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Nondestructive Evaluation Methods for Quality Acceptance of Hardened Concrete in Structures

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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*
Jordan J. Baruch, *Assistant Secretary for Productivity, Technology, and Innovation*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Nondestructive evaluation methods which can be used in quality acceptance programs for hardened concrete have been critically reviewed and are described in this report. Methods have been identified which provide information on the strength, uniformity, thickness, air content, stiffness, finish, density of concrete as well as the location and condition of steel reinforcement. Both commonly used methods and potentially useful test methods are covered. In addition, the feasibility of combining two or more test methods for improving the prediction of the strength or quality of concrete is explored.

Key Words: Concrete; construction; nondestructive evaluation; quality assurance; steel reinforcing bars; test methods.

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NONDESTRUCTIVE EVALUATION METHODS FOR
QUALITY ACCEPTANCE OF HARDENED CONCRETE

1. INTRODUCTION

Quality[1/] and uniformity of hardened concrete in a newly constructed building depends on a series of processes including the selection of concrete ingredients, design of the concrete mix, batching of and mixing the concrete ingredients, placing and consolidating plastic concrete, and curing operations. Specification codes, standard guidelines, and standard test methods form the basis for decision making in these processes. For example, concrete ingredients can be specified by citing the appropriate American Society for Testing and Materials (ASTM) standards. In addition, standard test methods are available for checking the characteristics of plastic concrete prior to placement. However, the quality and uniformity of hardened concrete also are affected by construction practices, workmanship, and curing conditions. It is the role of concrete inspectors to determine if the building contractor is adhering to acceptable practices and to the design specifications. Often, an inspector only can form subjective conclusions which are highly dependent on his level of training and experience. The present testing and inspection approach to quality control of concrete does not always adequately ensure that the hardened concrete in the structure is of the desired quality or uniformity. An effective quality control program also should include evaluation of hardened concrete and reinforcement at the time of acceptance of the building.

[1/] In this paper "quality of concrete" refers to the levels of the chemical and physical properties of concrete needed to meet the designed performance and service life.

Quality control testing of hardened concrete, i.e., quality assurance testing, is gaining recognition as being an important phase of quality acceptance programs. Because of the importance of such programs, an international symposium was held in 1979 [1] which addressed the "Quality Control of Concrete Structures." The nondestructive evaluation (NDE) approach is becoming the foundation for quality assurance testing of hardened concrete. NDE methods which can be used in quality acceptance programs are critically reviewed and described in this report. Quality acceptance programs based on NDE methods have been reported to be cost effective [2] and reliable [2, 3]. The on-job time for concrete inspectors can be reduced. In addition, poor quality or nonuniform concrete can be readily detected and the contractor required to replace it before a building is accepted. This can increase the service life of the building and also reduce maintenance costs.

Another application of NDE is in selecting sites for coring. Cores are often taken if hardened concrete appears to be substantially below the specified quality or strength. Taking and testing numerous cores from a concrete structure is undesirable for several reasons including the time consumed, the expense, and the damage to the structure. NDE can be used to identify those areas that should be cored, thereby reducing the number of cores needed to quantitatively evaluate the concrete.

2. SURVEY OF NONDESTRUCTIVE EVALUATION METHODS FOR CONCRETE

The selection of NDE methods for characterizing concrete should be based on considerations of its important functional properties. In quality acceptance testing of hardened concrete, properties and factors of concrete which might be determined include strength, uniformity, thickness, air content, stiffness, finish, density, and location and condition of steel reinforcment. NDE methods which can be used to obtain information on these factors are given in table 1. The Recommended Test Methods in table 1 are commonly used and their limitations are understood, while the reliability and feasibility of Possible Test Methods are still being assessed.

Operation, principles, and applications of commonly used NDE methods are outlined in table 2. The test equipment for all the methods is sufficiently portable so that the concrete can be tested in the field. In addition, results can normally be obtained and evaluated within one or two days. With the exception of gamma radiography and the neutron moisture meter, the equipment can be operated by most concrete testers or inspectors. These radiation techniques only can be used by personnel licensed by the Nuclear Regulatory Commission. The methods outlined in table 2 are described in more detail in section 3. The ASTM has recognized the need for standards and specifications covering nondestructive evaluation methods for a variety of materials and applications. ASTM standards for NDE methods for concrete and for taking test cores from concrete are listed in table 3.

The Possible Test Methods listed in table 1 may become recognized methods after their reliabilities and feasibilities have been demonstrated. Principles and potential applications of these methods are discussed in section 4. The feasibility of combining two or more test methods for predicting the strength or quality of concrete is being explored with some success. This subject is covered in section 5.

TABLE 1. NDE METHODS FOR QUALITY ASSURANCE TESTING OF HARDENED CONCRETE

CONCRETE PROPERTIES	RECOMMENDED TEST METHODS	POSSIBLE TEST METHODS
Strength	Windsor Probe Schmidt Rebound Hammer Cast-In-Place Pullouts Maturity Concept Cores	
General Quality and Uniformity	Windsor Probe Schmidt Rebound Hammer Ultrasonic Pulse Gamma Radiography Cores	Ultrasonic Pulse Echo Microwaves
Thickness	Covermeter Microwaves (Radar) Cores	Gamma Radiography Ultrasonic Pulse
Air Content	Cores	Neutron Density Gage
Moduli of elasticity		Dead Weight Loading with Acoustic Emission
Surface Properties	Visual Schmidt Rebound Hammer Cores	Microwaves Ultrasonic Pulse Echo
Density	Gamma Radiography Cores	Neutron Density Gage
Rebar Size and Location	Covermeter Gamma Radiography	Microwaves (Radar) Ultrasonic Pulse Echo
Corrosion State of Reinforcing Steel	Visual Electrical Potential Measurement	

TABLE 2. SURVEY OF COMMONLY USED METHODS FOR CONCRETE INSPECTION

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
1. Windsor Probe	Probe fired into concrete and depth of penetration is measured. Surface and subsurface hardness measured.	Estimations of compressive strength, uniformity and quality of concrete.	$900 plus cost of probes.	Low, can be operated by ordinary field personnel.	Equipment is simple and durable. Good for determining quality of concrete.	Slightly damages small area. Does not give precise prediction of strength.
2. Rebound Hammer	Spring loaded plunger strikes surface of concrete and rebound distance is given in R-values. Surface hardness is measured.	Estimation of compressive strength, uniformity and quality of concrete.	$250 to $600	Low, can be readily operated by ordinary field personnel.	Inexpensive. Large amount of data can be quickly obtained. Good for determining uniformity of concrete.	Results affected by condition of concrete surface. Does not give precise prediction of strength.
3. Cast-in-Place Pullout	Force required to pull out steel rod with enlarged head cast in concrete, is measured. Pullout forces produce tensile and shear stresses in concrete.	Estimation of compressive and tensile strengths of concrete.	$1000 to $4000	Low, can be used by field concrete testors and inspectors.	Only NDE method which directly measures in place strength of concrete. Appears to give good prediction of concrete strength.	Pullout devices must be inserted during construction. Cone of concrete may be pulled out, necessitating minor repairs.
4. Ultrasonic Pulse	Based on measuring the transit time of a wave propagating through concrete.	Estimation of the quality and uniformity of concrete.	$4000 to $5000	Moderate, user must understand method and recognize potential problems.	Excellent for determining the quality and uniformity of concrete.	Does not provide estimate of strength. Skill required in analysis of results. Moisture variations can affect results.
5. Gamma Radiography	Gamma radiation attenuates when passing through concrete. Extent of attenuation controlled by density and thickness of concrete.	Locating cracks, honeycombing, voids, and reinforcement in concrete.	around $5000	Must be operated by trained and licensed personnel.	Portable and relatively inexpensive compared to X-ray radiography.	Radiation intensity cannot be adjusted. Long exposure times can be required. Dangerous radiation.
6. Neutron Moisture Meters	Fast neutrons are slowed by interactions with hydrogen atoms. Back-scattered slowed neutrons are measured which gives amount of hydrogen atoms present in a material.	Moisture content and possibly density of concrete.	$3500 to $6300	Must be operated by trained and licensed personnel.	Portable moisture estimates can be made of in-place concrete.	Only measures moisture content of surface layers (50 mm). Dangerous radiation.
7. Covermeter	Presence of steel affects the magnetic field of a probe. Closer probe is to steel, the greater the effect.	Determination of presence, location, and depth of rebars in concrete.	$800 to $1500	Moderate. Easy to operate. Need training to interpret results.	Portable equipment, good results if concrete is lightly reinforced.	Difficult to interpret if concrete is heavily reinforced or if wire mesh is present.
8. Electrical Potential Measurements	Electrical potential of steel reinforcement measured. Potential indicates probability of corrosion.	Determining condition of steel rebars in concrete.	$1000 to $2000	Moderate. User must be able to recognize possible problems.	Portable equipment. Field measurements readily made. Appears to give reliable information.	Does not provide information on rate of corrosion.

TABLE 3. ASTM STANDARDS FOR CONCRETE NDE METHODS

Nondestructive Method	ASTM Standard and Designation
Rebound Hammer	Test for rebound number of hardened concrete: C805
Penetration Probe	Test for penetration resistance of hardened concrete: C803
Ultrasonic Pulse Velocity	Test for pulse velocity through concrete: C94
Cores	Drilled cores and sawed beams of concrete, obtaining and testing: C42
Nuclear Moisture Meter	Standard test method for moisture content of soil and soil-aggregate in place by nuclear methods (shallow depth): D3017
Cast-in-Place Pullouts	Tentative test method for pullout strength of hardened concrete: C900-78T
Visual	Standard recommended practice for examination of hardened concrete in construction: C823

3. COMMONLY USED NONDESTRUCTIVE EVALUATION METHODS

NDE methods which are commonly used and generally accepted for the evaluation of concrete are described herein.

3.1 Probe Penetration Method

The probe penetration method is based on measuring the depth to which a steel probe penetrates concrete when driven by a powder charge. Actually the exposed length of the probe is measured rather than the depth of penetration. This method is useful for assessing the quality and uniformity of concrete in situ, and for delineating areas of poor quality or deteriorated concrete in structures.

Probe results also have been used to estimate the compressive strength of concrete by using correlation graphs. The graphs are constructed by plotting the exposed lengths of probes versus experimentally measured compressive strengths.

3.1.1 Probe Equipment and Use

The Windsor Probe[2/] is the most commonly selected and possibly the only commercially available apparatus for measuring the penetration resistance of concrete. It consists of a special driving gun (figure 1) into which is inserted a high-strength steel probe that is driven into the concrete by firing of the powder charge (a calibrated 32 caliber blank cartridge). A series of three measurements is made in each area using the spacer

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[2/] Precise identification of NDE equipment is necessary to clearly describe the testing procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards.

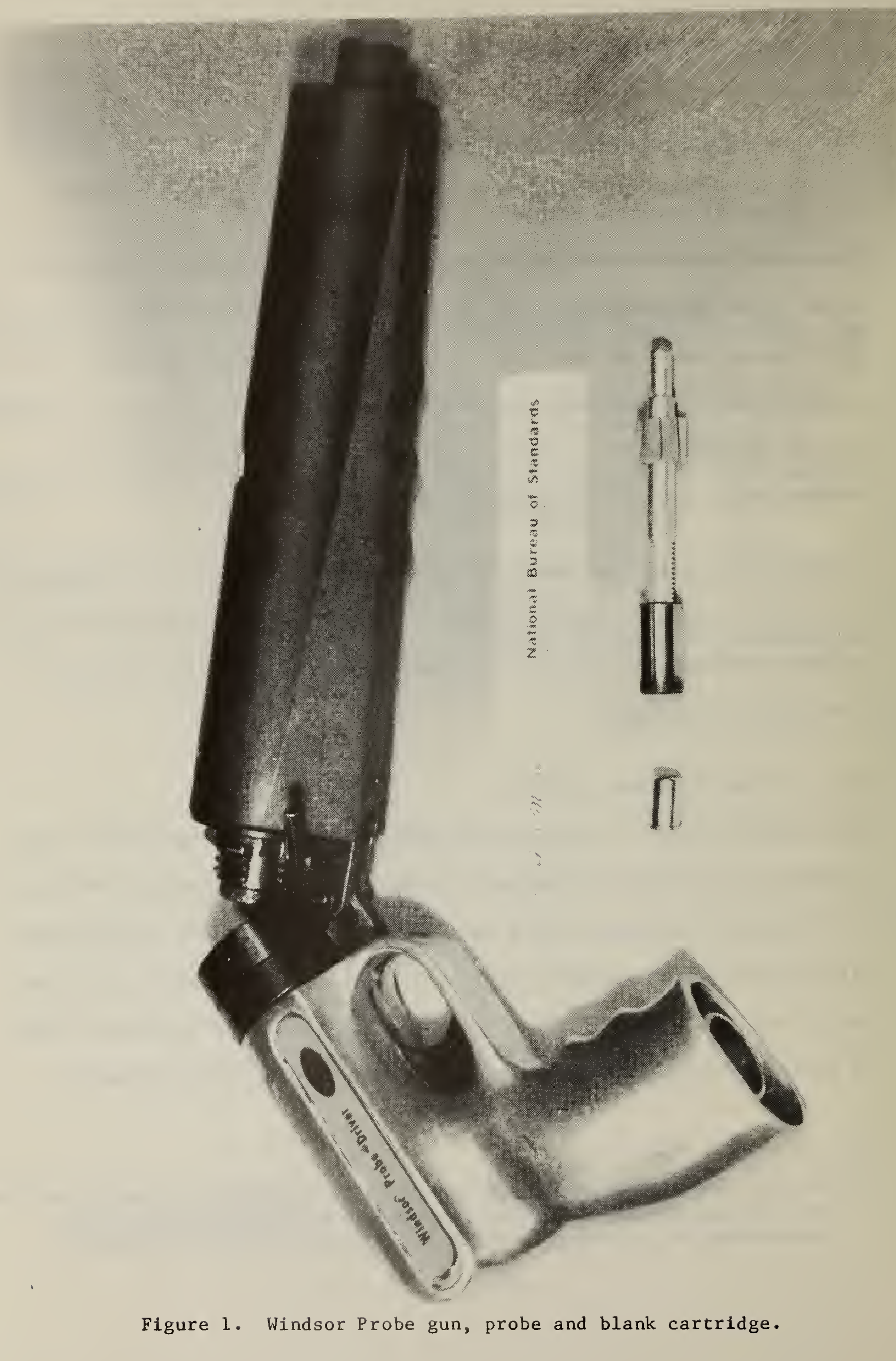

Figure 1. Windsor Probe gun, probe and blank cartridge.

plate shown in figure 2. The length of a probe extending from the surface of concrete can be measured using a simple device as shown in figure 3.

Operating procedures for the Windsor Probe are given by the manufacturer. In addition, testing procedures are given in ASTM Standard C803 [4]. The probe can be easily operated by concrete inspectors and is readily portable.

The manufacturer supplies a set of five calibration curves, each curve corresponding to a specific Moh's hardness for the coarse aggregate used in the concrete, by which probe measurements can be converted to compressive strength values. However, several investigators [5, 6] have observed that use of the manufacturer's calibration curves often results in grossly incorrect estimates of the compressive strength of concretes. Therefore, it is recommended that the Windsor Probe should be calibrated by the individual user and should be recalibrated whenever the type of aggregate or mix design is changed.

3.1.2 Applications

The Windsor Probe can be used for assessing the quality and uniformity of concrete because physical differences in a concrete will affect its resistance to penetration. A probe will penetrate deeper as the density, subsurface hardness, and strength of the concrete decreases. Areas of poor concrete can be mapped by making a series of penetration tests.

The Windsor Probe has been used to estimate the compressive strength of concrete. However, the relationship between the depth of penetration of the probe and the compressive strength can only be obtained empirically because penetration of the probe depends on a complex mixture of tensile, shear,

Figure 2. Windsor Probe in use.

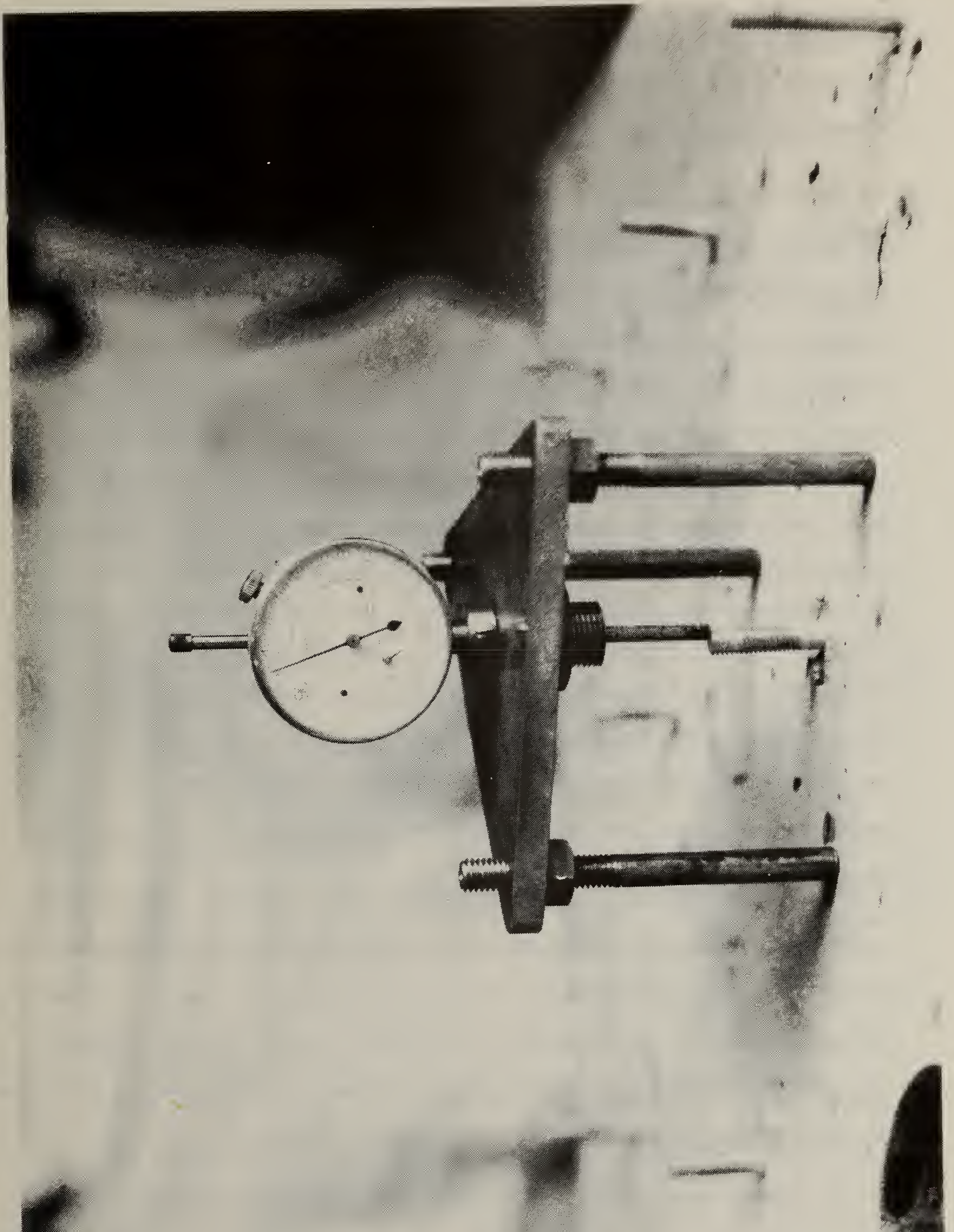

Figure 3. Device for measuring length of probe extending from surface of concrete.

frictional, and compressive forces [5]. The estimation of compressive strengths with the Windsor Probe, therefore, must be made using a correlation diagram with appropriate confidence limits.

The probe technique appears to be gaining acceptance as a practical NDE method for estimating the compressive strength of concrete. Improved correlations between probe results and in place strength can be obtained by keeping the curing conditions of the test specimens close to those of the in-place concrete and by making sure that the test concrete is representative of the mass concrete. If the Windsor Probe is calibrated using concrete specimens taken from an early construction stage, the calibration chart could be used to estimate the strength of concrete placed during later stages (assuming that the concrete design is the same).

3.1.3 Advantages and Limitations

The Windsor Probe equipment is simple, durable, requires little maintenance, and can be used by inspectors in the field with little training. Care must be exercised, however, because a projectile is fired and safety glasses should be worn. The gun can only be fired when the gun is pushed against a special spacer plate.

The Windsor Probe primarily measures surface and subsurface hardness and does not yield precise measurements of the in situ strength of concrete. However, useful estimates of the compressive strength of concrete may be obtained if the probe is properly calibrated. The probe test is very useful in assessing the general quality and relative strengths of concrete.

The Windsor Probe test does damage the concrete, leaving a hole of about 5/16 in. (8 mm) in diameter for the depth of the probe and, also, may cause minor cracking and some surface spalling, necessitating minor repairs.

3.2 Rebound Hammer Method

The rebound hammer method is similar to the penetration probe method in that it measures surface hardness. The rebound method is based on the rebound theories of Shore [7]. He developed the Shore Scleroscope method in which the height of rebound of a steel hammer dropped on a metal test specimen is measured. The only commercially available instrument based on the rebound principle for testing concrete is the Schmidt Rebound Hammer [8].

The Schmidt Rebound Hammer has gained wide acceptance by researchers and concrete inspectors 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 [6] standards have been drafted in Poland and Romania for the Rebound Hammer. The British Standards Institution has issued Building Standards 4408 which covers nondestructive test methods for concrete and includes the rebound hammer method in part 4 of the Standard [6]. Recently, ASTM issued a Standard C805, Test for Rebound Number of Hardened Concrete, which gives procedures for the use of the rebound hammer.

3.2.1 Description of Method

The Schmidt Rebound Hammer consists of a steel weight and a tension spring in a tubular frame (figure 4). When the plunger of the hammer is pushed against the surface of the concrete, the steel weight is retracted against the force

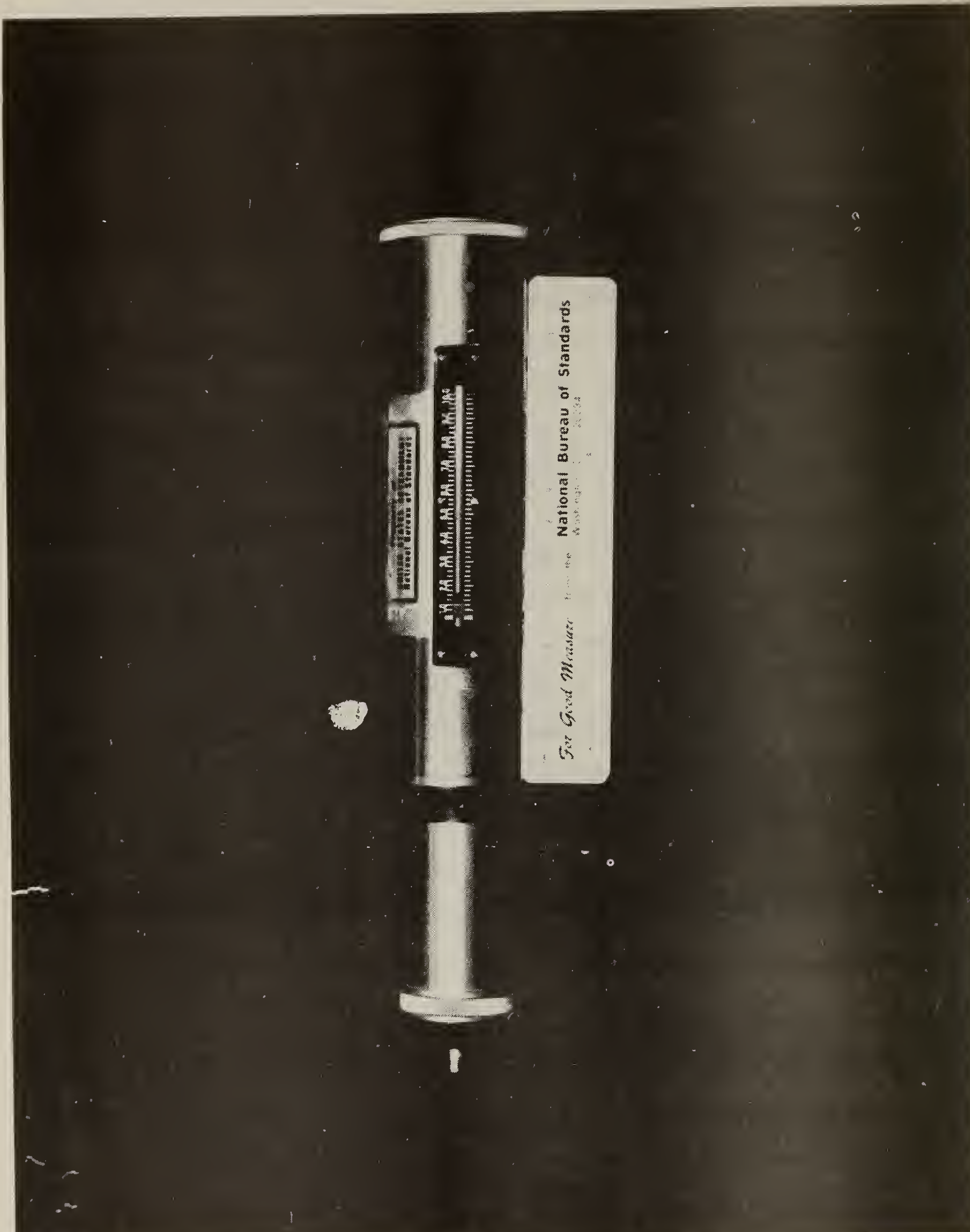

Figure 4. Schmidt Rebound Hammer

of the spring. When the head is completely retracted, the spring is automatically released, the weight is driven against the plunger and it rebounds. The rebound distance is indicated by a pointer on a scale that is usually graduated from zero 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. R-values give an indication of the hardness of the concrete with valves increasing with the hardness of the concrete.

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. However, users should not place too much confidence on the calibration chart and should develop their own for each concrete mix.

3.2.2 Applications

Numerous investigators [9-11] have shown that there is some correlation between compressive strength of concrete and the hammer rebound number. There is, however, extensive disagreement (e.g. references [12] and [13]) concerning the accuracy of the strength estimates from rebound measurements. Mitchel and Hoagland [14] found that the coefficient of variation for compressive strength, for a wide variety of specimens from the same concrete, averaged 18.8 percent. Arni [5] found that the rebound hammer gave a less reliable estimate of compressive strength than the Windsor Probe.

Several investigators [13, 15] 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 [14] attempted to correlate rebound numbers with the modulus of elasticity of the concrete specimens. They concluded that no valid correlations could be made. Peterson and Stoll [9] and Klieger [16] have developed some empirical relations between the dynamic modulus of elasticity and hammer rebound.

The rebound hammer, like the Windsor Probe, is very useful in assessing the general quality of concrete and for locating areas in which poor quality concrete is located. A large number of measurements can be rapidly taken so that large exposed areas of concrete can be mapped within a few hours.

3.2.3 Advantages and Limitations of the Rebound Hammer

The Schmidt Rebound Hammer is a simple and quick method for the nondestructive testing of concrete in situ. 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 [13, 17, 18]:

(1) Smoothness of the concrete surface

(2) Moisture content of concrete

(3) Type of coarse aggregate

(4) Size, shape and rigidity of specimen, e.g., a thin wall or beam

(5) Carbonation of the concrete surface.

The rebound method is largely an imprecise test and it does not provide a reliable estimation of the strength of concrete. The rebound hammer, however, is very useful in the rapid assessment of the relative quality of concrete.

3.3 Cast-In-Place Pullout

The pullout test measures the force required to pull out a steel insert, having an enlarged end, which has been cast in the concrete (figure 5). The concrete is subject to a complex state of stresses by the pullout force, and a cone of of concrete is removed at failure. The pullout force is usually related to the compressive strength of the concrete, with the ratio of pullout strength (force divided by surface area of the conic frustrum) to compressive strength being in the range of 0.1 to 0.3 [18]. Correlation graphs are used to relate relate pullout force to compressive strength. The pull-out technique is the only nondestructive method which directly measures a strength property of concrete in place (the measured strength is thought to be a combination of tensile and shear strengths). There are several commercially available test apparatuses for measuring the pullout resistance of concrete [19, 20], with prices varying from $1000 to $5000.

3.3.1 Test Method

ASTM has recently issued a tentative test method, C900-78T, which describes in detail the pullout assembly and gives allowable dimensions. The pullout insert is cast-in-place during placing of fresh concrete, and it is either pulled completely out of the concrete, or pulled until maximum load is reached, with a manually operated hollow tension ram exerting pressure through

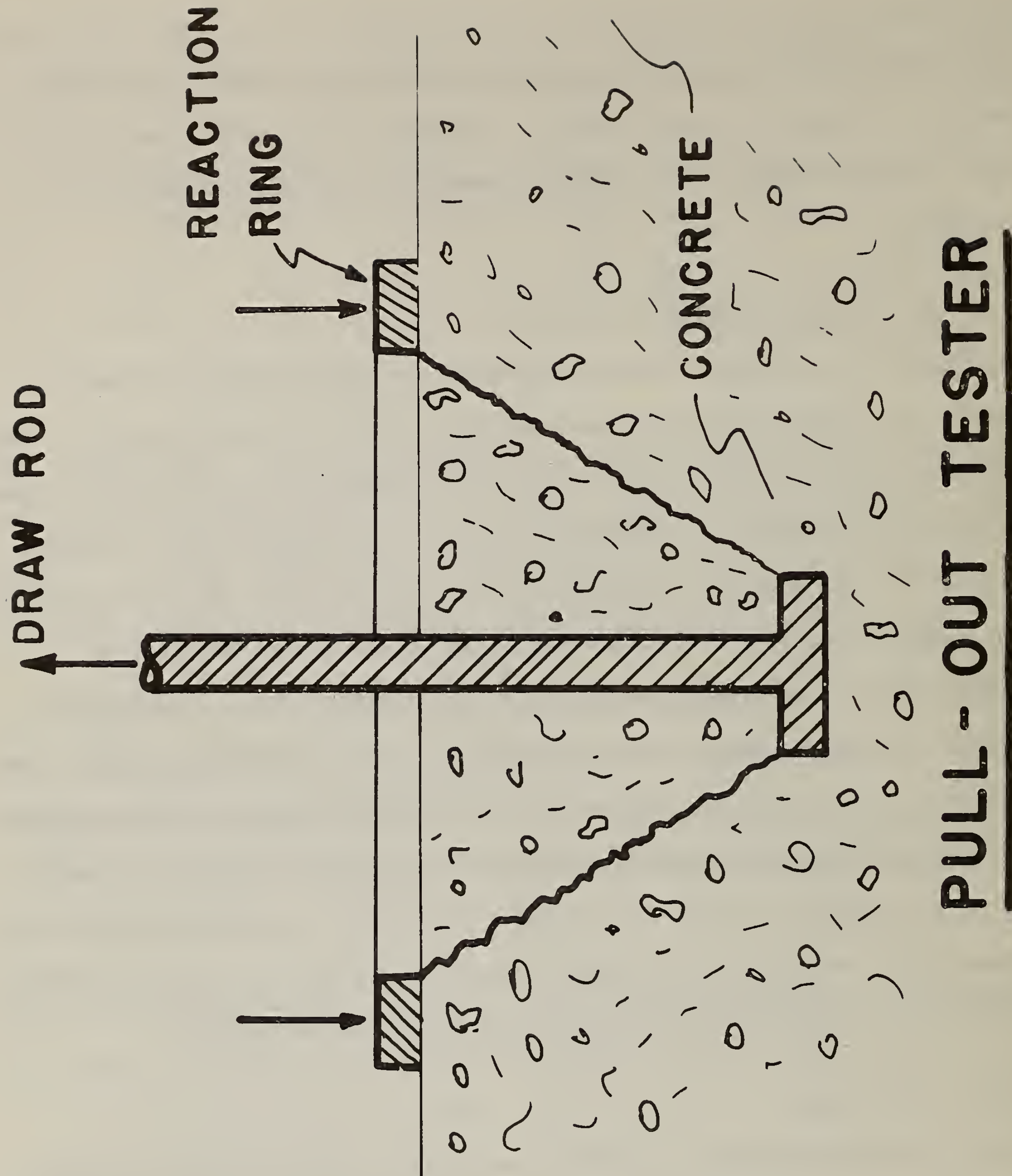

Figure 5. Schematic of cast-in-place pullout device

the steel reaction ring. Components of one possible test apparatus for pulling out the insert are shown in figure 6. Testing and calculation procedures are also given in ASTM C900-78T.

Because the pullout insert is usually cast-in-place during placing of the fresh concrete, these tests must be planned in advance. Alternatively, hardened concrete can be drilled to receive the pullout insert. This necessitates drilling through the bottom or backside of a concrete slab, for example, 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; the insert is placed through the bottom or backside; and the test carried out.

Techniques have been developed so that the inserts can be embedded deep in concrete, thereby permitting testing of the interior concrete.

3.3.2 Reliability of Method

Malhotra [18] and Richards [19] have shown that the pullout method is a reliable method for estimating the compressive strength of concrete. Malhotra found that the coefficients of variation for pullout test results was in the same range as obtained from testing standard cylinders in compression. Correlation coefficients of 0.97 to 0.99 for normal weight concrete have been obtained from curve fitting of pullout and compression test results [19].

3.3.3 Advantages and Limitations

The pullout technique is the only nondestructive test method which directly measures a strength function of concrete in place.

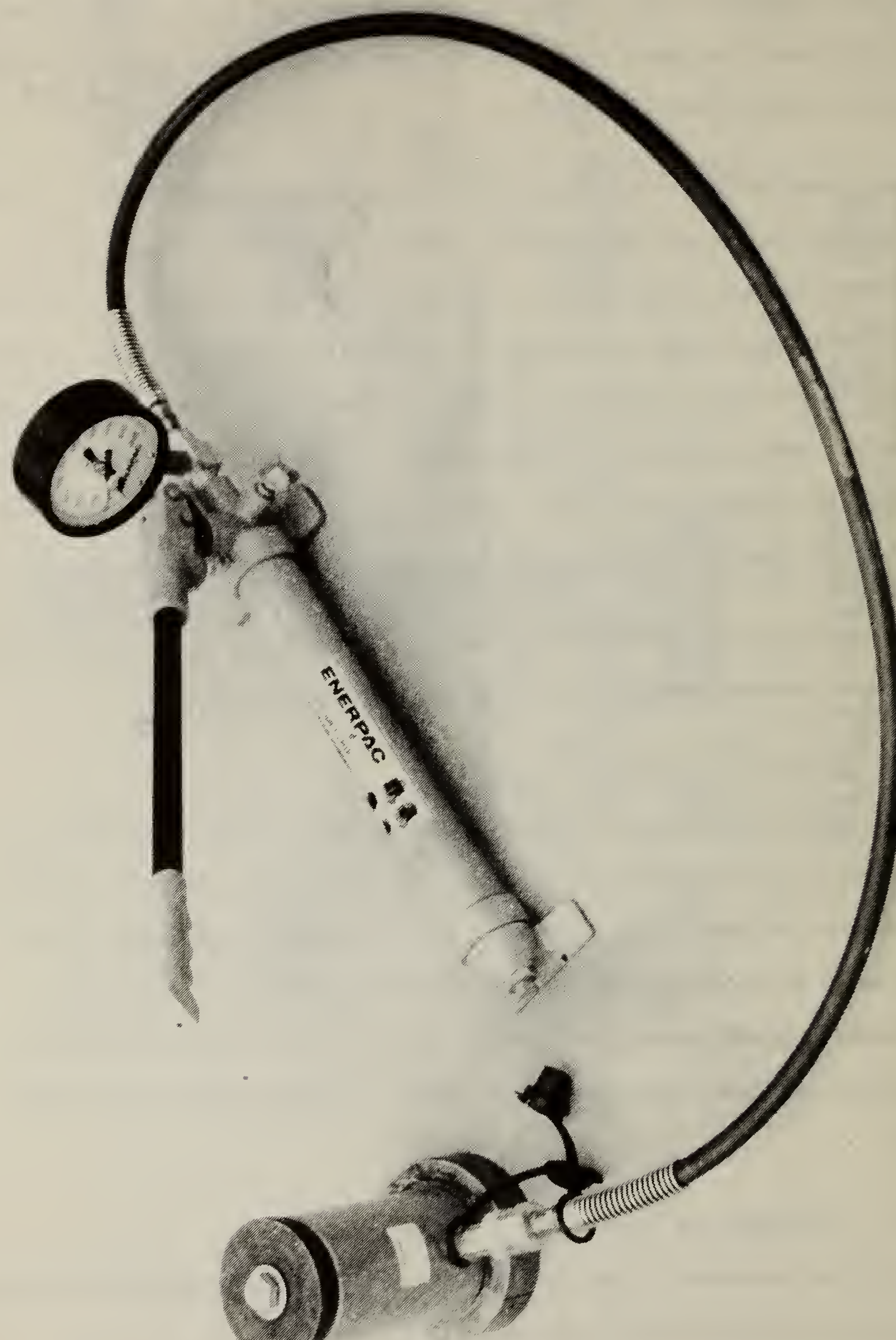

Figure 6. Components of pullout test apparatus

The major disadvantage of the pullout test is that a cone of concrete is sometimes pulled out necessitating minor repairs. However, if the pullout forces are quickly released when failure is just initiated, the pullout assembly and concrete cone will not be torn loose, and no repairs will be required. Another disadvantage is the need to plan where inserts are to be placed and to make provisions for their placement prior to placing concrete.

3.4 Ultrasonic Pulse Velocity Method

Several types of nondestructive test methods have been developed based on wave propagation principles such as the measurement of acoustic pulse velocities, seismic velocities, and ultrasonic pulse velocities. These often are collectively termed sonic tests [21]. 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.

3.4.1 Principle of Method

The ultrasonic pulse velocity method is based on measuring the travel time of an ultrasonic pulse passing through concrete. The pulse generated by an electroacoustic transducer is picked up by a receiver transducer and amplified. The time of travel of the pulse is measured electronically. A commercial instrument for measuring the ultrasonic pulse velocity of concrete is shown in figure 7.

When a mechanical pulse is applied to concrete by an electroacoustic transducer, waves are induced in the concrete. Usually longitudinal waves are used in testing concrete. These waves are transmitted by particles

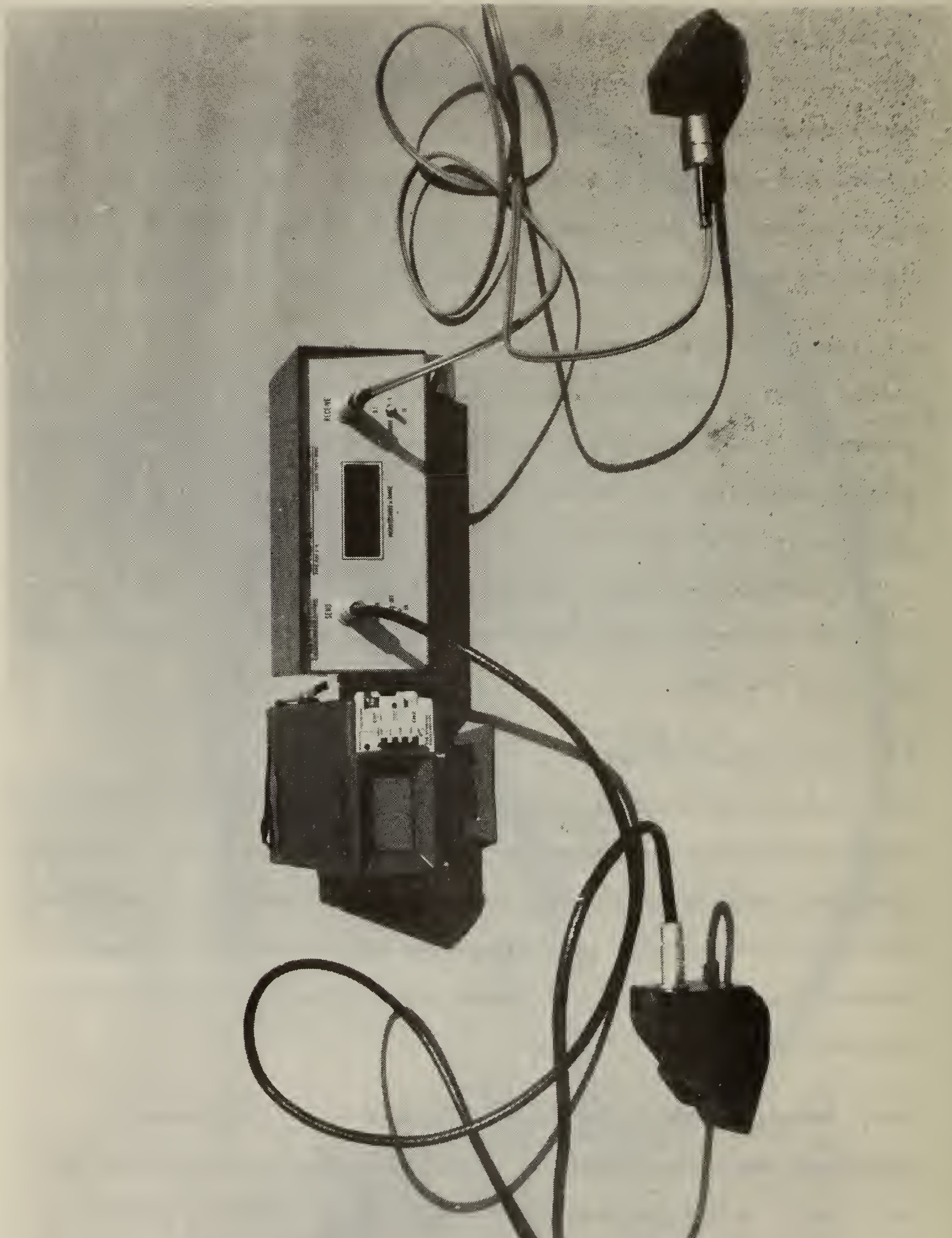

Figure 7. Ultrasonic pulse velocity equipment

vibrating parallel to the direction of propagation. The velocity of the wave is controlled by the elastic properties and the density of the material being tested. It is virtually independent of the geometry of the concrete object being tested.

If a longitudinal wave encounters a discontinuity such as a crack or void, it may "bend," i.e., be diffracted around the discontinuity. This will increase the internal distance the wave must pass between the transmitting and pickup transducers, and consequently its travel time. Therefore, for a given separation of the transducers, and for a given concrete, the travel time of a longitudinal wave will be less in a region where the concrete is sound than where the concrete is more porous or contains cracks. In addition, the velocity of the longitudinal wave will be effected by changes in density and plastic properties of concrete.

At least three ultrasonic pulse velocity units are commercially available [18, 21] including the Ultrasonic Concrete Tester, the Soniscope, and Pundit. The Ultrasonic Concrete Tester has a testing range of about 50 feet (15.6 m), whereas both the Soniscope and Pundit can be used to test concrete having a thickness up to about 75 feet (30 m). Their respective operating frequencies are 150 kHz, 50 kHz, and 50 kHz.

3.4.2 Assessment of the Uniformity and Quality of Concrete

Ultrasonic pulse velocity methods are considered to be the best NDE methods for determining the uniformity of in situ concrete. For example, velocity measurements have been successfully used to detect deteriorated regions in concrete bridges and the uniformity of concrete in walls [21]. In general, if substantial variations in pulse velocities are found in a structure, without any apparent reason (such as intentional changes in materials, concrete mix, or construction procedures), this indicates that unsound concrete is present [21].

A general rating which has been proposed to assess the relative quality of concrete is presented in table 4. These criteria should be used with caution as differences in the qualities of concrete cannot be as sharply delineated as indicated in table 4. In addition, velocity is affected by the density of the aggregate and the amount of aggregate in concrete. A crude assessment of the quality of similar types of concrete can be made, however, using these criteria. For example, if one concrete has a pulse velocity above 15,000 ft/sec (4570 m/sec) while another concrete with a similar composition has a velocity below 10,000 ft/sec (3050 m/sec), then there is clearly a significant difference in their qualities.

Table 4. Pulse Velocities in Concrete [22]

Pulse Velocity ft. per sec	(m. per sec)	General Condition
Above 15,000	(4570)	Excellent
12,000-15,000	(3660-4570)	Good
10,000-12,000	(3050-4570)	Questionable
7,000-10,000	(2130-3050)	Poor
Below 7,000	(2130)	Very Poor

3.4.3 Estimation of Strength Properties

Numerous investigations have attempted to correlate compressive and flexural strengths of concrete with pulse velocity. Some correlations have been obtained in laboratory studies, provided that mix proportions, the cement, types of aggregate, and curing conditions were not varied [6]. If these factors were varied, however, no usable correlations were obtained. For example, Parker [23] made a comparison of pulse velocities and compressive strengths for concretes made from only one type of aggregate but containing different cements from different sources and a variety of admixtures. His analysis of the total data indicated that at the 95 percent confidence level the estimated 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). Obviously, the ultrasonic pulse method cannot be used to obtain any reliable estimates of the compressive or flexural strengths of concrete in a structure when its composition is unknown.

Probably the best concluding remarks regarding strength prediction from wave propagation methods are those stated by Jones [24]:

> "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.")

3.4.4 Extraneous Effects on Measurements

The measurement of the pulse velocity of concrete is affected by several factors which are not intrinsic properties of concrete, and, therefore, are not a function of the quality or strength of concrete [18]:

(1) smoothness of concrete at transducer contact area. Good acoustical contact between the transducers and concrete is required. In addition, a coupling agent, such as an oil or a jelly must be used.

(2) Concrete temperatures outside of the range between 41 and 86°F (5 and 30°C) affect the measured pulse velocity. Below this temperature range, the velocity is increased, and above the velocity is decreased.

(3) Moisture condition of concrete. Pulse velocity generally increases as the moisture content of concrete increases, while compressive strength decreases as moisture increases.

(4) Presence of reinforcing steel. The pulse velocity in steel is 1.2 to 1.9 times the velocity in concrete. Measurements made near steel reinforcing bars, therefore, may not be representative of the concrete. If possible, measurements should be made perpendicular to the main axis of the bars. If measurements must be made parallel to the main axis of the steel bars, crude correction factors are available.

3.5 Gamma Radiography

Gamma radiography is similar to X-ray radiography except that gamma rays are generated by a radioactive isotope, while X-rays are electronically generated.

In addition, the gamma source is stored in a portable lead-shielded wheeled container permitting field inspections while most high energy X-ray equipment is less portable.

3.5.1 Principle and Application

Gamma radiation is attenuated when passing through materials. The extent of attenuation is dependent on the density and thickness of material, and on the energy of the gamma rays. In gamma radiography differences in radiation attenuation produced by variations in the density and thickness of a material are recorded on photographic film. For example, when reinforced concrete is radiographically inspected, steel reinforcement attenuates the radiation more than concrete and appears as a lighter area in the film. Voids and cracks in the concrete will appear as darker areas on the film due to little attenuation of the incident radiation.

In practice, gamma rays generated by a suitable radioactive isotope are allowed to pass through concrete, with the emerging radiation being recorded on X-ray film held in a light-tight cassette. Commonly used gamma sources are listed in table 5. Note that the relative penetration abilities of the gamma rays are controlled by their energies.

Table 5. Gamma Sources [26]

Radioactive Source	Gamma Energy (MeV)	Half-life ($t_{1/2}$)	Optimum Working Thickness of Concrete (mm)	Dose Rate[1]
Iridium 192	0.296 and 0.613	70 days	30-200	
Cesium 137	0.66	33 years	100-300	0.39
Cobalt 60	1.17 and 1._2	5.3 years	150-450	1.35

[1]Roentgens per hour per curie at 1 meter. On curie is equal to 3.7 x 10^{10} disintegrations per second.

Some of the applications for gamma radiography in inspecting concrete include locating reinforcement and splices, determining if voids, cracks, or honey-combing are present and determining if ungrouted tendons are present in post-tensioned concrete [18, 25].

3.5.2 Limitations

Because exposure to gamma rays is injurious to the body tissues and the effect may be accumulative, the use of gamma-producing isotopes is closely controlled by the Nuclear Regulatory Commission. This means gamma radiography work should only be performed by licensed and qualified NDE inspectors using approved equipment. Therefore, such inspection work is normally contracted to a firm specializing in gamma radiographic NDE.

Unlike X-rays, the energy of gamma radiation cannot be increased (except by changing the radioactive isotope). The usual sources require exposure times of hours when inspecting concrete slabs or beams over 450 mm thick.

3.6 Neutron Moisture Meters

Nuclear meters have been used to nondestructively detect moisture in roofing materials, soils, and concrete [18, 27]. It is conceivable that this method could be used to gain information concerning the density of concrete.

3.6.1 Principle and Applications

Fast neutrons are slowed by collision with the nuclei of atoms. Hydrogen atoms are the most effective moderators in slowing the neutrons because their nuclear mass is nearly equal to that of neutrons.

Collision of neutrons with heavier nuclei do not reduce the energy of fast neutrons as much. During the collisions, some of the slowed neutrons are reflected back to the surface near the source of the fast neutrons. These backscattered slow neutrons can be counted using a slow neutron detector such as a scintillator crystal or a boron trifluoride type detector. The number of slow neutrons being counted gives a measure of the hydrogen content of a material. In the case of concrete, water and hydroxyl groups are the main source of hydrogen. Therefore, if calibrated against concrete of known moisture content, a neutron moisture meter can give an indirect measure of the moisure content of the concrete.

Several commercial neutron moisture meters are available. The most commonly used sources of fast neutrons are mixtures of americium-beryllium and radiumberyllium. Both americium and radium are alpha particle emitters and

and their alpha particles interact with beryllium, with fast neutrons being emitted as a result of the nuclear reactions.

In addition to neutron sources, most commercial nuclear moisture meters also have gamma sources. The gamma rays are used to determine the density of materials.

3.6.2 Limitations

Similar to gamma radiography, a license must be obtained from the Nuclear Regulatory Commission to use the radioactive isotopes in the neutron source of the neutron moisture meters.

Neutron moisture meters give reliable information of the moisture content of only the surface layers of concrete, about the first two inches (50 mm). In addition, nonuniformities in the surface moisture contents of concrete can lead to erroneous results.

3.7 Cover Meters

Cover meters are portable, battery-operated magnetic devices that are primarily used to estimate the depth that reinforcing steel (bars and tendons) is embedded in concrete and to locate its position. In addition, some information can be obtained regarding the dimensions of the reinforcement [18].

3.7.1 Principle and Applications

Cover meters are magnetic devices that are based on the eddy current principle. A typical meter is shown in figure 8. A magnetic field is induced between the two faces of the probe, which houses a magnetic core, by an alternating current passing through a coil. If the magnetic field passes through concrete containing reinforcement, eddy currents will be produced in the reinforcement. Those

Figure 8. Cover meter used to detect steel reinforcement

eddy currents will in turn induce a current in the probe which slightly changes the inductance of the probe. The magnitude of this change in inductance is measured by a meter. For a given probe, the magnitude of the induced current is largely controlled by the distance between the steel reinforcement and the given probe, the magnitude of the induced current is largely controlled by the distance between the steel reinforcement and the probe.

The relationship between the induced current and the distance of the reinforcement is nonlinear, largely because the magnetic flux intensity of a magnetic material decreases with the square of the distance. In addition, the magnetic permeability of the concrete, even though it is low, will have some affect on the reading. Therefore, the calibrated scales on the meters of commercial equipment are nonlinear. Also, a meter must be readjusted if a different probe is attached.

The probe is highly directional, i.e., a sharp maximum is induced current is observed when the long axis of the probe and reinforcement are aligned and when the probe is directly above the reinforcement.

The commercial cover meter shown in figure 8 can measure concrete cover over reinforcement up to 8 inches (200 mm). Through the use of spacers of known thickness, the size of reinforcing between 3/8 to 2 inches (6 to 51 mm) can be estimated.

Another possible application of the cover meter is to estimate the thickness on both sides. If a steel plate is aligned on one side with the probe on the other side, the measured induced current will give an indication of the thickness of the slab.

3.7.2 Limitations

Cover meters are most useful when reinforced concrete has only one layer of widely separated reinforcing bars. In highly reinforced concrete, the presence of secondary reinforcement makes the satisfactory determination of the depth of concrete cover extremely difficult. Furthermore, reinforcing bars running parallel to that being measured influence the induced current if the distance between bars is less than two or three times the cover distance [18].

3.8 Electrical Potential Measurements

Information on the corrosion state of steel reinforcing bars in concrete can be obtained from measuring the electrical potential of the rebars using a standard reference electrode and a voltmeter. If the steel has a certain electrical potential then the probability of the occurrence of active corrosion is high.

3.8.1 Principle

The electrical potentials of steel reinforcement are measured by making an electrical connection from a voltmeter to the reinforcement and a second electrical contact from the voltmeter to a reference cell making physical contact with the surface of the concrete (figure 9). Dry concrete must first be moistened before making electrical measurements. A saturated copper-copper sulfate electrode is usually used as the reference cell. The electrical potential of the reinforcement below the reference cell is measured.

If the electrical potential of the steel reinforcement is more negative than -0.35 volts versus the copper sulfate electrode, active corrosion is probably taking place. Values in the range of -0.30 to -0.35 volts seem to suggest

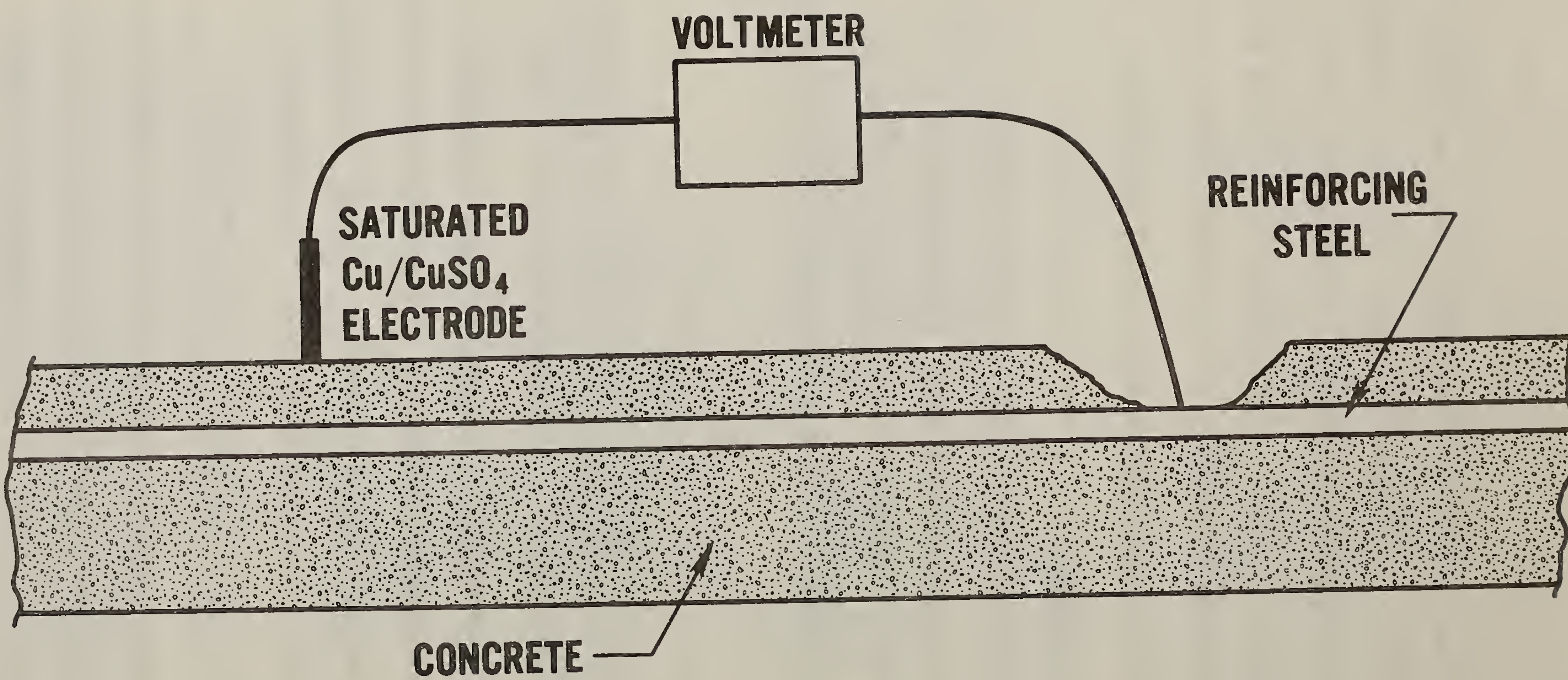

Figure 9. Measurement of electrical potential of steel reinforcing bars in concrete

that corrosive conditions are developing within the concrete, while values less negative than -0.30 volts indicate that the steel is probably passive, i.e., not corroding [28, 29].

An electrical potential diagram of a concrete slab can be rapidly constructed in which areas of similar potentials are outlined. This can be used to identify those areas where the reinforcement may be corroding.

3.8.2 Limitations

Measurements of the electrical potential of steel reinforcement provide information concerning the probability for the occurrence of corrosion but do not indicate either the rate or the extent of corrosion.

A direct electrical connection must be made to the reinforcing steel. If the steel is not exposed, then some concrete covering must be removed.

4. APPLICATION OF OTHER NDE METHODS FOR CONCRETE

The feasibilities of applying other NDE methods to the inspection of concrete are currently being assessed. Methods which appear to be the most promising are described herein. All of these methods need further development before their usefulness or reliability for inspecting concrete can be determined.

4.1 Ultrasonic Pulse Echo

Ultrasonic pulse echo is similar to the ultrasonic pulse velocity technique (section 3.4) in that vibrational waves are induced in concrete. However, in the echo method waves which are reflected off of discontinuities (e.g., cracks and voids) and from interfaces (e.g., interface between concrete and air) are recorded. Both the transmitting and receiving transducers are contained in the same probe, thus, only those waves which are reflected back at nearly 180° to the incident waves are detected.

Echo techniques have been extensively used to identify and locate discontinuities and defects in metals and welds. The echo technique is one of the most versatile and accepted NDE methods for metals. However, its application to concrete has been slow, largely because the extensive pore system, presence of cracking, and the heterogeneous nature of concrete result in multiple reflections which both significantly attenuate the reflected waves and complicate the interpretation of the observations. Recent results suggest that the echo method could be used to measure the thickness of concrete pavements. Thornton and his colleagues at the U.S. Army Engineering Waterways Experiment Station (Vicksburg, Mississippi) are exploring the use of ultrasonic pulse echo to assess the condition of concrete piles [30].

4.2 Microwaves

Microwaves (or radar waves) are a form of electromagnetic radiation which have frequencies between 300 MHz and 300 GHz[1] corresponding to wavelengths of one meter to one millimeter. Microwaves are usually generated in special vacuum tubes called klystrons and transported in a circuit by waveguides. Diodes are commonly used to detect microwaves.

The use of microwaves to estimate the moisture contents of roofing materials [27] and concrete [18] has been explored. Boot and Watson reported [31] that the microwave technique only estimated the moisture content of concrete to

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[1] M = mega = 10^6

G = giga = 10^9

within 12 to 30 percent of its mean value. Its low accuracy was largely attributed to the heterogeneity of concrete, and the internal scattering and diffraction it caused.

Other possible applications of microwaves that are being explored, by the Boulder, Colorado laboratories of the National Bureau of Standards, are to locate voids and cracks in concrete, to measure the thickness of concrete slabs and to provide information on the quality of concrete finishing.

4.3 Infrared Thermography

Infrared thermography measures surface temperature and infrared NDE is based on the principle that heat flow in a material is altered by the presence of some type of anomaly. Changes in heat flow cause localized temperature differences on the material surface above the anomaly.

The temperature and temperature distribution at the surface of an object controls the infrared radiation being emitted by it. The relationship between temperature (T) of an object and the intensity of its infrared radiation (W) is given by the Stefan Boltzmann Law,

$$W = e\,\sigma T^4 \qquad (1)$$

where

e is the emissivity

σ is the Stefan Boltzmann constant (5.67×10^{-12} watt/cm^2/°K^4).

The infrared radiation emitted by an object is normally measured using a radiometer which collects and focuses the radiation on an infrared detector. The temperature profile (i.e., temperature distribution) of an object is usually displayed on a video screen.

Infrared thermography has been successfully used to detect heat loss through buildings and roofs [27]. Clemena [32] has reported that it can also be used to detect deteriorated regions in bridge decks. However, infrared thermography was recently performed on a series of concrete specimens with varyng degrees of freeze-thaw damage at the Nationl Bureau of Standards and the results were inconclusive. Clearly, additional work needs to be performed to develop the emthod for application to concrete to assess its reliability for detecting deteriorated concrete.

4.4 Maturity Concept

The maturity concept has been proposed as a method for predicting the early age strength development of hardening concrete. It relates the combined effect of temperature and hydration time of concrete to its strength [33, 34]. Maturity (M) is usually expressed as:

$$M = \sum (T-To)\Delta t \tag{2}$$

where T is temperature of the concrete, T_o is the highest temperature below which the strength of hardening concrete does not change, and Δt is the increment of time for each temperatur. One proposed relationship for the prediction of compressive strength (f_c') from maturity has taken the form:

$$F_c = A + B \log M$$

where A and B are regression constants.

Lew and Reichard [35] have recently studied the compressive strength and maturity relationship for concrete and developed the following nonlinear regression relationship

$$f_c' = \frac{K}{1 + Ka\,[\log(M - 30)]^b} \tag{3}$$

where K, a and b are numerical constants and 30° F-days is the maturity below which concrete has no measurable strength. They found that the compressive strength-maturity relationship is dependent on the type of cement and on the water-to-cement ratio.

The maturity concept appears to be a promising method for predicting the early age compressive strength of concrete. Such information will be useful in deciding when formwork can be safely removed. Conceivably, the mechanical properties of mature concrete also could be estimated.

One commercially available instrument which automatically computes the maturity of concrete is produced in Denmark [36]. This instrument is called "Maturity Computer" and costs around $2000. The Maturity Computer has been largely used in the production of precast concrete. Its applicability has not been evaluated in the United States. Alternatively, a continuous recording thermometer will suffice for obtaining the necessary data to make maturity calculations.

4.5 Acoustic Emission

Acoustic emissions are elastic stress waves created by localized but real movements in a material under stress [18]. Acoustic emissions are created by several processes, e.g., when concrete cracks or when the reinforcement disbonds from concrete. The intensity or energy of acoustic emissions and their rate of development gives information on the extent of cracking of concrete and can be used to detect impending failures.

Commercial instruments are available to detect acoustic emission and to monitor crack development. In the simplest case, only one transducer is required, which is attached to the object being tested. Acoustic emission instruments are sophisticated and expensive (above $10,000). Their use has been largely confined to the laboratory. However, concrete pressure tanks are currently being checked for crack development when pressurized using acoustic emission techniques. In this case several transducers are placed around suspicious regions so that the location of cracks can be determined. Acoustic emission possibly can be combined with dead weight load tests on concrete structures to assess their stiffness and structural integrity. Further work is required, however, before relationships between acoustic emission and structural integrity are developed.

5. COMBINATIONS OF NONDESTRUCTIVE EVALUATION METHODS

While no single NDE method is entirely satisfactory for predicting the strength or quality of concrete, combinations of methods which respond to different factors may give more definite information.

To predict the compressive strength of in situ concrete more accurately, two or even three different NDE are performed, and their results combined. The most popular combination has been the ultrasonic pulse velocity method in conjunction with the rebound hammer [37]. Other common combinations are the ultrasonic pulse velocity method and the measurement of the damping constant of concrete [38], and the ultrasonic pulse velocity and pulse attenuation methods [39]. The latter two combinations are essentially laboratory research techniques and therefore will not be discussed further.

The results of two methods can be combined in a linear equation of the form:

$$f_c' = A(NDE_1) + B(NDE_2) + C \tag{4}$$

Where f_c' is the estimated comprehensive strength from the combined method, NDE_1 and NDE_2 are the results of the individual methods, and A, B, and C are empirically determined constants.

5.1 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 [40,-43]. In this combined approach ultrasonic pulse velocity measurements are made on in situ concrete, and the rebound number is measured with the Schmidt Rebound Hammer. The pulse velocity and rebound number are substituted into a previously derived regression equation to predict compressive strength [38]. It is believed that the multiple regression equation should give a more accurate estimate of compressive strength than given by either of the individual measurements.

Facaoaru [40] 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 [40,42]. Based on his experiences, Facaoaru contends that by using the combined method, the following accuracy in predictions of compressive strengths can be obtained:

(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.

5.2 Other Possible NDE Combinations

Possible combinations of NDE techniques for estimating the compressive strength of concrete are listed in table 6. The first combination series, i.e., with the maturity concept being the basic method, is mostly applicable to formwork removal decisions. The remaining series are more applicable to determining the uniformity and strength of mature concrete.

Note that the ultrasonic pulse velocity, the rebound hammer, and the probe do not give a direct measure of the strength properties of concrete, whereas the pullout method does. Therefore, combination series No. 2 in table 6 should give a better estimation of strength than series No. 3. However, less planning is required with the methods in series No. 3 and a large amount of data can be rapidly obtained.

Table 6. Possible Combinations of Nondestructive Test Methods

Basic Method[1/]	Properties Predicted by Basic Methods	Interacting Methods	Important Properties of Concrete Measured by Interacting Methods
1. Maturity concept	Compressive strength	Pullout	Tensile & shear strength
		Probe	Surface hardness
		Rebound hammer	Surface hardness
		Ultrasonic pulse velocity	Elastic modulus[2/]
2. Pullout	Tensile and shear strength	Rebound hammer	Surface hardness
		Probe	Surface hardness
		Ultrasonic pulse velocity	Elastic modulus
3. Ultrasonic Pulse velocity	Elastic modulus	Rebound hammer	Surface hardness
		Probe	Surface hardness

1/ Reference method, cores.

2/ Elastic Modulus can be determined if density is known.

6. SUMMARY

Nondestructive evaluation of hardened concrete is becoming an important part of quality acceptance of completed buildings. Quality acceptance programs based on nondestructive evaluation methods (NDE) have been found to be cost effective, reliable, and may increase the service life of buildings while reducing maintenance costs.

In quality acceptance testing of hardened concrete, information which should be obtained includes strength, general quality and uniformity, thickness, air content, stiffness, finish, density and location and condition of steel reinforcement. Nondestructive evaluation methods which can be used to obtain such information have been critically reviewed in this report. Both commonly used test methods and potentially useful test methods have been discussed. In addition, the feasibility of combining two or more test methods for improving the prediction of the strength or quality of concrete has been explored.

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Nondestructive test methods which can be used in quality acceptance programs for hardened concrete have been critically reviewed and are described in this report. Methods have been identified which provide information on the strength, quality and uniformity, thickness, air content, stiffness, finish, density of concrete as well as the location and condition of steel reinforcement. Both commonly used methods and possible test methods are covered. In addition, the feasibility of combining two or more test methods for improving the prediction of the strength or quality of concrete is explored.

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)*

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