if the pull-out force sufficient to initiate failure is reached and then quickly relaxed, the pull-out assembly and concrete cone will not be torn loose, and no repairs are required.

The pull-out tests do not measure the interior strength of mass concrete as the pull-out assembly only extends to about 2 to 3 inches (.051 to .076 m) into the concrete.

2.3.4 Research Required

Considerable research is necessary before the pull-out test methods will gain wide acceptance (this acceptance will probably be quickened by the issuance of specifications by the ASTM in the near future). The studies which must be performed to establish the pull-out measurements as criteria for form removal include the following:

(1) Study of the relationships of pull-out strengths versus age for hardening concretes. Also more measurements are necessary to statistically evaluate the realiability of the method.

(2) Determination of whether the ratio of pull-out strength to compressive strength is affected by the composition of the concrete, i.e. water to cement ratio, and the types, size gradation and amounts of aggregates, etc.

(3) The effect of the geometrical design of the pull-out apparatus and the positioning of the pull-out apparatus in the concrete on the reproducibility of the pull-out strengths should be determined.

2.3.5 Concluding Remarks

The pull-out method could possibly become the most reliable nondestructive test method of the future and could form a basis for the determination of when formwork could be safely removed. Further studies, as previously described, are necessary before the potential of this method can be reasonably evaluated.

2.4 Push-Out Cylinders

A push-out cylinder (6 x 12 inches (.15 x .30 m)) is prepared in a cylindrical plastic mold (figure 8) which is housed in a metal sleeve, placed on a horizontal slab form. Concrete is manually placed in the mold at the same time concrete is being placed in the slab, and is finished and cured in the same manner as the bulk concrete. At the desired time, the push-out cylinder is removed and its compressive strength is measured in the laboratory. Therefore, the push-out cylinder is not an in situ test method but is an alternate method to drilling cores or to the standard cylinder test. The push-out cylinder method is included in this report because by this method the in situ strength of concrete can be easily estimated.

2.4.1 Review of Push-Out Cylinder Studies

The compressive strengths of pairs of slabs from three concretes were measured by Bloem [49] using cores and push-out cylinders; he also compared these results with the compressive strengths of field-cured 6 x 12 inch (.015 x .030 m) cylinders. The coefficient of variation of the compressive strengths of 216 push-out cylinder specimens was 3.9

percent compared with 6.0 percent for an equal number of core specimens; the coefficient of variation for the field cured specimens was 2.4 percent. The compressive strengths determined with the push-out cylinders were about 7 percent higher than those strengths obtained with cores. Bloem concluded "that push out cylinders cast in the slabs provided a fairly reliable measure, relatively, of core strengths." He also stated the "field-cured cylinders may provide useful information but do not quantitatively reflect core strength."

Richards[2/] has also found that the pull-out cylinder method gives an accurate estimation of the in situ compressive strength of concretes.

2.4.2 Advantages and Limitations

The push-out cylinder method yields a closer determination of the in situ compressive strength of concrete than field cured or laboratory cured specimens, and test specimens can be more easily obtained than by drilling cores. This could be a reliable method to determine when the formwork can be safely removed.

To obtain accurate determinations of the compressive strengths of the push-out cylinders, they will usually be tested in a laboratory. Therefore, verification of safe times to remove forms will not be immediately available. Furthermore, concrete is manually placed in the push-out cylinder and therefore, these specimens may not be consolidated to the same extent as the bulk concrete, which can result in a slight difference in compressive strengths. The push-out cylinder method is probably only applicable to testing horizontally laid concrete slabs. Removal of the push-out cylinders will leave relatively large cavities which must be filled.

2.4.3 Research Required and Concluding Remarks

The push-out cylinder methods appears to be a viable alternate to drilling cores or to field cured specimens for estimating the in-situ compressive strength; therefore, little research is needed. The push-out cylinder method should be included in a test program and the compressive strengths obtained could be used as the reference values.

2.5 Ultrasonic Pulse Velocity Method

Several types of nondestructive test methods have been developed based on wave propagation principles (often collectively termed sonic test [12]) such as the measurement of resonant frequencies [50-52], acoustic pulse velocities [53], seismic velocities [54], and ultrasonic pulse velocities [11, 12, 55, 56]. The ultrasonic pulse velocity is by far the most widely accepted vibrational method for field use and is one of the most universally used nondestructive test methods for assessing the quality of concrete. Only this method will be discussed in detail.

2.5.1 Principle of the Ultrasonic Pulse Velocity Method

The ultrasonic pulse velocity method is based on measuring the travel time of an ultrasonic pulse passing through concrete. The pulse is generated by an electro-acoustic transducer and picked up by a transducer and amplified before being presented on a cathode ray oscilloscope for analysis. The time of travel of the pulse is measured electronically. The basic theory of the ultrasonic pulse velocity method is discussed in references 11-13 and 57. The velocity of the ultrasonic pulse propagating through concrete is dependent on the density, elastic modulus, and Poisson's ratio of the concrete as well as the geometry of the tested specimen [12].

2/ These results of Richards are based on his private records.

At least three ultrasonic pulse velocity units are commercially available [13] including the Ultrasonic Concrete Tester, the Soniscope and PUNDIT. The Ultrasonic Concrete Tester has a testing range of only 7 feet (2.1 m), whereas both the Soniscope and PUNDIT can be used to test concrete having a thickness up to about 75 feet (22.7 m). Their respective operating frequencies are 150 kHz, 20 kHz, and 50 kHz.

2.5.2 Estimation of Strength of Concrete

Numerous investigators have attempted to correlate compressive and flexural strengths of concrete with pulse velocity. Jones [11] has suggested that reasonably good correlation (statistical data were not given) can be obtained between cube compressive strength and pulse velocity, provided the aggregates and mix proportions are kept constant. The effect of the type of aggregate and aggregate to cement ratio on the relationship between pulse velocity and compressive strength is illustrated by figures 9 and 10 (from references 11 and 13). Jones and Gaffield [59] have also found that the relationships between flexural strengths and pulse velocities are dependent on the aggregate:cement ratio, as indicated in figure 11. According to Jones [11], some researchers have established relations between pulse-velocity and compressive strength. These relations enable the strength of structural concrete to be predicted to within 20 percent. However, to obtain this accuracy, corrections must be made for the type of cement, mix-proportions and curing conditions. (These studies were performed under optimum laboratory conditions and, probably, under normal field conditions much higher variations in strength predictions could be anticipated). Kaplan [59] also found that the relationships between the pulse velocity and the flexural or compressive strengths are influenced by the type of aggregate and the mix proportions, as well as the degree of consolidation [60].

Whitehurst [61] performed tests on a series of 180 prisms prepared from four portland cements, one type of aggregate, with three different water to cement ratios and three types of curing. He found that no usable correlation between either compressive or flexural strength and pulse velocity could be established. Parker [62] made a comparison of pulse velocities and compressive strengths on standard cylinders made from only one type of aggregate but containing cement from several sources and a variety of admixtures. His analysis of the total data indicated that at the 95 percent confidence level the estimated compressive strength of 4440 psi (30.7 MN/m^2) concrete ranged from about 2100 to 6000 psi (14.5 to 41.8 MN/m^2).

2.5.3 Determination of Formwork Removal Times

Similar to strength, the velocity of pulses passing through concrete increases with age. At early ages the curve relating pulse velocity with age has a sharp ascent, but after about seven days it reaches a plateau. Malhotra [63] briefly studied the relationship between compressive strength of concrete at early ages and ultrasonic pulse velocity, and suggested that possibly the ultrasonic pulse velocity method could be used to determine formwork removal times. Kaplan [64], however, found that the ratio of pulse velocity to compressive strength changes with age, with the greatest change taking place within the first week. Furthermore, Rushing and Burt [65] found little correlation between the pulse velocity and the compressive strength of 7-day old concrete. Therefore, this author feels that the ultrasonic pulse velocity method cannot be used with confidence to determine form removal times.

2.5.4 Advantages and Limitations

Ultrasonic pulse velocity methods are excellent for determining the uniformity of concrete and are a definite asset in quality control. The testing procedures have been standardized by ASTM [66] and several types of test apparatus are commercially available.

A large number of variables affect the relationships between the strength of concrete and its pulse velocity. Some of these variables have been identified in Sections 2.5.2 and 2.5.3, other important factors having an affect are [63]:

(1) Smoothness of the concrete surface at contact point

(2) Path length

(3) Moisture condition of concrete

(4) Temperature of concrete

(5) Presence of reinforcing steel.

Therefore, the use of ultrasonic pulse velocity or any dynamic method to predict the compressive or flexural strengths of concrete is not recommended.

2.5.5 Research Required

The ultrasonic pulse velocity should only be considered in combination with another nondestructive test method (see Sections 3 and 4).

2.5.6 Concluding Remarks

Probably the best concluding remarks regarding strength prediction from the complete variety of wave propagation methods are those stated by Jones [67]:

> "In spite of some of the promising results of the early investigations, it must be concluded that no general relation has been found between the dynamic modulus of elasticity and its flexural or compressive strength". (This statement still holds if one substitutes "pulse velocity" for "dynamic modulus of elasticity".)

Several investigators have advocated [63, 68-70] the use of the ultrasonic pulse velocity method as a standard test in its own right. This author agrees with the opinion expressed by Whitehurst [71]:

> "In conclusion, it may be stated that none of the several sonic test available to the investigator is in any way a substitute for other tests normally performed on concrete....They constitute no cure-all for the problems of the concrete testing engineer, but do constitute a valuable addition to the techniques available to him."

This certainly applies to the determination of formwork removal times.

2.6 Predictions of Strength Development by Maturity and Equivalent Age

Several investigators [72-75] have suggested that the compressive strength of a concrete can be related to its maturity, where maturity is defined by

$$\Sigma(\theta + 10°)\ \Delta t \qquad (1)$$

where θ is the instantaneous temperature in °C of the concrete and Δt is the time increment at this temperature.

An important postulate of this theory is that samples of the same concrete will have equal compressive strengths if their maturities are the same, regardless of their temperature histories. Sadgrove [76, 77] has measured the compressive strengths of a concrete cured at ages between 5 hours to 28 days, at constant temperatures in the range of 1° to 45°C. He observed that a good relationship was obtained for the more mature concrete (more than 3 days old), however, there was considerable scatter at low maturities. The results are illustrated in figure 12, where compressive strength is plotted versus maturity equivalent. (The maturity equivalent is the maturity divided by 30°C and expressed as days at 20°C). To reduce this scatter an empirical factor F, related to temperature, was developed by which the actual age at a specific temperature is expressed in terms of age at 20°C. The F factor is calculated by the equation

$$F = \frac{(\theta + 16°C)^2}{36} \qquad (2)$$

where θ is the instantaneous temperature, with the constraint that θ cannot be less than -10°C.

The summation of the product of the F factor and the increments of time associated with each F factor, i.e.

$$\Sigma (F \cdot \Delta T) \qquad (3)$$

is termed the equivalent age and is expressed in days at 20°C. Replotting the values of compressive strength of figure 12 versus equivalent age, figure 13, gave better agreement at early ages. Sadgrove suggested that compressive strengths of concretes less than 3 days equivalent age should be predicted on the basis of equivalent age, while the strength of older concretes should be estimated using the maturity equivalent.

2.6.1 Prediction of Formwork Removal Times

Weaver [78] has developed a method of predicting the temperature history of a hydrating concrete element that considers biaxial heat flow, and constant ambient temperature. Based on this method, he has also developed a computer program which predicts the temperature of a hydrating concrete element at given time intervals. The equivalent age increment of each time interval is calculated and the total equivalent age determined. This theoretical value is then compared with the experimental equivalent age required for a given concrete to reach specific compressive strengths. When the equivalent age required for the concrete to reach a specific compressive strength is experimentally determined, the actual age is tabulated and a series of form removal times (striking times) are tabulated [79].

In addition to the data required for the temperature prediction, data for the concrete design strength and the desired strength levels, for which times are to be predicted, must be inputed into the computer program. A series of striking times prepared by Weaver and Sadgrove [6, 8] are given in table 1 for strength D, the level at which no damage to concrete would occur by frost, and for strengths corresponding to 33 percent and 66 percent of the design strength specified in the British Code of Practices [80]. At present, a version of the striking time tables conforming to acceptable practices in the United States is being prepared by Weaver and Sadgrove.

2.6.2 Advantages and Limitations

Based on the maturity equivalent and equivalent age methods, the time for hardening concretes to reach specified compressive strengths can be estimated. If strength criteria for form removal are developed, these methods should be useful in determining when the formwork can be safely removed. These methods do not cause any damage to the concrete specimen and require little on-site preparation.

The use of the maturity equivalent and the equivalent age methods necessitates that both the properties of the concretes and the placing conditions, which affect heat flow, be well characterized; the potential compressive strength of the concrete at the standard age must also be known. Highly trained personnel and computer programming are necessary to prepare those tables of form removal times.

2.6.3 Research Required

Before the maturity equivalent and equivalent age methods may be widely used in the United States for determining safe form removal times, extensive evaluations need to be performed and tables developed which consider:

(1) wide range of ambient temperatures

(2) range of concrete designs including type of cement, type of and graduation of aggregate, and water to cement ratio

(3) different types of concrete; insulating, lightweight, dense, etc.

The statistical reliability of the maturity equivalent and the equivalent age methods has not been ascertained and needs to be investigated before these, methods may be incorporated into standards and codes. Possibly, the maturity equivalent and equivalent age

Table 1 (from reference 77)

STRIKING TIMES IN HOURS AFTER PLACING—Ordinary Portland Cement

SECTION 500 * 300

PLACING TEMP 10°C

CEMENT CONTENT		330 kg/m³			380 kg/m³			380 kg/m³			450 kg/m³			450 kg/m³			490 kg/m³		
CHARACTERISTIC STRENGTH		22.5 N/mm²			22.5 N/mm²			30.0 N/mm²			30.0 N/mm²			37.5 N/mm²			37.5 N/mm²		
G	θA	D	33%	66%	D	33%	66%	D	33%	66%	D	33%	66%	D	33%	66%	D	33%	66%
	−5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	0	155	245	–	150	240	–	115	240	–	110	240	-	85	200	–	85	200	–
18.9	5	88	140	476	88	140	472	64	140	452	64	140	452	52	116	432	48	116	432
	10	60	93	309	57	93	309	42	93	297	42	90	294	33	75	282	33	75	282
	15	42	66	219	42	63	219	30	63	210	30	63	207	24	54	198	21	51	198
	−5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	0	140	230	–	135	225	–	100	225	–	95	220	–	70	180	–	70	180	–
10.0	5	80	132	464	80	128	460	56	128	440	52	124	436	40	104	416	40	100	416
	10	54	87	303	51	84	300	36	84	285	36	81	282	27	66	270	27	63	270
	15	39	60	213	36	60	210	27	60	201	27	57	198	21	45	189	21	45	189
	−5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	0	120	208	–	116	204	–	80	204	–	72	196	–	52	156	–	52	152	–
6.5	5	69	120	447	66	114	441	48	114	420	42	108	414	33	87	396	33	84	390
	10	48	78	292	44	74	286	34	74	274	30	68	266	24	56	256	24	52	252
	15	36	56	206	34	52	202	26	52	192	24	48	186	20	40	178	20	38	176
	−5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	0	105	192	–	99	183	–	66	183	–	57	171	–	42	132	663	39	126	654
5.0	5	62	110	434	58	104	426	42	104	406	38	94	394	30	74	376	28	68	370
	10	44	72	282	41	67	276	32	67	262	29	60	253	24	49	242	23	45	236
	15	35	53	199	32	49	194	26	49	184	24	44	176	20	37	168	19	34	164
	−5	•	•	•	•	•	•	•	•	•	•	•	•	52	220	–	48	200	–
	0	81	156		72	144	–	51	144	657	42	123	633	33	90	600	33	81	585
3.4	5	52	90	404	48	82	392	36	82	370	32	70	352	28	56	334	26	50	322
	10	40	62	261	37	57	250	30	57	237	27	49	222	23	41	211	22	38	201
	15	33	48	183	31	44	174	25	44	165	23	39	152	20	34	144	20	31	136
	−5	68	156	–	56	116	–	40	116	–	36	76	–	32	60	–	28	52	–
	0	48	81	570	42	69	525	36	69	489	30	54	420	27	45	393	24	42	345
2.0	5	40	60	316	36	52	286	30	52	266	28	44	218	24	38	202	22	36	170
	10	35	50	201	33	45	179	27	45	167	25	38	133	22	34	124	21	32	105
	15	32	43	142	29	39	125	25	39	118	23	34	95	21	31	90	20	29	78
	−5	48	76	–	40	64	–	32	64	–	28	48	576	24	44	512	24	40	356
	0	42	60	429	36	51	357	30	51	321	27	42	213	24	39	189	21	36	141
1.3	5	36	52	238	34	46	196	28	46	180	26	40	130	22	34	120	22	32	100
	10	34	47	163	31	42	138	26	42	129	24	36	101	21	32	95	20	30	83
	15	32	43	127	29	38	110	25	38	104	23	33	85	20	30	81	19	28	72

Key to column entries

G: Formwork conductance (W/m² degC)

θA: Ambient temperature (°C)

D: Resistant to damage

33%: 33% of characteristic strength reached

66%: 66% of characteristic strength reached methods can be used to predict other mechanical properties of concrete, such as flexural and shear strengths; this also should be investigated.

2.6.4 Concluding Remarks

The maturity equivalent and equivalent age are attractive methods for determining when forms may be removed. However, in both methods the concrete mix design must be known to calculate the strength as a function of age and the calculated strengths could be grossly different than the in-situ strengths if the mix design is changed, e.g. by the addition of more mix water. Therefore, the predicted in situ strength obtained from these methods should be verified by another nondestructive test such as the pull-out or the rebound hammer, methods.

3. COMBINATION OF NONDESTRUCTIVE TESTS

To predict the compressive strength of in situ concrete more accurately, two different nondestructive tests are performed consecutively. The most popular combination has been the ultrasonic pulse velocity method in conjunction with the rebound hammer [81]. Other common combinations are the ultrasonic pulse velocity method and the measurement of the damping constant of concrete [82], and the ultrasonic pulse velocity and pulse attenuation methods [83]. These latter two combinations are essentially laboratory research techniques and therefore will not be discussed further.

3.1 Combination of Ultrasonic Pulse Velocity and Rebound Hammer Methods

This combination of nondestructive tests has been used in Europe, primarily, with the most exhaustive studies being carried out by Facaoaru [84-87]. In this combined approach, ultrasonic pulse velocity measurements are made on in situ concrete, while the rebound number is measured with the Schmidt Rebound Hammer. The pulse velocity and rebound number are then combined to yield a linear regression equation with the independent variable being compressive strength [82]. It is believed that the regression equation should give a more accurate estimate of compressive strength than given by either of the individual measurements, i.e. pulse velocity or rebound number.

Facaoaru [84] has developed calibration charts for standard concrete mixes from which the compressive strengths can be estimated when the pulse velocities and rebound numbers are known. Correction factors have also been developed to be used in the case of nonstandard concrete mixes.

This combined method has been used often in Romania to estimate the compressive strength of in-situ concrete, with improved accuracy [84-86]. Based on his experiences, Facaoaru contends that by using the combined method, the following accuracy in predictions of compressive strengths can be realized:

(1) When composition is known and test specimens or cores are available for calibration purposes, accuracy is within 10 to 15 percent.

(2) When only the composition of the concrete is known, accuracy is within 15 to 20 percent.

(3) When neither the composition is known nor test specimens or cores are available, accuracy is within 20 to 30 percent.

This suggests that for case (3), the combined method gives no better prediction of the compressive strength than can be obtained by measuring only the ultrasonic pulse velocity or only the rebound number; in case (2), the improvement is marginal. Therefore, only when the concrete is well characterized is this combined method better than the individual nondestructive methods.

3.2 Concluding Remarks

The combined method, ultrasonic pulse velocity and rebound hammer, involves relatively simple techniques which can be used on in situ concrete. However, to gain any significant increase in accuracy, the composition of the concrete should be known and specimens for calibrating the respective methods should be available.

This review did not disclose any reported uses of combined nondestructive test methods to determine when formwork could be safely removed (research requirements are discussed in Section 4).

4. PROPOSED RESEARCH AND RECOMMENDATIONS

The individual nondestructive test methods (Section 2) do not appear to form an adequate basis for the accurate prediction of the in situ strength of either immature or mature concrete. (The push-out cylinder is not being regarded as an authentic nondestructive test. It is an alternative to cores, and can provide an effective calibration method for nondestructive test methods.) Therefore, it is recommended that formwork removal times should not be based upon the results of individual nondestructive test methods. Furthermore, it is recommended that detailed strength requirements, with reasonable statistical tolerances, be developed upon which formwork removal times can be based.

This author believes that a combined nondestructive test approach (as discussed in Section 3) has promise and should be investigated further. The proposed combinations are listed in table 2, in order of decreasing importance. The priority sequence is based on comparing the important properties of concrete predicted by the individual tests. For example both the maturity concept (or equivalent age concept) and the pull-out method give predictions of strength properties of concrete and the combination of these methods should give a better prediction of the compressive strength of concrete than the individual methods. The results of the two methods can be combined in a linear regression equation of the form:

$$\alpha_c = A\alpha_p + BP + C \qquad (4)$$

where α_c is the estimated compressive strength from the combined methods α_p is the compressive strength estimated by the maturity concept (or equivalent age concept), P is the pull-out strength; and A,B and C are empirically determined constants.

Neither the ultrasonic pulse velocity nor the rebound hammer give a direct prediction of the strength properties of concrete. Therefore, the combination of these methods can not be expected to give a significantly better prediction of the compressive strength than the individual methods. Furthermore, using the probe as the interacting method will probably not improve the accuracy of the combined method. The push out cylinder method should be used as the reference method and also for calibration purposes.

The proposed research project should accomplish the following tasks:

(1) Determine the accuracy of the combined methods in predicting the compressive strength of hardening concretes, especially at common formwork removal times.

(2) Determine whether the combined methods are more accurate than the individual methods.

(3) Determine the effects of variation in concrete composition, concrete consolidation, ambient temperature, the formwork itself, and the other variables noted in Section 2, on the accuracy of the individual and also the combined methods.

(4) Develop criteria upon which formwork removal times can be based. Possibly, the results of the combined nondestructive test method could constitute the criteria for basing formwork removal times.

(5) Investigate the possibilities of predicting mechanical properties besides compressive strengths by the individual and combined nondestructive test methods. For example, the flexural and shear strengths of a concrete at the time of formwork removal may be more important than its compressive strength.

5. SUMMARY AND CONCLUSIONS

Individual and combined nondestructive test methods have been critically reviewed as potential methods for determining formwork removal times. It has been recommended that future research emphasize combined methods. The most universally used combined method, ultrasonic pulse velocity and rebound number measurements, does not give an adequate estimation of the in-situ strength of concrete; other combinations have been proposed which should give improved estimates.

Regardless of the nondestructive test method chosen to determine formwork removal times (or to estimate the in situ strength of concrete, at any age), the effectiveness of a method depends directly on how much is known about the tested concrete.

TABLE 2. Combined Nondestructive Test Methods

Basic Method[1/]	Important Properties of Concrete Predicted	Interacting Methods	Important Properties of Concrete Predicted	Priority[2/]
1. Maturity concept and equivalent age	Compressive strength	Pull-out Probe Rebound hammer Ultrasonic pulse velocity	Tensile & shear strengths Surface hardness Surface hardness Density and elastic modulus	1
2. Pull-out	Tensile and shear strengths	Rebound hammer Probe Ultrasonic pulse velocity	Surface hardness Surface hardness Density and elastic modulus	2
3. Ultrasonic Pulse velocity	Density and elastic modulus	Rebound hammer Probe	Surface hardness Surface hardness	3

1/ Reference method, push out cylinders.

2/ Priority sequence: 1>2>3

6. REFERENCES

1. J. Feld, "Construction Problems: Formwork Failures", Chapter 5, pp. 95-114, 15 Lessons from Failures of Concrete Structures, ACI Monograph No. 1, 1964; and the reference therein.

2. E. V. Leyendecker and S. G. Fattal, "Investigation of the Skyline Collapse in Fairfax County, Virginia", NBSIR 73-222, June 1973.

3. Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, London, 1969.

4. RILEM International Symposium on Nondestructive Testing of Materials and Structures, Paris, 1954.

5. Nondestructive Testing of Concrete, HRB Record No. 378, 1972.

6. New Developments in Nondestructive Testing of Nonmetallic Materials, RILEM IInd International Symposium, Romania, 1974.

7. S. Li and J. E. Russell, "The State-of-the-Art of Nondestructive Evaluation in Concrete Technology", 7th Symposium on Nondestructive Evaluation of Components and Materials in Aerospace Weapons Systems and Nuclear Applications, Proceedings of American Society for Nondestructive Testing, South Texas Section, 1969.

8. S. T. Li, V. Ram Akrishman and J. E. Russell, "Where Standards Nondestructive Testing of Concrete and Whither?" Int. J. of Nondestructive Testing, 2, 281 (1970).

9. V. M. Malhotra, "Nondestructive Methods for Testing Concrete", Mines Branch Monograph 815, Ottawa, 1968.

10. R. Jones, "A Review of the Nondestructive Testing of Concrete, Paper 1A, Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, London, 1969.

11. R. Jones, "Nondestructive Testing of Concrete", Cambridge University Press, 1962.

12. E. A. Whitehurst, "Evaluation of Concrete Properties from Sonic Tests", ACI Monograph No. 2, 1966.

13. V. M. Malhotra, "Nondestructive Methods for Testing Concrete, ACI Monograph, in press.

14. A. Voellmy, "Examination of Concrete by Measurement of Superficial Hardness", RILEM International Symposium on Nondestructive Testing of Materials and Structures, Paris, France, Volume 2, pp. 323-336, 1954.

15. T. R. Cantor, "Status Report on The Windsor Probe Test System", presented to Highway Research Board Committee A2-03, at 1970 Annual Meeting of Highway Research Board, Washington, D.C., Januar 1970.

16. S. Freedman, "Field Testing of Concrete Strength", Modern Concrete 14 (2), 31 (1969).

17. S. M. Law and W. T. Burt, "Concrete Probe Strength Study", Louisiana Department of Highways Research Report 44, 1969.

18. R. D. Gaynor, "In-Place Strength of Concrete - A Comparison of Two Test Systems", National Ready-Mix Concrete Association Technical Information Letter No. 272, 1969.

19. H. T. Arni, "Impact and Penetration Tests of Portland Cement Concrete", Federal Highway Administration Report No. FHWA-RD-73-5, 1972.

20. H. T. Arni, "Impact and Penetration Tests of Portland Cement Concrete", in Nondestructive Testing of Concrete, HRB Record 378, pp. 55-67, 1972.

21. V. M. Malhotra and K. Painter, "Evaluation of the Windsor Probe Test for Estimating Compressive Strength of Concrete", Mines Branch Investigation Report IR 71-50, Ottawa, Canada, 1971.

22. J. R. Keeton and V. Hernandez, "Calibration of Windsor Probe Test System for Evaluation of Concrete in Naval Structures", Technical Note N-1233, Naval Civil Engineering Laboratory, Port Hueneme, California, 1972.

23. A. T. Shore, "Properties of Hardness in Metals and Materials", Proceedings ASTM, XI, 733 (1911).

24. E. Schmidt, "Der Beton-Prufhammer", Schweiz Bauzeitung, July 15, 1960.

25. E. Schmidt, "Versuche mit dem neuen Beton-Prufhammer zur Qualitasbestimmung des Betons", Schweitzer Archiv fur Angewandete Wissenschaftund technik, Drub and Verland, No. 5, (1951).

26. E. Schmidt, "A Nondestructive Concrete Test", Concrete 59 (8), 34 (1951).

27. L. Brunarski, "Draft Instructions on the Application of Selerometric, Ultrasonic and Resonance Methods", Bulletin RILEM No. 27, 121 (1965).

28. I. Facaoaru, "L' experiende del l'application des normes roumaines provisoires pour la determination de la resitance du beton a l'aide du Solerometre Schmidt", Bulletin RILEM No. 27, 121 (1965).

29. British Standards Institution, "Recommendations for Nondestructive Methods of Test for Concrete", Part 4. Surface Hardness Methods, BS 4408: Part 4; 1971.

30. P. H. Petersen and U. W. Stoll, "Relation of Rebound-Hammer Test Results to Sonic Modulus and Compressive-Strength Data", Proceedings HRB, 34, 387 (1955).

31. Discussion of Reference 30, by P. Klieger, Proceedings HRB, 34, 392 (1955).

32. C. A. P. Boundy and G. Hondros, "Rapid Field Assessment of Strength of Concrete by Accelerated Curing and Schmidt Rebound Hammer", J. Am. Conc. Inst., 61, (1), 11 (1964): Discussion J. Am. Conc. Inst., 61 (9), 1185 (1964).

33. D. J. Victor, "Evaluation of Hardened Field Concrete with Rebound Hammer", Indian Conc. J., 37 (11), 407 (1963).

34. G. W. Greene, "Test Hammer Provides New Method of Evaluating Hardened Concrete", J. Am. Conc. Inst., 26 (3), 249 (1954).

35. Discussion of Reference 33, J. Am. Conc. Inst., 27 (4), 256 (1955).

36. L. J. Mitchel and G. G. Hagland, "Investigation of the Impact-Type Concrete Test Hammer", HRB Bulletin 305, 14 (1961).

37. C. H. Williams, "Investigation of the Schmidt Concrete Test Hammer", Miscellaneous Report No. 6-267, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1958.

38. G. A. Erickson, "Investigation of the Impact-Type Concrete Test Hammer, Model 11", Concrete Laboratory Report No. C-928, Division of Engineering Laboratories, Dept. of the Interior, Denver, 1959.

39. J. Kolek, "Nondestructive Testing of Concrete by Hardness Methods, Paper 3A, Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, London, 1969.

40. B. G. Skramtajew, "Determining Concrete Strength for Control of Concrete in Structures", J. Am. Conc. Inst., 34, 285 (1938).

41. T. Yoshida, "Studies on Concreting in Freezing Weather, Part 2", Department of Civil Engineering, Tokyo Imperial University, January 1942.

42. B. Tremper, "The Measurement of Concrete Strength by Embedded Pull Out Bars", proceedings of the annual meeting, ASTM, 880 (1944).

43. P. K. Hansen, "Method for Testing the Strength of the Material of Cast Structures, Particularly Concrete Structures", U. S. Patent No. 3,541,845 (1970).

44. M. Teeni, "Testing of Concrete", U. S. Patent No. 3,640,126 (1972).

45. F. Kaindl, "Method and Apparatus for Early Strength Testing of In-Place Concrete", U.S. Patent Application Serial No. 368 325, filed June 1973.

46. O. Richards, "Pull Out Strength Tests of Concrete", paper presented at the Research Session, 1972 Annual Meeting of ACI, Dallas, Texas.

47. V. M. Malhotra, "Evaluation of the Pull Out Test to Determine Strength of In-Situ Concrete", Mines Branch Investigation Report IR 72-56, Ottawa, 1972.

48. T. P. Tassios and C. A. Demiris, "Standard Nails Extraction, A New Method for Concrete's Strength Determination", Natural Technical University of Athens, Athens, Greece, 1970.

49. D. L. Bloem, "Concrete Strength in Structures", J. Am. Conc. Inst., 65 (3), 176 (1968).

50. T. C. Powers, "Measuring Young's Modulus of Elasticity by Means of Sonic Vibrations" ASTM 38 (Part II), 460 (1938).

51. F. B. Hornibrook, "Application of Sonic Method to Freezing and Thawing Studies of Concrete", ASTM Bulletin No. 101, 5 (1939).

52. Standard Method of Test for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens. ASTM Designation C215-60.

53. G. Swift and W. M. Moore, "Investigation of Applicability of Acoustic Pulse Velocity Measurements to Evaluation of Quality of Concrete in Bridge Decks" in Nondestructive Testing of Concrete, HRB Record 378, pp. 29-39, 1972.

54. W. E. Brownfield, "Nondestructive Testing of Concrete by Wave Velocity Methods: A Laboratory and Field Study", in Nondestructive Testing of Concrete, HRB Record 378, pp. 12-19, 1972.

55. W. J. Cheesman, "Dynamic Testing of Concrete with the Soniscope Apparatus", Proceedings HRB, 29, 176 (1949).

56. R. Jones, "The Effect of Frequency on the Dynamic Modulus and Damping Coefficient of Concrete", Mag. of Conc. Res., 9 (26), 69 (1957).

57. J. Anderson, P. Nerenst, and N. M. Plum, "The Nondestructive Testing of Concrete, with Special Reference to the Wave-Velocity Method", Building Research Report No. 3, The Danish National Institute of Building Research, Copenhagen, 1950.

58. R. Jones and E. N. Gatfield, "Testing Concrete by an Ultrasonic Pulse Technique", USIR Road Research Technical Paper No. 34, London.

59. M. F. Kaplan, "Ultrasonic Pulse Velocity, Dynamic Modulus of Elasticity, Poisson's Ratio and The Strength of Concrete Made with Thirteen Different Coarse Aggregates", RILEM Bulletin No. 1, 58 (1959).

60. M. F. Kaplan, "Effects of Incomplete Consolidation on Compressive and Flexural Strength, Ultrasonic Pulse Velocity, and Dynamic Modulus of Elasticity of Concrete," J. Am. Conc. Inst., 56 (3), 853 (1960).

61. E. A. Whitehurst, "Dynamic Testing of Concrete Evaluated", Civil Eng. 12, 863 (1951).

62. W. E. Parker, "Pulse Velocity Testing of Concrete", Proceedings ASTM, 53, 1033 (1953).

63. V. M. Malhotra, "Ultrasonic Pulse Velocity Method" in Nondestructive Methods for Testing Concrete, ACI SP, in press.

64. M. F. Kaplan, "The effects of age and water/cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete", Mag. of Conc. Res., 11 (32), 85 (1959).

65. H. B. Rushing and J. O. Burt, "Nondestructive Testing of Concrete", Research Report No. 51, Louisiana Department of Highways; NTIS PB-204.

66. Tentative Method of Test for Pulse Velocity Through Concrete, ASTM Designation C597-68T.

67. Page 33 of reference 11.

68. R. G. Drysdale, "Variation of Concrete Strength in Existing Buildings", Mag. of Conc. Res., 25 (85), 201 (1973).

69. N. J. Lowe, "What's Wrong with our Codes?" Symposium on Quality Control, Cement and Concrete Association, London, 1964.

70. A. R. Collins, "Methods of Specifying Concrete" Proceedings of the Symposium on Mix Design and Quality Control of Concrete, Cement and Concrete Association, London, pp. 488-502, 1954.

71. Page 82 of reference 12.

72. R. W. Nurse, "Steam Curing of Concrete", Mag. of Conc. Res., 1 (2) 79 (1949).

73. A. G. A. Saul, "Principles Underlying the Steam Curing of Concrete", Mag. of Conc. Res., 2 (6), 127 (1951).

74. S. G. Bergstrom, "Curing Temperature, Age and Strength of Concrete", Mag. of Conc. Res., 5 (14), 61 (1953).

75. J. M. Plowman, "Maturity and the Strength of Concrete", Mag. of Conc. Res., 8 (22), 13 (1956).

76. B. M. Sadgrove, "The Strength and Deflection of Reinforced Concrete Beams Loaded at Early Age", Construction, Industry Research and Information Association (London), Technical Note 31, 1971.

77. B. M. Sadgrove, "Prediction of Strength Development in Concrete Structures", presented at the 54th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1975.

78. J. Weaver, "Temperature development in hydrating concrete," Ph.D. Thesis, University of London, 1971.

79. J. Weaver and B. M. Sadgrove, "Striking times of formwork - tables of curing periods to achieve given strengths", Construction Industry Research and Information Association (London), Report 36, 1971.

80. Draft British Code of Practice for the Structural Use of Concrete, The Council for Codes of Practice, British Standards Institution, 1969.

81. R. Jones and I. Facaoaru, "Analysis of Answers to a Questionnaire on the Ultrasonic Pulse Technique", RILEM Materials and Structures, 1 (5), 457 (1968).

82. J. G. Wiebenga, "A Comparison between Various Combined Nondestructive Testing Methods to Derive the Compressive Strength of Concrete", Report No. B1-68-61/IHI.8, Institut TNO Voor Bouwmaterialen en Bouwconstructies, Delft, Netherlands, 1968.

83. A. Galan, "Estimate of Concrete Strength by Ultrasonic Pulse Velocity and Damping Constant", J. Am. Conc. Inst., 64 (10), 678 (1967).

84. I. Facaoaru, "Nondestructive testing of concrete in Romania", Paper 4C, Symposium on Nondestructive Testing of Concrete and Timber, Institution of Civil Engineers, London, 1969.

85. I. Facaoaru, I. Dumitrescu, and L. Constaninescu, "Concrete Strength Determination by Nondestructive Combined Methods" RILEM Report, Achen, 41 (1966).

86. I. Facaoaru, I. Dumitrescu, and Gh. Stamate, "New Developments and Experience in Applying Combined Nondestructive Methods for Testing Concrete", RILEM Report, Varna, 26 (1968).

87. I. Facaoaru, "Chairman's Report of the RILEM Committee on Nondestructive Testing of Concrete", RILEM, Materials and Structures 2 (10), 253 (1969).

7. FIGURE CAPTIONS

Figure 1. Windsor Probe in operation.

Figure 2. Shapes and sizes of probes used with the Windsor Probe.

Figure 3. Device to measure length of probe extending from the surface of tested concrete.

Figure 4. Plot of probe heights versus compressive strengths, with 95 percent confidence limits of the regression line (from reference 19).

Figure 5. Schmidt Rebound Hammer in operation.

Figure 6. Plot of rebound numbers versus compressive strengths, with 95 percent confidence limits of the regression line (from reference 19).

Figure 7. Schematic of pull-out tester embedded in concrete.

Figure 8. Schematic of push-out cylinder in place.

Figure 9. Effect of type of aggregate on relationship between ultrasonic pulse velocity and compressive strength (from reference 13).

Figure 10. Effect of cement:irregular-river aggregate ratio on relationship between ultrasonic pulse velocity and compressive strength (from reference 11).

Figure 11. Effect of type of aggregate and cement:sand:aggregate ratio on relationship between ultrasonic pulse velocity and flexural strength (from reference 11).

Figure 12. Plot of compressive strength versus maturity equivalent. Maturity is expressed as days at 20°C (from reference 77).

Figure 13. Plot of compressive strength versus equivalent age. Equivalent age is expressed as days at 20°C (from reference 77).

USCOMM-NBS-DC

Figure 1.

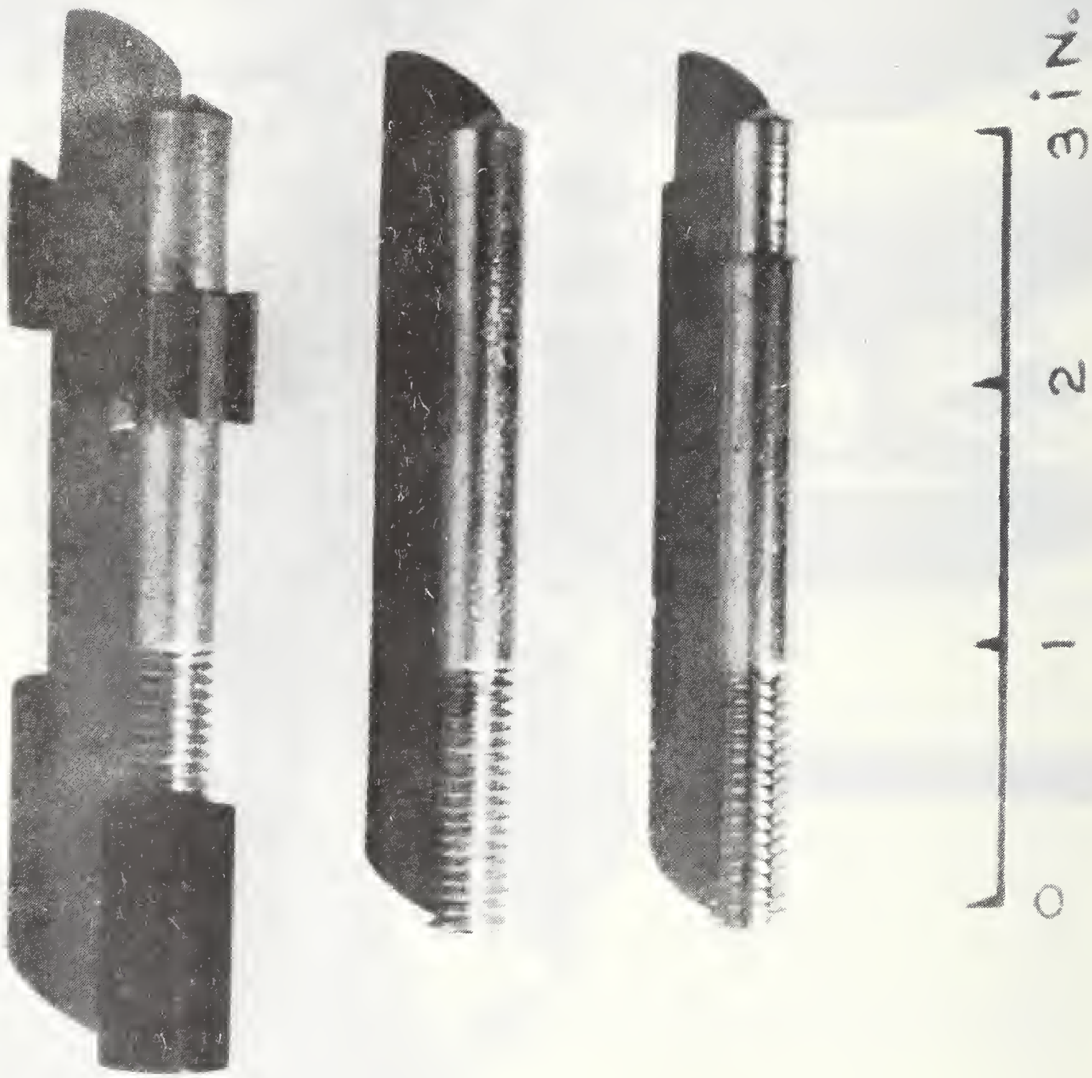


Figure 2.

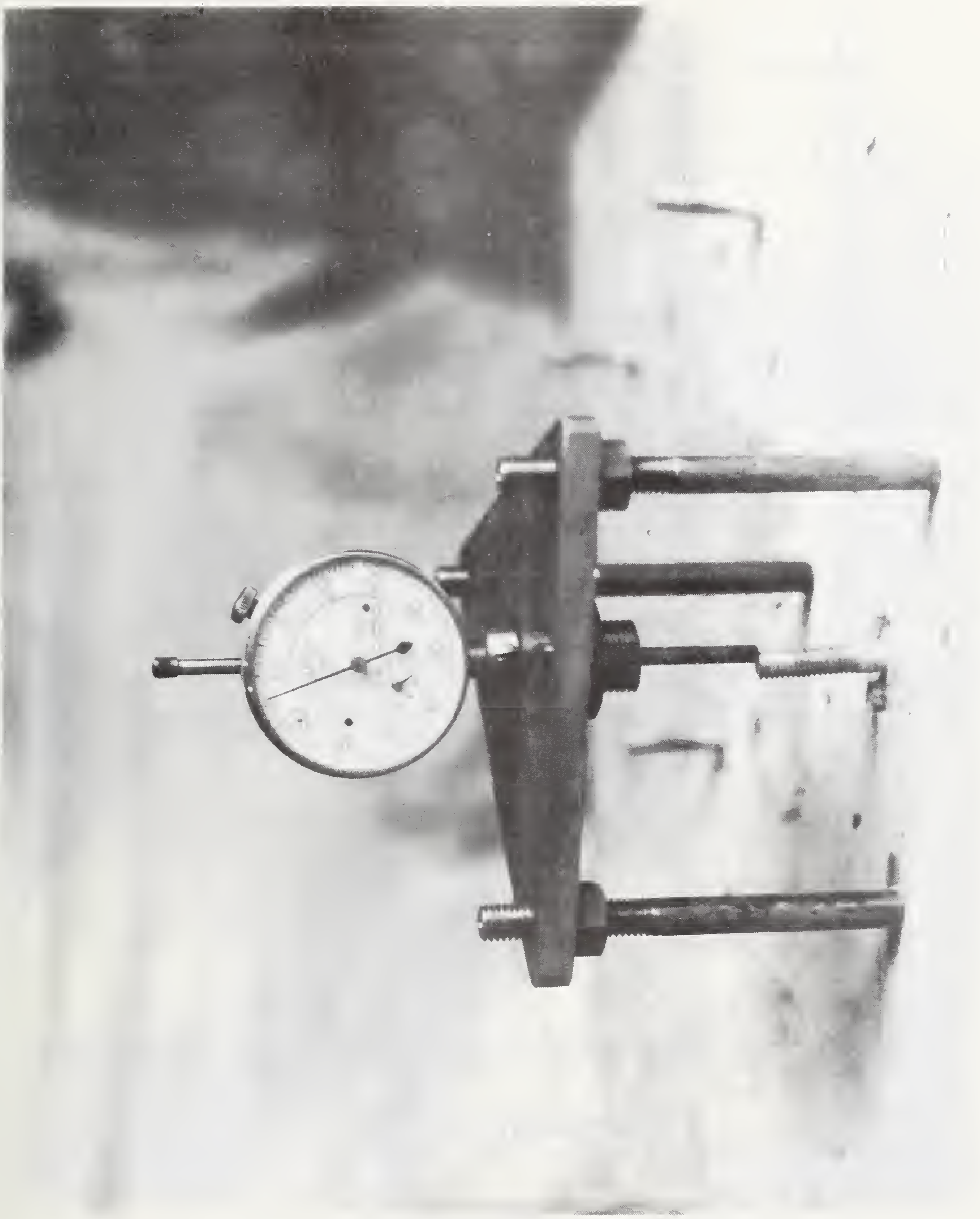
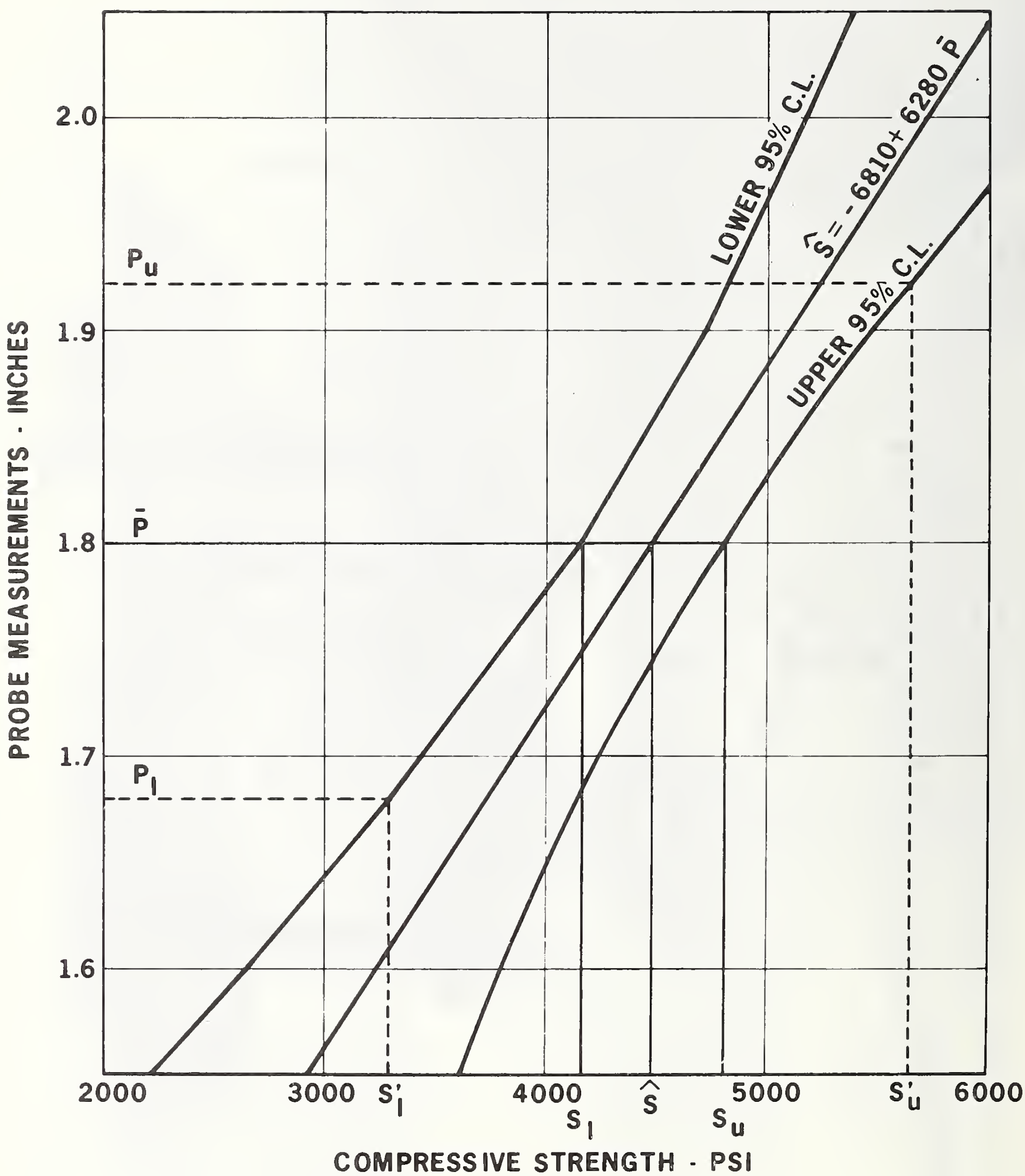


Figure 3.



PROBE MEASUREMENTS - INCHES
2.0
1.9
1.8
1.7
1.6
P u
P̄
P l
LOWER 95% C.L.
Ŝ = -6810+ 6280 P̄
UPPER 95% C.L.
2000
3000
S'l
4000
S l
Ŝ
5000
S u
S'u
6000
COMPRESSIVE STRENGTH - PSI

Figure 4.

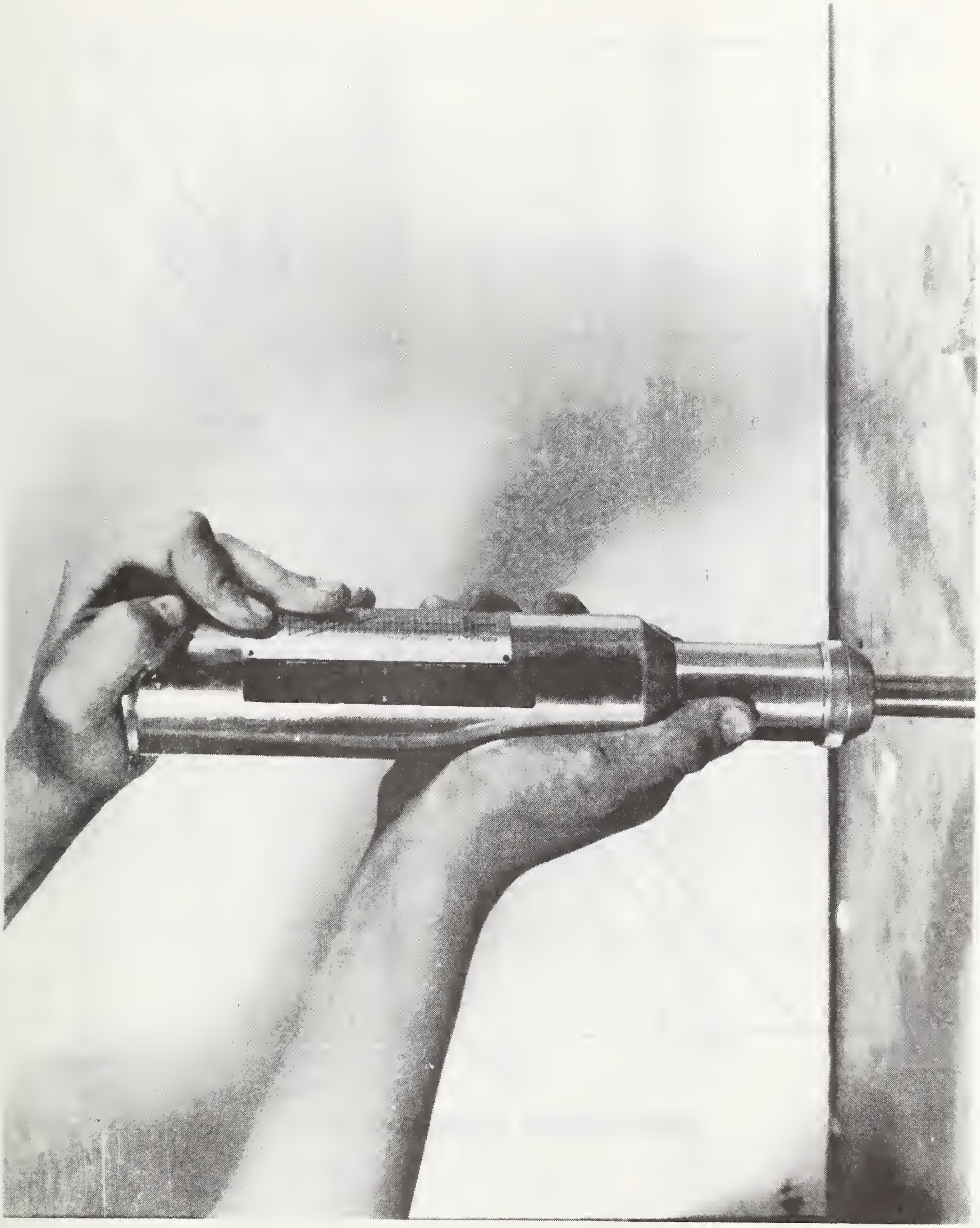


Figure 5.

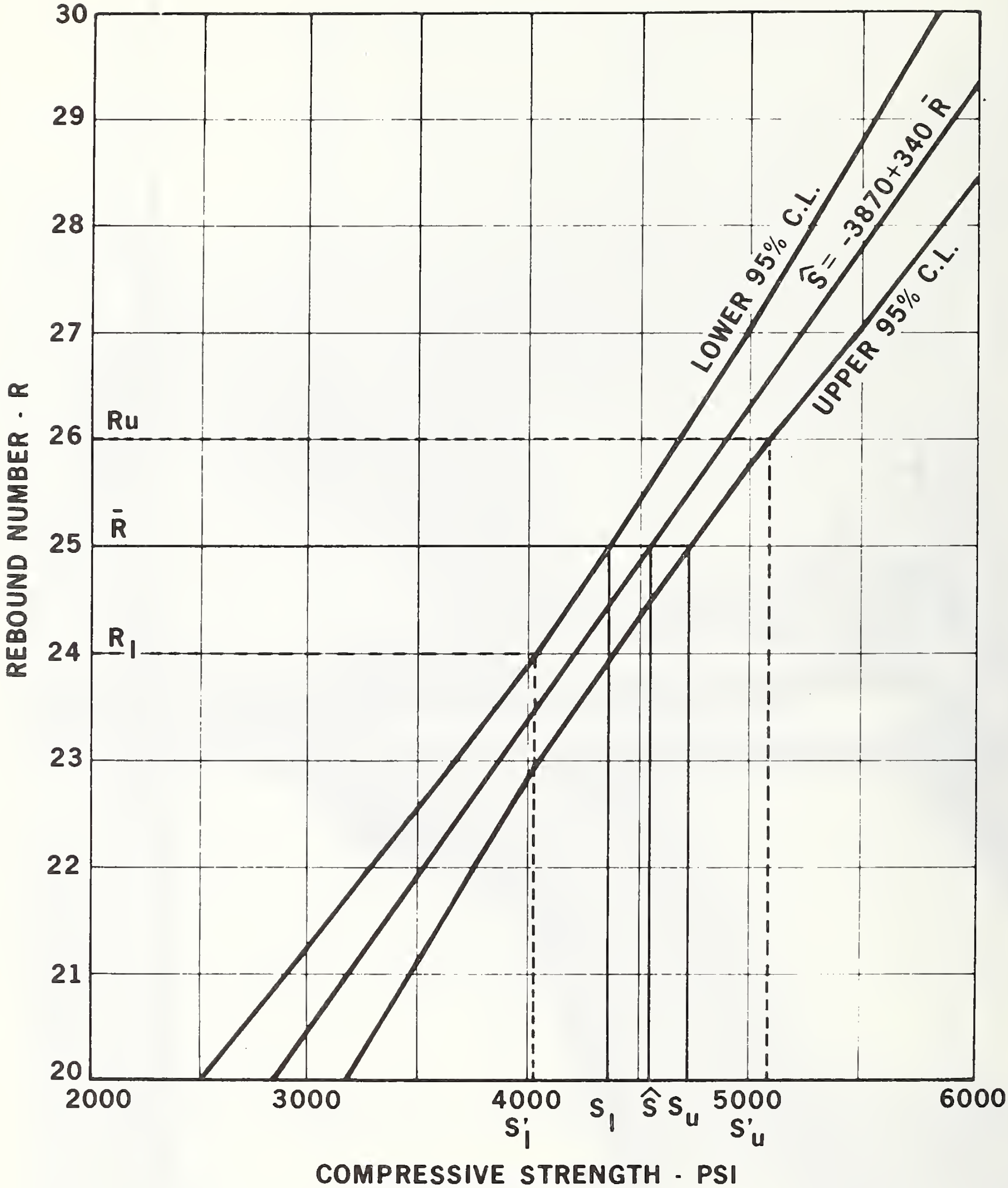

REBOUND NUMBER - R
30
29
28
27
26
25
24
23
22
21
20
Ru
$\bar{R}$
R_l
LOWER 95% C.L.
$\hat{S} = -3870 + 340\bar{R}$
UPPER 95% C.L.
2000
3000
4000
5000
6000
S'_l
S_l
$\hat{S}$
S_u
S'_u
COMPRESSIVE STRENGTH - PSI

Figure 6.

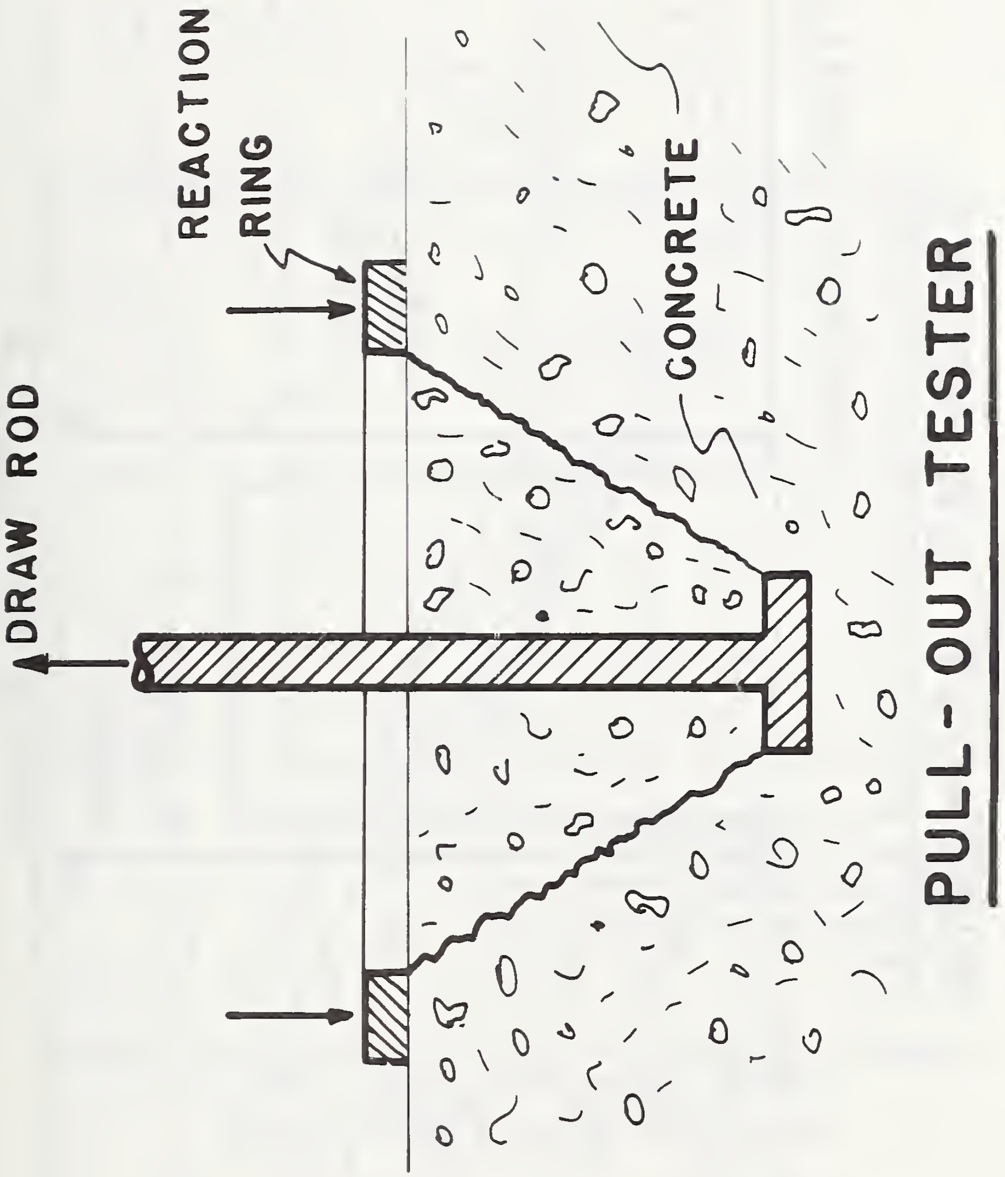


Figure 7.

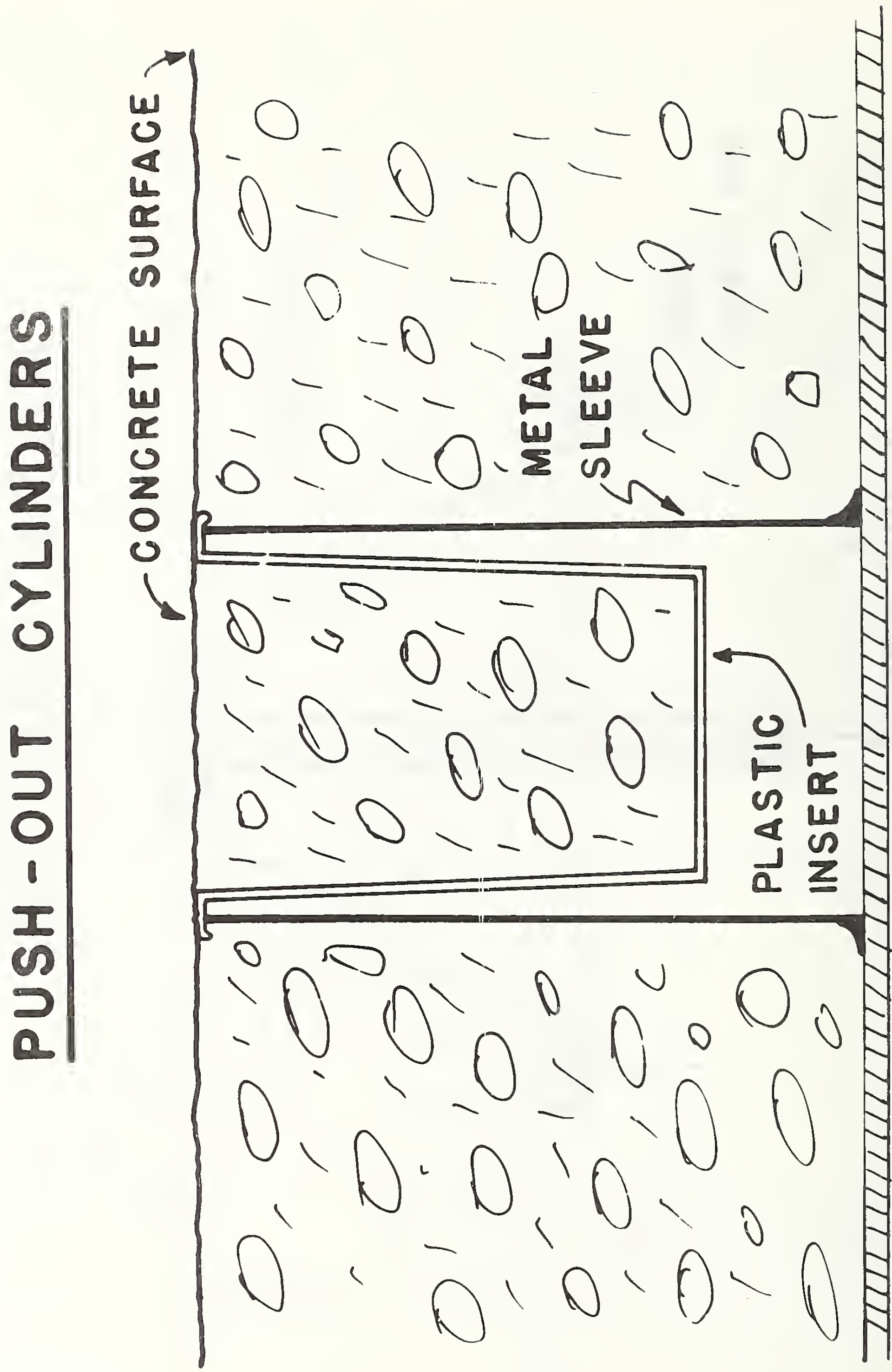

PUSH-OUT CYLINDERS
CONCRETE SURFACE
METAL SLEEVE
PLASTIC INSERT
FORM

Figure 8.

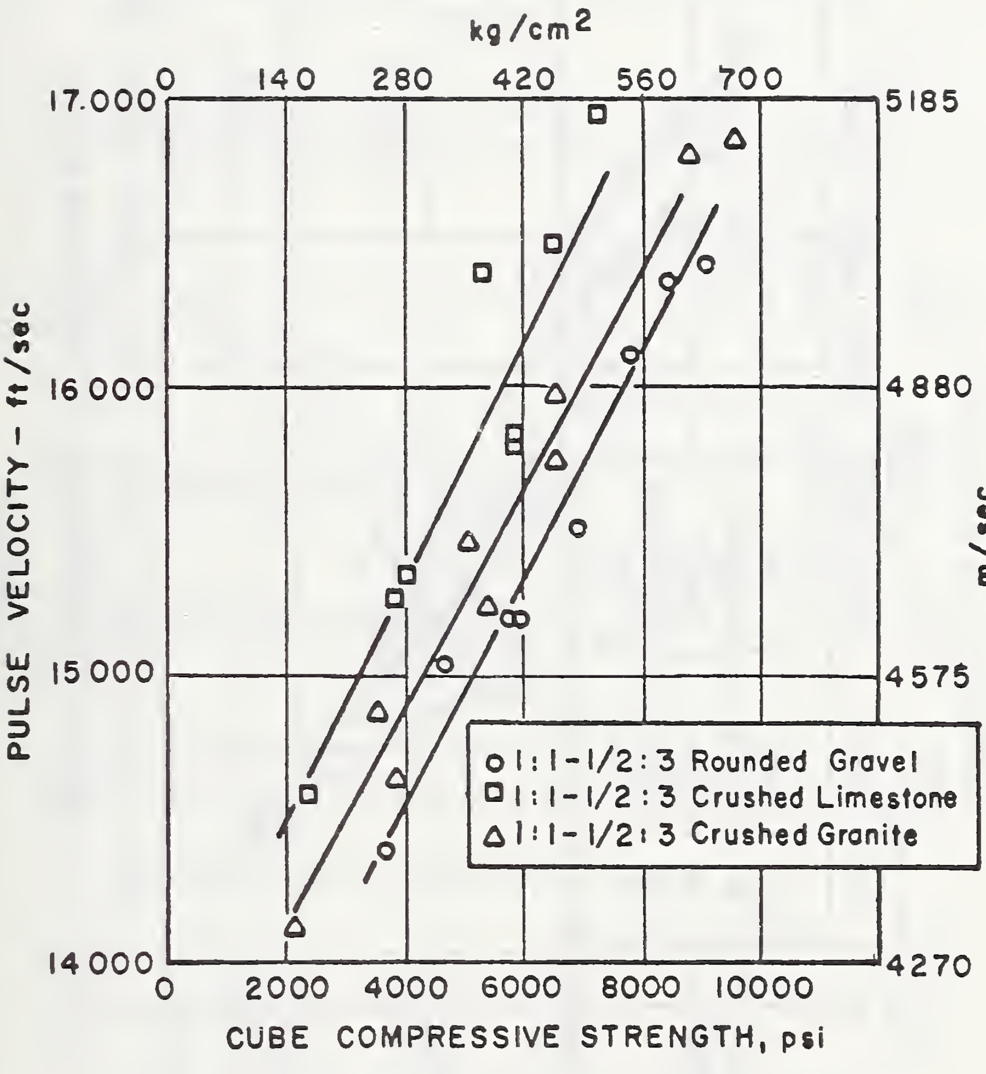
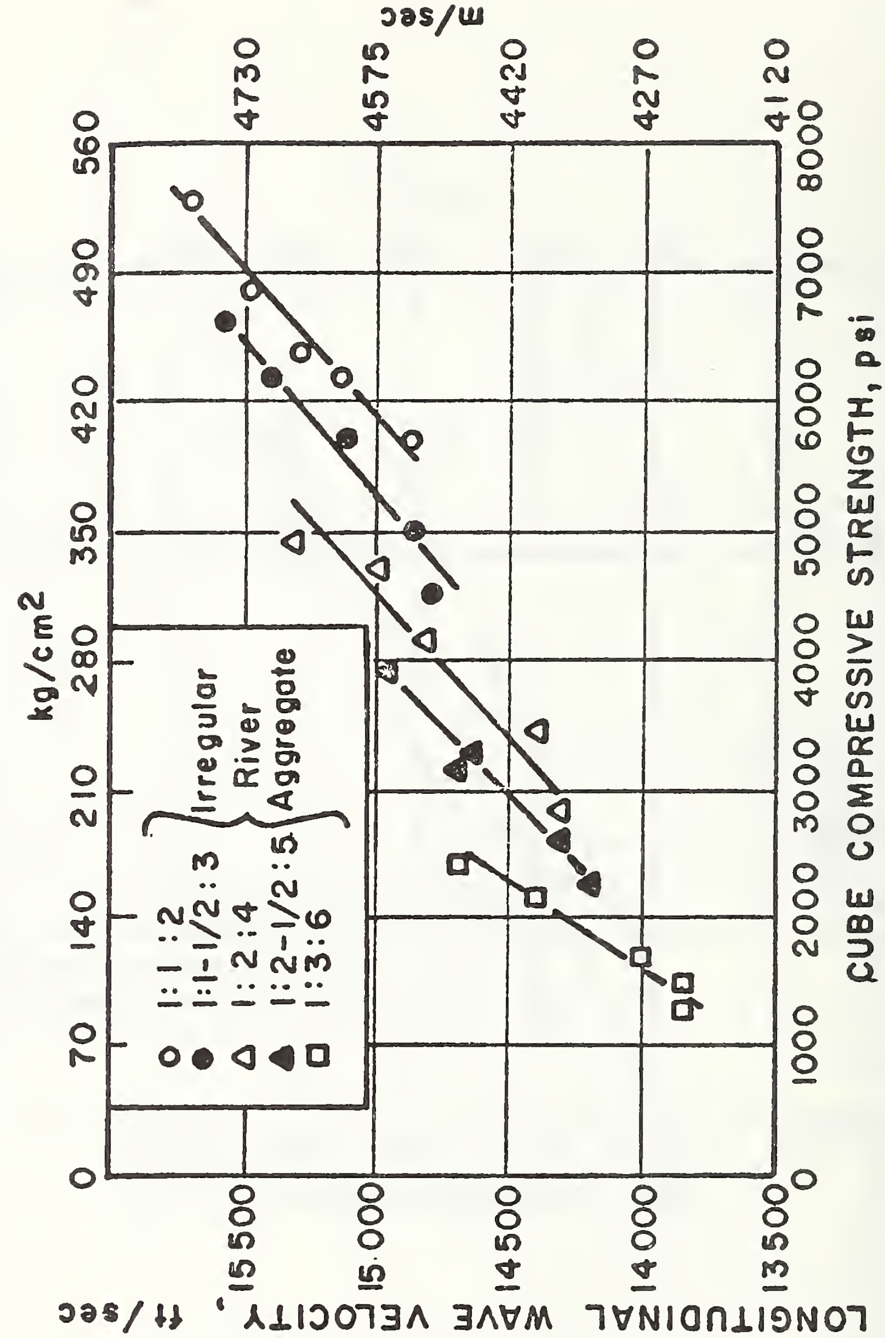
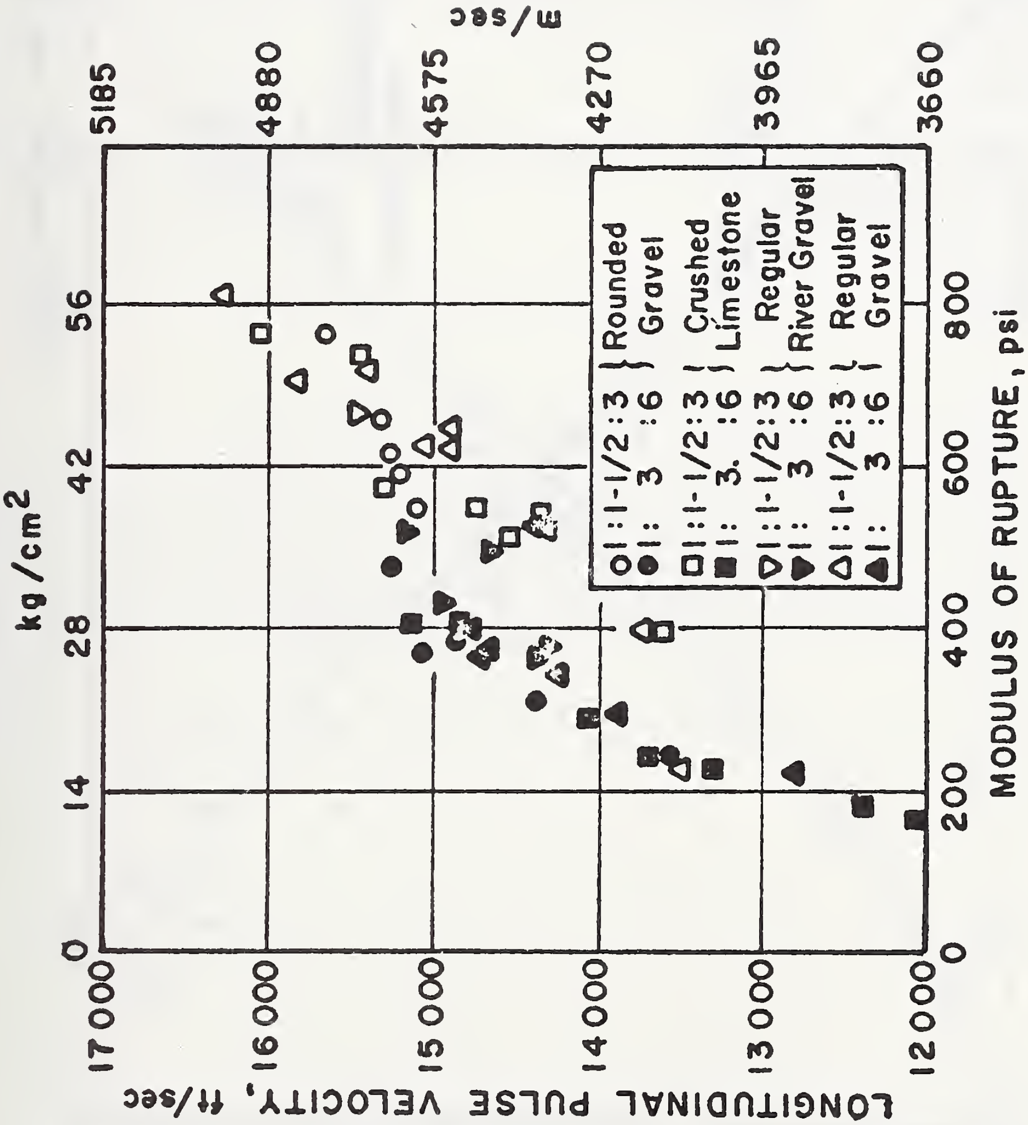

kg/cm2
0
140
280
420
560
700
17.000
16 000
15 000
14 000
5185
4880
4575
4270
PULSE VELOCITY - ft/sec
m/sec
0
2000
4000
6000
8000
10000
CUBE COMPRESSIVE STRENGTH, psi
1:1-1/2:3 Rounded Gravel
1:1-1/2:3 Crushed Limestone
1:1-1/2:3 Crushed Granite

Figure 9.



CUBE COMPRESSIVE STRENGTH, psi
kg/cm2
LONGITUDINAL WAVE VELOCITY, ft/sec
m/sec
1:1:2
1:1-1/2:3
1:2:4
1:2-1/2:5
1:3:6
Irregular River Aggregate

Figure 10.



LONGITUDINAL PULSE VELOCITY, ft/sec
17000
16000
15000
14000
13000
12000
m/sec
5185
4880
4575
4270
3965
3660
kg/cm2
0
14
28
42
56
MODULUS OF RUPTURE, psi
0
200
400
600
800
1:1-1/2:3 } Rounded
1: 3 :6 } Gravel
1:1-1/2:3 } Crushed
1: 3. :6 } Limestone
1:1-1/2:3 } Regular
1: 3 :6 } River Gravel
1:1-1/2:3 } Regular
1: 3 :6 } Gravel

Figure 11.

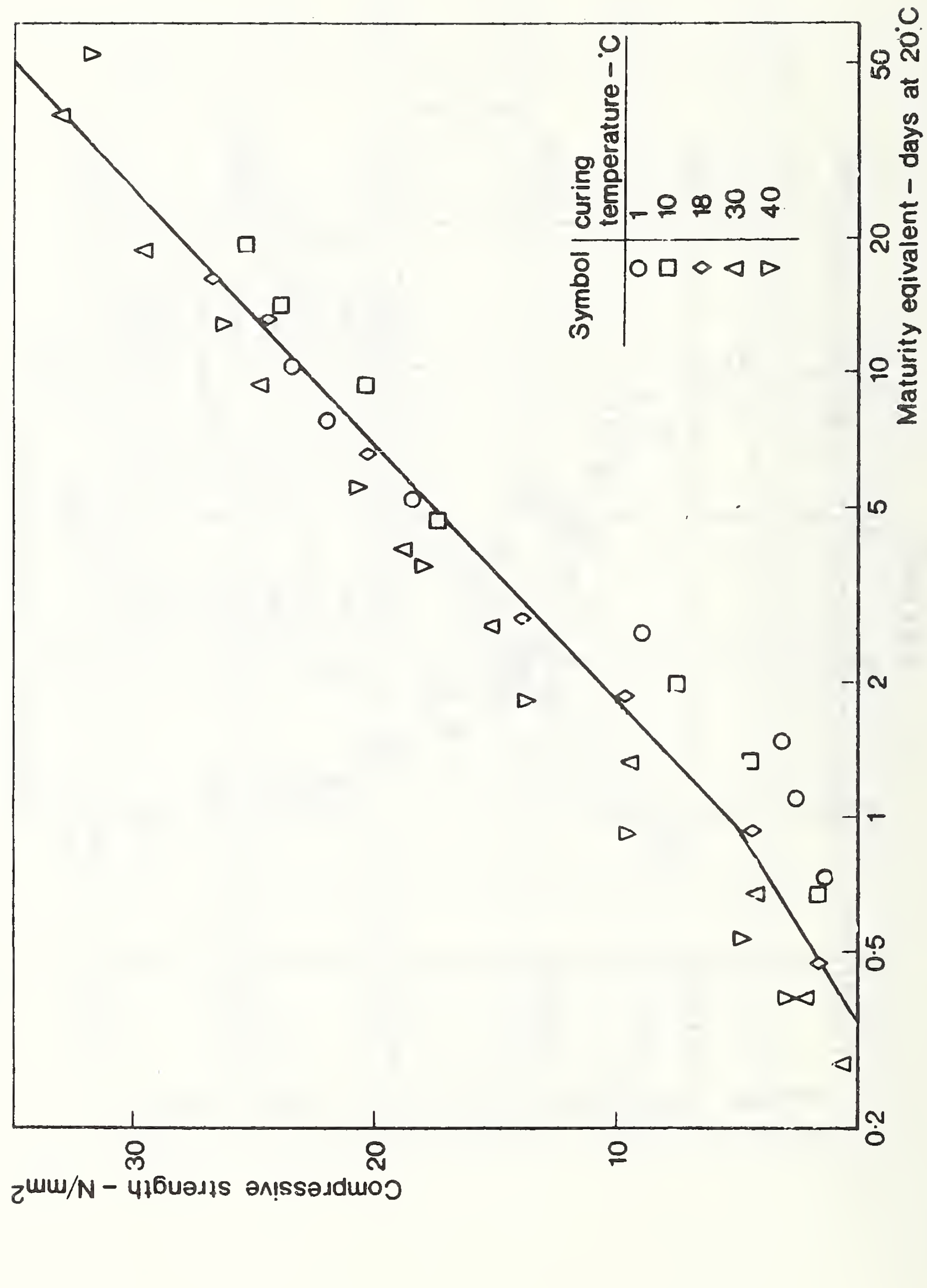
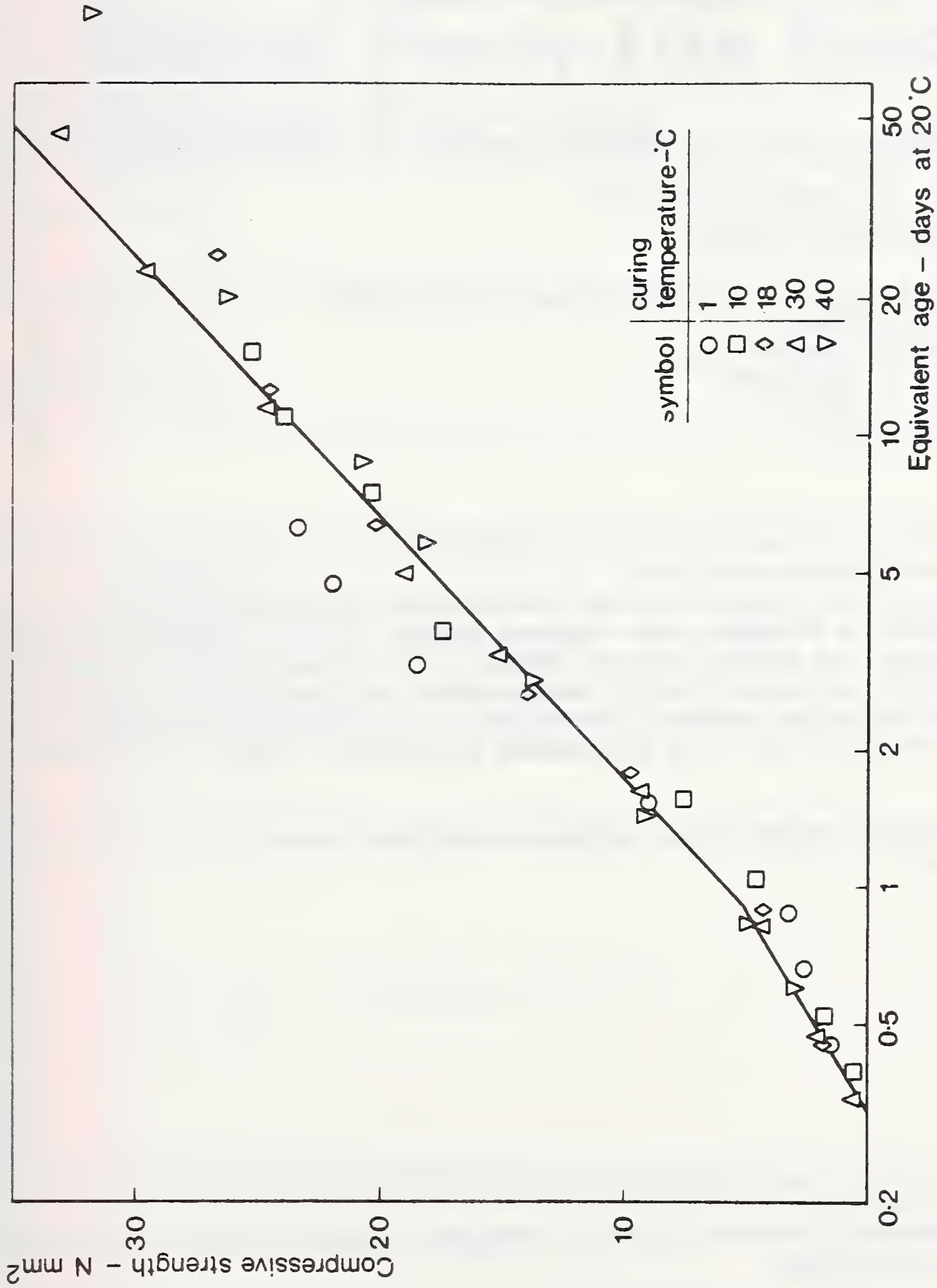

Compressive strength – N/mm²
10
20
30
Maturity eqivalent – days at 20°C
0·2
0·5
1
2
5
10
20
50
Symbol
curing temperature – °C
1
10
18
30
40

Figure 12.



Compressive strength – N mm²
30
20
10
0·2
0·5
1
2
5
10
20
50
Equivalent age – days at 20°C
symbol
curing temperature – °C
1
10
18
30
40

Figure 13.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-729	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE NONDESTRUCTIVE TESTS TO DETERMINE CONCRETE STRENGTH - A STATUS REPORT			5. Publication Date July 1975
			6. Performing Organization Code 461.02
7. AUTHOR(S) James R. Clifton			8. Performing Organ. Report No. NBSIR 75-729
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Building Safety Section Center for Building Technology National Bureau of Standards Washington, D.C. 20234			13. Type of Report & Period Covered Final
			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Individual and combined nondestructive test methods have been critically reviewed as potential methods to determine safe formwork removal times. The techniques reviewed are the Windsor probe, the Schmidt Rebound Hammer, pull-out measurements, push-out cylinders, ultrasonic pulse velocity measurements, and the maturity and equivalent age concepts. The individual methods, themselves, do not give good estimates of the in situ strengths of concretes and it is recommended that future research emphasize combined methods.

A proposed research program which emphasizes combined nondestructive test methods has been developed.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Compressive strength; concrete; flexural strength; formwork removal; nondestructive testing; surface hardness

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[XX] Unlimited [ ] For Official Distribution. Do Not Release to NTIS	UNCLASSIFIED	42
[ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 [ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price

USCOMM-DC 29042-P74