DETECTION OF BRIDGE DECK DETERIORATION

by

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A Study of Reinforced Concrete Bridge Deck Deterioration:
Diagnosis, Treatment and Repair
Research Study 2-18-68-130

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PREFACE

This is the ninth report issued under Research Study 2-18-68-130, A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment and Repair. The previous eight are as follows:

1. "A Study of Concrete Bridge Deck Deterioration: Repair," by Raouf Sinno and Howard L. Furr, Research Report 130-1, Texas Transportation Institute, March, 1969.

2. "Reinforced Concrete Bridge Deck Deterioration: Diagnosis Treatment and Repair - Part I, Treatment," by Alvin H. Meyer and Howard L. Furr, Research Report 130-2, Texas Transportation Institute, September, 1968.

3. "Freeze-Thaw and Skid Resistance Performance of Surface Coatings on Concrete," by Howard L. Furr, Leonard Ingram and Gary Winegar, Research Report 130-3, Texas Transportation Institute, October, 1969.

4. "An Instrument for Detecting Delamination in Concrete Bridge Decks," by William M. Moore, Gilbert Swift and Lionel J. Milberger, Research Report 130-4, Texas Transportation Institute, August, 1970.

5. "Bond Durability of Concrete Overlays," by Howard L. Furr and Leonard L. Ingram, Research Report 130-5, Texas Transportation Institute, April, 1971.

6. "The Effect of Coatings and Bonded Overlays on Moisture Migration," by Leonard L. Ingram and Howard L. Furr, Research Report 130-6, Texas Transportation Institute, June, 1971.

7. "An Investigation of the Applicability of Acoustic Pulse Velocity Measurements to the Evaluation of the Quality of Concrete in Bridge Decks," by Gilbert Swift and William M. Moore, Research Report 130-7. Texas Transportation Institute, August, 1971.

8. "Concrete Resurfacing Overlays for Two Bridge Decks," by Howard L. Furr and Leonard L. Ingram, Research Report 130-8, Texas Transportation Institute, August, 1972.

This research was conducted at the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and the United States Department of Transportation, Federal Highway Administration.

The author wishes to thank the many members of the Institute who contributed to this research. Special appreciation is expressed to Mr. Gilbert Swift for his advice and assistance throughout the study and to Mr. Rudell Poehl for his assistance in the field evaluations.

The support given by Texas Highway Department personnel is also appreciated, particularly that of Mr. M. U. Ferrari and Mr. Don McGowan who provided advice and assistance throughout the study and that of the personnel of Districts 2, 4, 5, 7, 8, 18, 22 and 24, who helped in many bridge deck investigations.

ABSTRACT

Delamination is probably the most serious form of deterioration which is commonly found in bridge decks. It ultimately results in large scale spalling necessitating costly repairs. This type of failure is believed to be caused chiefly from salt induced corrosion of the reinforcing steel. An instrument designed to detect delamination, and tests conducted to validate its performance, are briefly described. The instrument has been used by Texas Highway Department maintenance personnel and has been found to be an effective and practical tool, especially on resurfaced decks.

Other bridge deck evaluation techniques investigated were: (a) Corrosion Potential, (b) Acoustic Velocity, (c) Windsor Probe, (d) Schmidt Rebound Hammer, and (e) Direct Tensile Strength. It appears that all of these techniques have merit. It is believed that any of them can be used to search out weak spots or deterioration in bridge decks.

Key Words: Concrete; Deterioration; Testing Evaluation; Delamination; Nondestructive testing.

SUMMARY

Two types of defects have been considered to be of paramount importance in the evaluation of concrete bridge decks. They are (a) delamination (a separation of the original slab into two or more approximately horizontal layers) and (b) poor quality concrete. One portion of this research effort has been directed toward providing a rapid and reliable means for detecting delamination through the development of a practical and fieldworthy instrument. The other portion of this research has been devoted toward investigating various techniques for the detection of poor quality concrete. This effort has resulted in the development of a velocity meter and an in situ tensile testing device. The investigation included two commercially available quality indicating devices, the Schmidt Rebound Hammer and the Windsor Probe. It appears that each of these four techniques has merit and can be used to locate poor quality concrete in bridge decks.

IMPLEMENTATION STATEMENT

The delamination detector has been found to be a practical and fieldworthy tool for use by highway maintenance personnel. Research has demonstrated that multiple-path automatic detection is practical.

The Direct Tensile Test, Velocity Meter, Rebound Hammer, and Windsor Probe are each designed to measure a different characteristic property of in situ concrete. All of them have merit and any one of them can be used to locate weak spots or deterioration in bridge decks. These tests can supply valuable data to the engineer faced with the problem of possible major maintenance of a bridge deck.

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1. INTRODUCTION

This report summarizes the results in Phase 1 of a research study entitled "A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment and Repair." The study is being conducted by the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and the United States Department of Transportation, Federal Highway Administration. The specific objective of Phase 1 of the research is the development of methods to evaluate the extent of deterioration in bridge decks.

Two defects have been considered to be of paramount importance in the evaluation of concrete bridge decks. They are (a) delamination (a separation of the original slab into two or more approximately horizontal layers) and (b) poor quality concrete. Research Report 130-4, entitled "An Instrument for Detecting Delamination in Concrete Bridge Decks," described the development and preliminary testing done in the "delamination" portion of the research. Research Report 130-7, entitled "An Investigation of the Applicability of Acoustic Pulse Velocity Measurements to the Evaluation of the Quality of Concrete in Bridge Decks" described the development and initial testing directed toward the detection of poor quality concrete. In both of these research efforts, primary emphasis was placed on non-destructive testing techniques for diagnosing deterioration. In later research, some slightly destructive concrete evaluation techniques were investigated. Specifically the following measurement techniques were examined:

(a) Delamination Detection,

(b) Corrosion Potential,

(c) Acoustic Velocity,

(d) Windsor Probe,

(e) Schmidt Rebound Hammer, and

(f) Direct Tensile Strength.

The present report describes each one of these measurement techniques and discusses the interpretation of their results. For the convenience of the reader, section 2, Delamination Detection and section 4, Acoustic Velocity contain some background information which has been previously reported. A detailed analysis of comparative in-situ strength measurement techniques is currently in progress and will be reported at a later date.

2. DELAMINATION DETECTION

Probably the most serious form of deterioration commonly found in reinforced concrete bridge decks is delamination which ultimately results in large scale spalling and costly repairs. This type of deterioration occurs most frequently where salt is used for winter deicing and is believed to result chiefly from salt induced corrosion of the reinforcing steel (1, 2, 3, 4).

The normal maintenance procedure for repairing delaminated areas in bridges is to remove the material above the plane of delamination and replace it with a relatively fast setting material (Figure 1). Epoxy or fast setting cement mixes are normally used for these repairs to minimize delay to traffic.

Delamination has been detected by maintenance personnel based on their subjective judgment of the sound produced by striking the deck with a hammer or some other object. Wooden blocks, drag chains, steel rods and specially designed hammers have been used for such detection (Figure 2). These techniques are very dependent upon the operators ability to judge the distinctive "hollow sound" produced at the location of a delamination.

An instrument for detecting delamination was developed in this study to replace the techniques which involve subjective judgment (Figures 3 and 4). The basic design of the instrument and the results of preliminary field evaluations were described in an earlier report (5). The ability of the detector to distinguish delaminated concrete from solid concrete has been verified by specially constructed test slabs (both delaminated and solid) as well as by coring ten different bridges. On each bridge, one core was taken at a location where delamination was not indicated and another at an

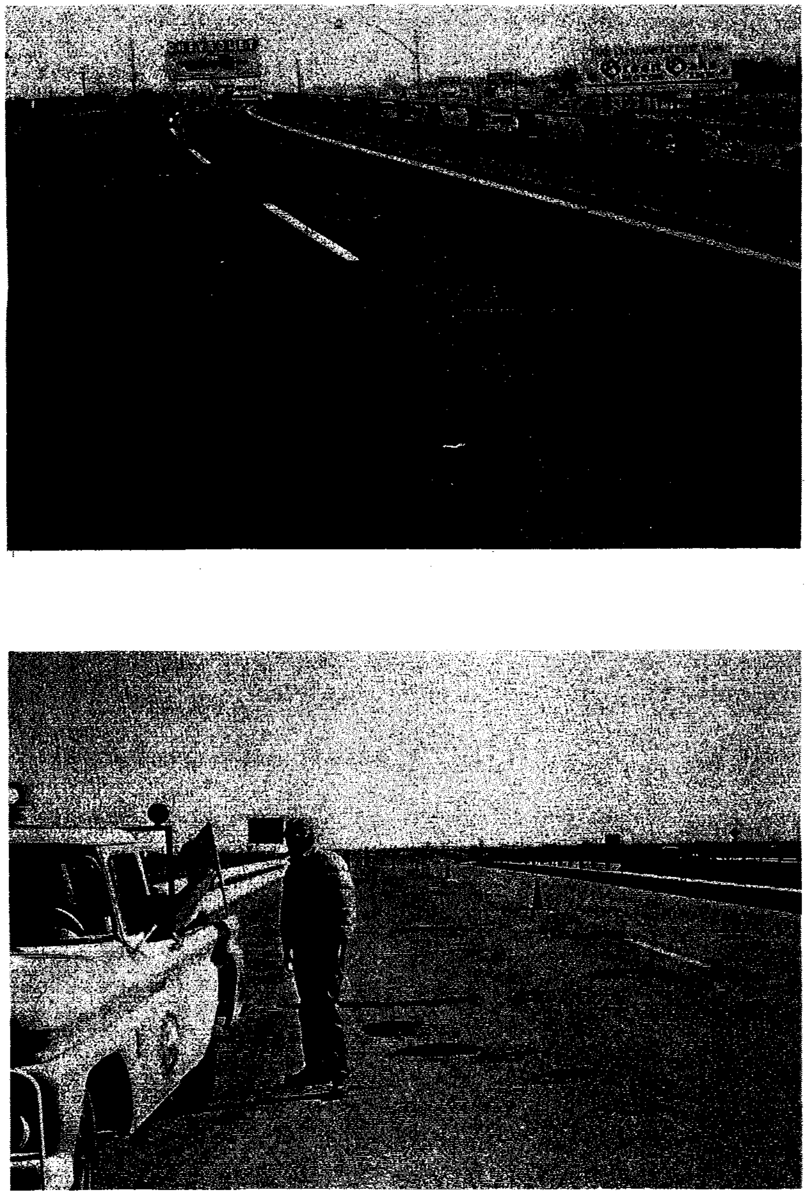
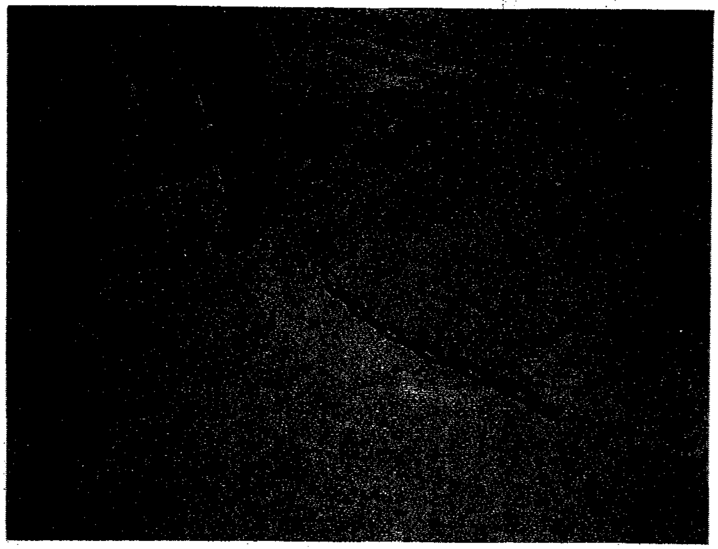


FIGURE 1: Delamination in bridges often necessitates extensive and costly repairs.



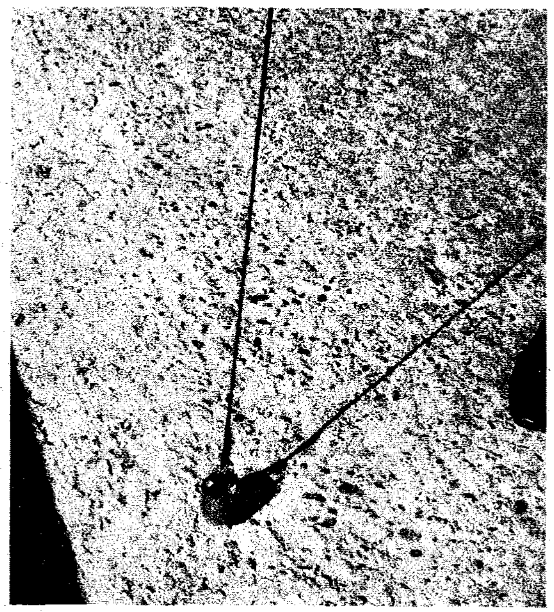


FIGURE 2: Sounding - with chain drag (top) and with "Texas Hammer" (bottom) - to find the "hollow" areas is a method of locating shallow delaminations in non-resurfaced bridge decks.

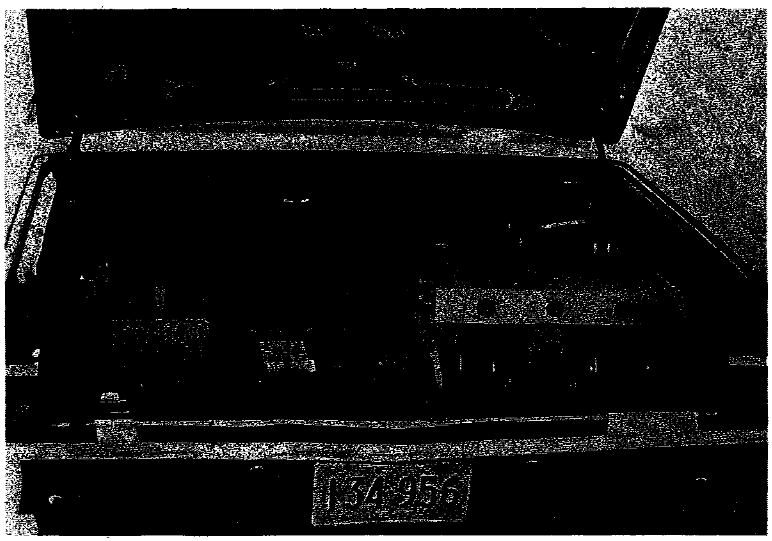


FIGURE 3: Instrument developed to detect delamination on bridge decks. It can be disassembled and stowed in an automobile trunk.

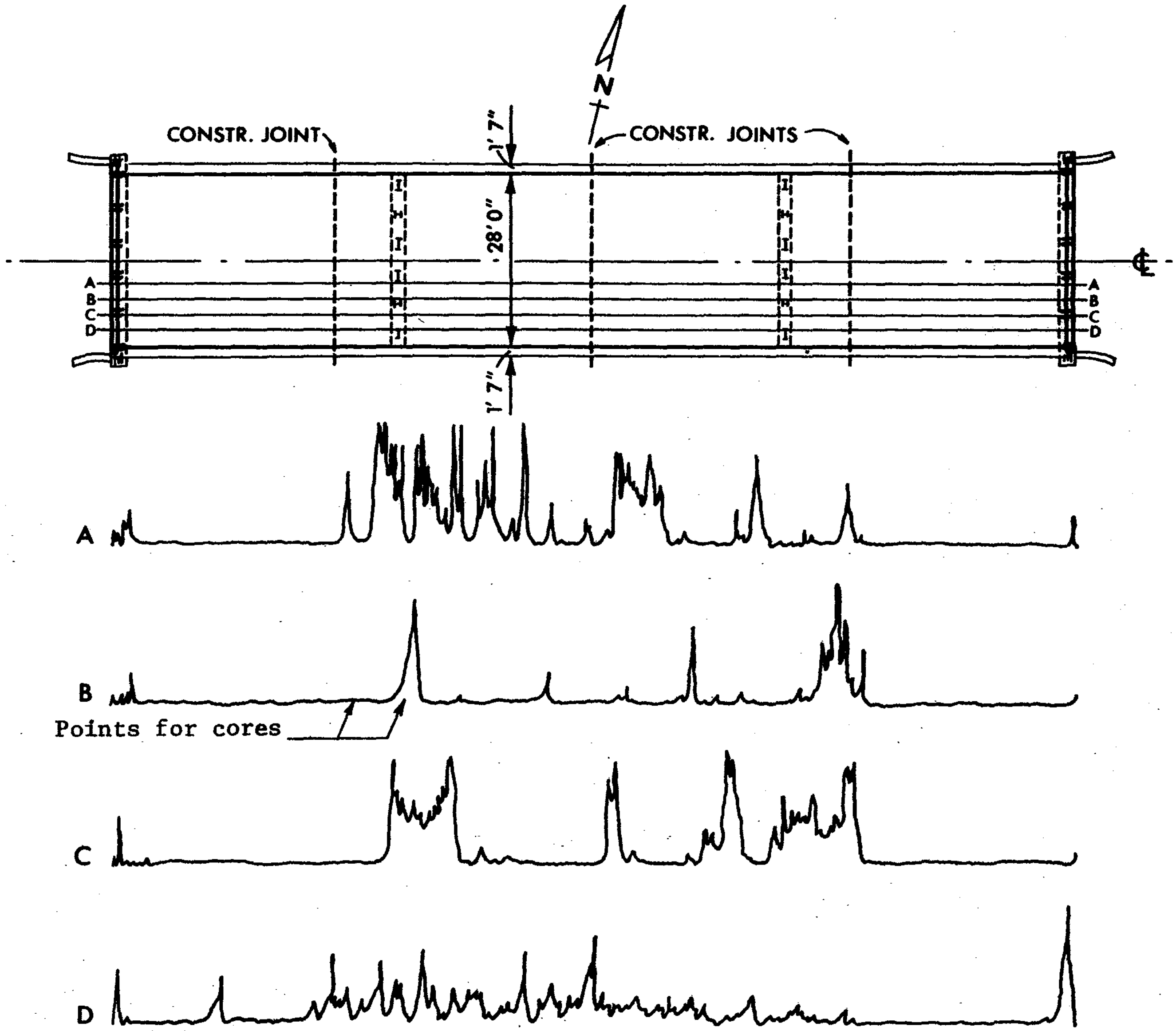


FIGURE 4: Typical record produced by Delamination Detector. Arrows illustrate method of selecting points for taking comparative cores for instrument verification.

apparently identical location where delamination was indicated (Figure 5). Agreement has been perfect. No evidence of delamination or horizontal cracking could be found upon examination of the walls of the core holes at the ten locations where delamination was not indicated; whereas delamination was visible in each of the other ten core holes. Six of the ten bridges had asphaltic surfacing layers which varied in thickness from 1/4 to 3-1/2 inches. The delaminations found in these six bridges varied in depth from 1 inch to 4-1/2 inches. In one instance the delamination was 3 inches below a 1-1/2 inch asphaltic concrete overlay. In another it was 1 inch below a 3-1/2 inch asphaltic concrete overlay. These findings were felt to be particularly significant because the characteristic hollow sound produced by conventional techniques is greatly diminished by asphaltic surfacing layers. The delaminations found in the four unsurfaced bridges varied in depth from 1/2 to 2-1/2 inches. It is doubtful that conventional sounding techniques could have been used to locate the delaminated areas in most of the ten bridges cored.

Since the earlier report (5) the instrument has been used by maintenance personnel in several Texas Highway Department Districts. Through this more or less continuous use, several design problems in the instrument were found which were eliminated by subsequent modifications. The major modifications consisted of the following:

1. Modification of the electrical power pack to permit more than 8 hours of continuous use.
2. Modification of the acoustic receivers to eliminate transducer deterioration.
3. Development of a calibrator to standardize and equalize the sensitivity of the acoustic receivers.

FIGURE 5: Verification of the ability of the instrument to detect delamination was made by coring two locations in each of ten bridges (one in an indicated and one in a non-indicated area). Note typical horizontal separation visible in core hole at a location where delamination was indicated by the unit.

Probably the most extensive use of the instrument was by maintenance personnel in the El Paso District who surveyed about 130 bridges (Figure 6). Most of these bridges contained asphaltic concrete or epoxy overlays. El Paso maintenance personnel report that conventional sounding techniques were not effective on most of these decks because of the overlays.

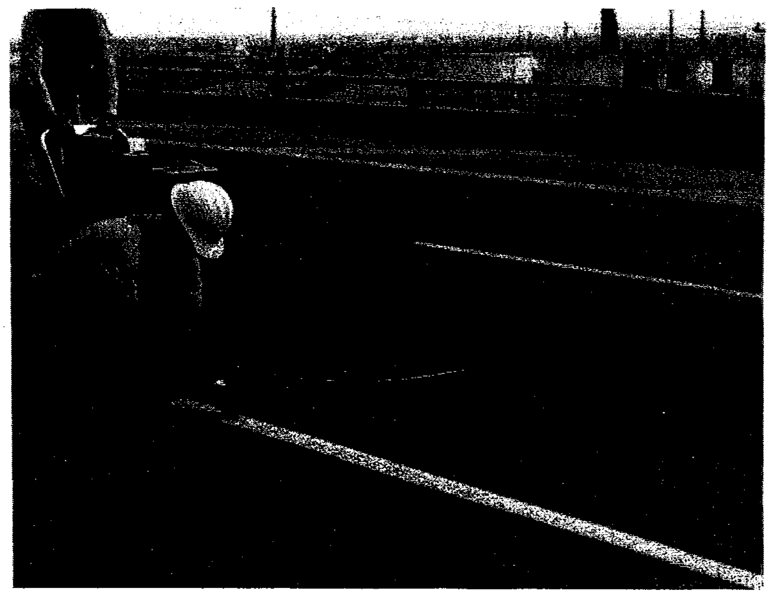


FIGURE 6: The delamination detector has been used for bridge deck inspections by maintenance personnel in several Texas Highway Department Districts. Probably the most extensive use was by the El Paso District personnel who accurately surveyed about 130 bridges.

3. CORROSION POTENTIAL

As mentioned previously, bridge deck delamination is believed to result chiefly from salt induced corrosion of the reinforcing steel. If this corrosion can be detected before it causes delamination, it may be possible to arrest the corrosion prior to its damaging effects on a deck. Currently, cathodic protection is being investigated as a possible means of arresting corrosion under the National Cooperative Highway Research Program project number 12-13,"Cathodic Protection for Reinforced Concrete Bridge Decks."

The California Division of Highways has reported that electrical potential measurements can be made on the surface of a concrete bridge deck which are indicative of active corrosion of reinforcing steel (2, 6, 7). These measurements are obtained by making an electrical connection to the reinforcing steel and a second electrical connection between a saturated copper-copper sulfate half cell and the upper surface of the deck (Figure 7). The latter connection is made with a sponge saturated with copper sulfate solution. The electrical potentials are measured using a high input impedance voltmeter.

Typical results of an electrical potential survey using the California technique are shown in Figure 8. These measurements were made by a Federal Highway Administration demonstration team under the Region 15 Research and Development Demonstration Projects Program. In this survey a core was taken in the area of the highest potential indicated and rust was found on the reinforcing steel at that location.

Under this Federal Highway Administration program, the demonstration team has made measurements on bridges in forty-eight states and the District of Columbia. Their results to date indicate that the system gives reasonably

FIGURE 7: Electrical potentials between a copper-copper sulfate half cell and the steel reinforcement are measured with a high impedance voltmeter. The half cell is used as a probe to measure the potentials at various points on a deck.

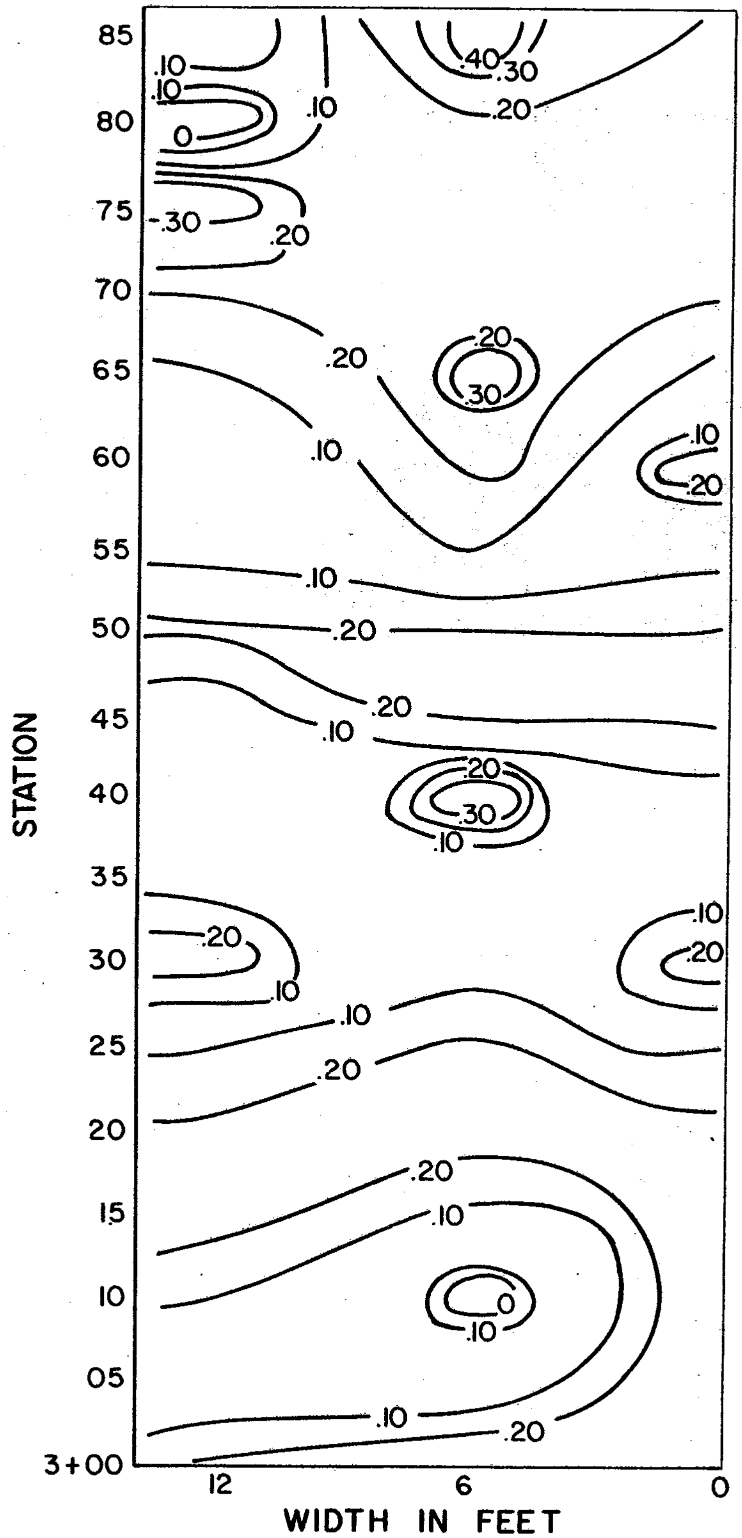


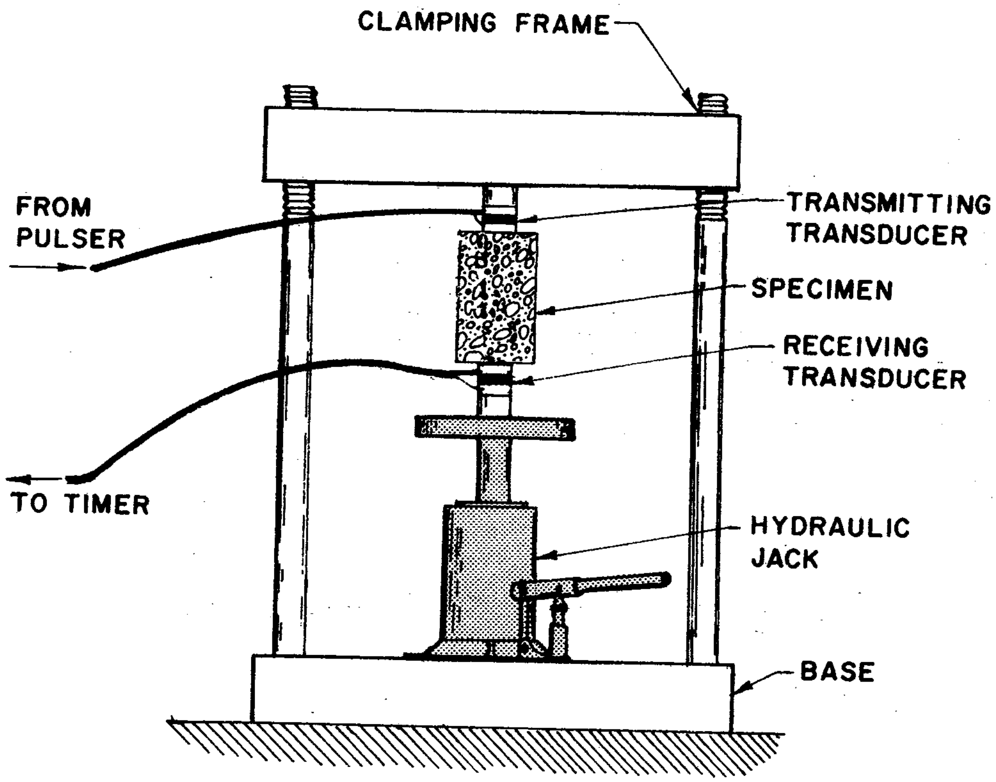
FIGURE 8: Typical results of an electrical potential survey made by the FHWA demonstration team. A core was taken in the area of highest potential and rust was found.

accurate indications of the degree of corrosion in bridges. Measurements have been confirmed with actual on site inspections. Because a complete inspection required measurements to be made at numerous points on a deck, considerations are being given by the Federal Highway Administration research team to automate the device.

4. ACOUSTIC VELOCITY

From the literature acoustic pulse velocity measurements appeared to offer a promising method for determining the quality of concrete in bridge decks (8, 9, 10, 11, 12, 13, 14, 15). Thus, as a first step, the relationship of acoustic wave velocity to other properties of concrete was explored. Laboratory measurements were made on a wide variety of concrete specimens and the relationships between measurements of acoustic compressional wave velocity, unit weight, elastic modulus and strength were examined. The results of this investigation as well as a description of an instrument designed for field-type measurements has been reported previously (16).

In the laboratory investigation two measuring techniques for determining acoustic velocity were investigated (Figure 9). The simplest technique, referred to as "timing through," is based upon the time required for an acoustic wave train to travel the distance between a pulsed transducer and a receiving transducer which are coupled to opposite sides of a specimen. The other technique, which is applicable to making measurements on the accessible upper surface of bridge decks, is referred to as the "timing along" technique. This method is based on determining the travel-time of the wave train between two points on the same surface as the pulsed transducer. Using either technique attainment of accuracy requires consideration of the effects of time delay in the transducers and their couplings. Comparison measurements indicated a satisfactory agreement between the two techniques. Upon comparison of the measurements, substantial agreement was found between the dynamic elastic modulus as determined by ASTM C215 and an estimate based on



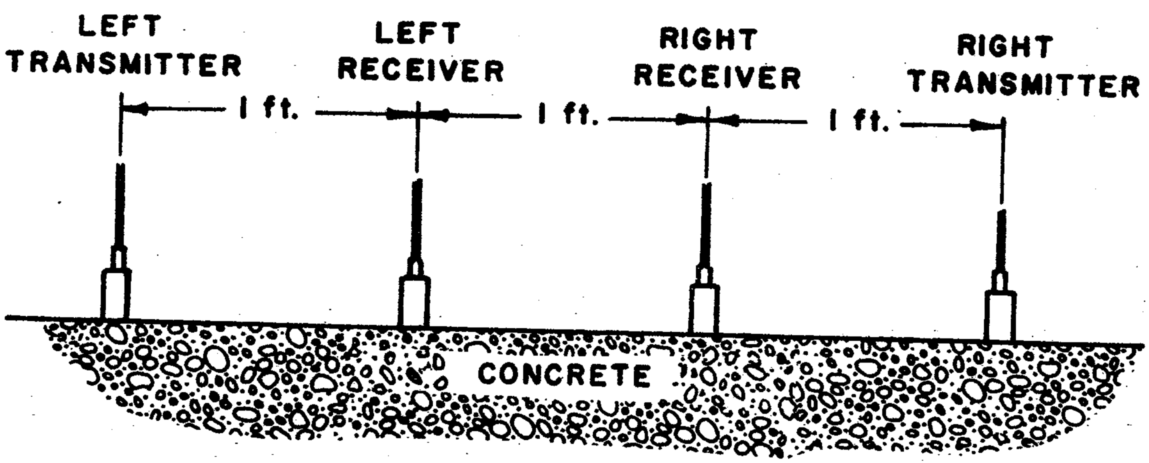


FIGURE 9: The "timing through" technique for measuring acoustic wave velocity (top) determines the time required for a wave-train to travel the distance between transducers coupled to opposite sides of a specimen. The "timing along" technique (bottom) measures the acoustic wave travel time between points on the same surface.

velocity and unit weight. Similar agreement was found for the chord modulus as determined by ASTM C469. The estimating equations found are as follows:

$$\hat{E}_r = \frac{V_c^2 W}{5670} \text{ ---------------- Eq. 1}$$

$$\hat{E}_r = \frac{V_c^2 W}{6630} \text{ ---------------- Eq. 2}$$

where $\hat{E}_r$ = estimated dynamic modulus in psi,

$\hat{E}_c$ = estimated chord modulus in psi,

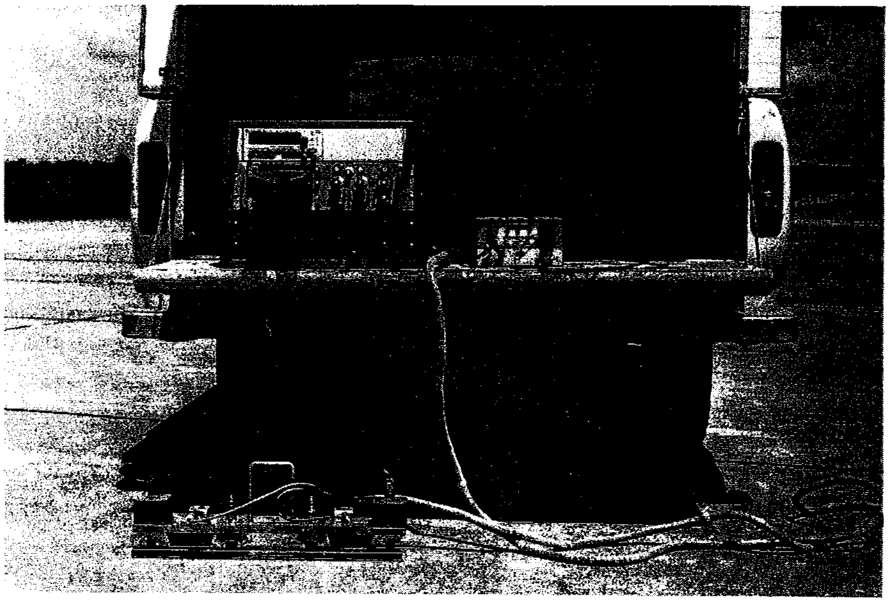
V_c = compressional wave velocity in ft/sec, and

W = unit weight in pcf.

The coefficients of variation for equations 1 and 2 were found to be 9.5 and 12.0 percent, respectively.

No consistent relationship to velocity was found among the compressive strength measurements made on cylindrical specimens; however, separate trends were found for velocity to increase with strength within each group of cast cylinders containing a specific type of coarse aggregate. These comparisons of laboratory measurements indicate that velocity measurements used with discretion are generally indicative of the concrete quality.

As mentioned previously a portable field-type velocity measuring instrument was developed in this study for use on the accessible upper surfaces of bridge decks (Figure 10). It employs a probe which places an array of four acoustic transducers into contact with the concrete. Velocity is measured, using the "timing along" technique, by observing the time of travel of the acoustic waves between two identical receiving



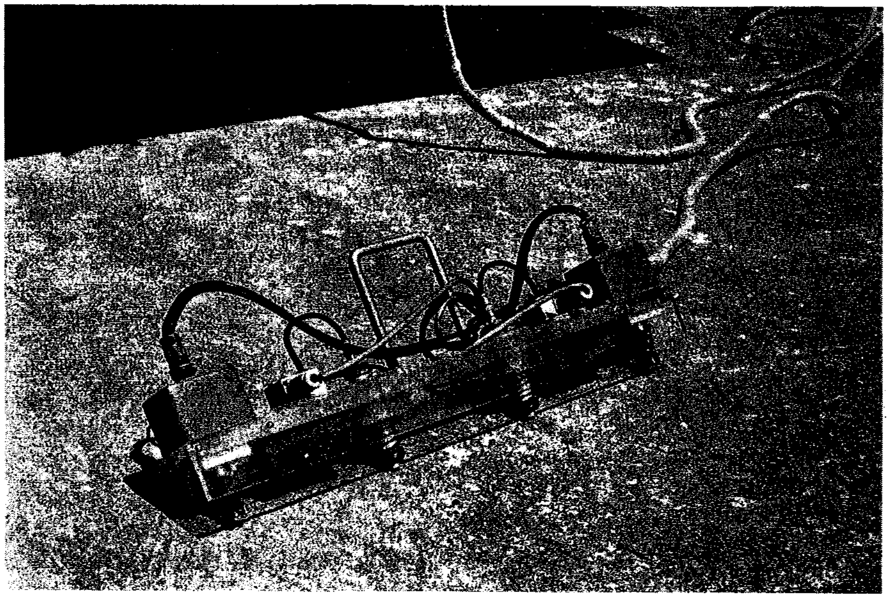


FIGURE 10: The control unit of the field-type velocity measuring instrument is conveniently operated from a pickup tail gate as the probe unit is moved to various points on the deck.

transducers. Waves are produced and propagated successively in opposite directions and the two time-intervals are measured and averaged in order to cancel coupling delay errors. Other design features include a precise digital timer used in combination with a novel timing method in the oscilloscope display, and low power consumption which permits the instrument to be operated from a vehicle battery.

Since the previous report the field instrument has been used to make measurements on 25 different bridge slabs and 12 specially constructed laboratory slabs. Normally the average of three velocity measurements was determined for each slab. It was found that on many of the bridges which have been in service for several years, it is difficult to measure the acoustic velocity due to the attenuation introduced by numerous small surface cracks. Often these surface cracks were visible only after moistening the surface. This problem was not encountered on the newer slabs.

The compressive strengths of air dried cores taken from the slabs were found to be slightly correlated with the slabs' average acoustic velocities. In a linear regression analysis to estimate slab core strength from its average acoustic velocity the coefficient of variation was found to be 19.9%.

The instrument is believed to be practical for use in research studies when it is desirable to non-destructively estimate the modulus of elasticity (Equations 1 & 2). It is not believed to be practical for routine bridge deck measurements, since on too many in-service bridges the measurement process is difficult and time consuming even for a highly trained operator. A single measurement requires about 3 minutes on a new slab but may require up to 30 minutes on an older slab that contains surface cracks.

5. WINDSOR PROBE

The Windsor Probe Test System has been used in field investigations to estimate the in-situ strength of concrete in pavements, bridges, walls, pipes, etc. (17, 18, 19). The device is easy to use and requires no surface preparation prior to testing. Basically the tests consist of shooting a standard probe into the concrete with a standard cartridge. The depth of penetration is determined by measuring the height of the exposed probe. A special gun or driver unit is provided for shooting the probes (Figure 11). Gage plates are also provided to measure of the average height of the exposed probes in a standard group of three shots. The higher the probes, i.e., the more resistant to penetration, the stronger the concrete.

Windsor Probe Test Systems, Inc. provided a complete measurement system and a set of minerals for performing scratch tests to determine Moh's hardness for temporary use at no charge in this study. Probes and cartridges were furnished for a nominal charge. Measurements were made with this instrument on 38 different portland cement concrete slabs which contained many different kinds of aggregates.

From the average of three probe penetration values and the Moh's hardness of the coarse aggregate, estimates of the compressive strengths were made using tables furnished by the manufacturer. These estimates were generally higher than the measured compressive strengths of air dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the probe values. In a linear regression to estimate core strengths directly from probe values without any correction for aggregate hardness the coefficient of variation was found to be 20.3 percent.

This test system is believed to be practical for bridge deck survey measurements to locate weak spots. The test is slightly destructive. In addition to the small hole made by the probe penetration, a spall about six inches in diameter and up to three fourths of an inch deep at the center is often produced by the test. A standard group of three probes can be shot and measured in about 5 to 7 minutes.

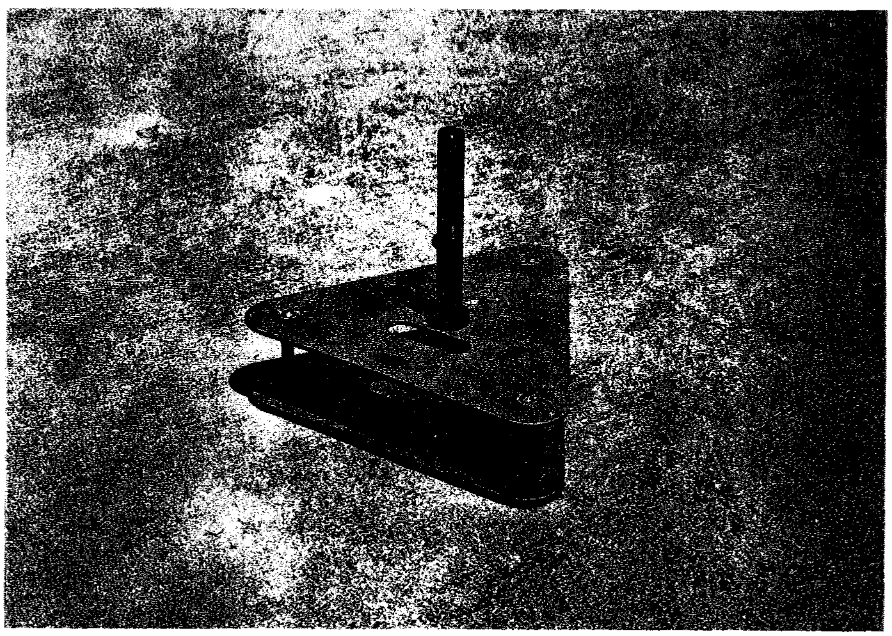


FIGURE 11: A standard stud is shot into concrete with the Windsor Probe Test System to determine concrete quality. The average penetration resistance of three shots is measured using a depth gage and special templates.

6. SCHMIDT REBOUND HAMMER

The Schmidt Rebound Hammer is a very widely used instrument for estimating the quality of in situ concrete. Basically, the test consists of striking a rod, in contact with the concrete, with a standard hammer and measuring the height of the hammer rebound. The higher the rebound, the stiffer (and better quality) the concrete.

Several authors have suggested that the Schmidt rebound hammer can be used to estimate the compressive strength of in-situ concrete (20, 21, 22). They agree that the type of coarse aggregate, surface condition of the concrete, its moisture condition, etc., have a pronounced effect on the relationship between rebound reading and strength. Also, there is common agreement that the instrument can be used to determine the uniformity of concrete and thus is an effective tool for locating weak spots.

A Soiltest Model CT200 rebound hammer was used for this study (Figure 12). Measurements have been made with it on 38 different portland cement concrete slabs which contained many different kinds of aggregate. From the average of fifteen rebound readings at each site, estimates of the compressive strength were made using curves furnished by the manufacturer. These estimates were generally much higher than the measured compressive strengths of air dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the rebound values. In a linear regression to estimate core strengths from rebound values, the coefficient of variation was found to be 21.2 percent.

The rebound hammer is fast and easy to use and is believed to be practical for bridge deck measurements to locate weak spots. Prior to measurements the surface of the deck should be ground smooth with a hand grinder. The smoothing operation and 15 tests can be made in about 3 to 5 minutes.

FIGURE 12: A Soiltest Model CT200 rebound hammer is used to estimate concrete strength. Prior to testing the surface is smoothed with a hand grinder.

7. DIRECT TENSILE TEST

An important characteristic of concrete, which is seldom considered in field evaluations, is its tensile strength. This characteristic is highly significant in quality bridge deck construction.

In 1956, the Shell Chemical Corporation introduced a "Highway Tensile Tester" (Figure 13). This tester was developed for evaluating the quality of resinous cement overlays and to pre-evaluate the surfaces upon which they were to be applied. A device similar to the Shell tester was fabricated in this study (Figure 14). The chief modification was that a hydraulic cylinder, instead of a screw, was used to apply tension in order to eliminate the possibility of horizontal forces on the screw handle being converted into unwanted tension.

Another tensile tester, quite similar to the Shell device, is described in Test Method California 420-A "Method of Testing Cleanness and Soundness of Portland Cement Concrete Surfaces and Quality of Resinous Cement Overlays," published by the California Division of Highways. The procedure used to measure tensile strength in this study is the same as that described in Part II of the California test method, "Evaluation of Soundness of Portland Cement Concrete Surfaces."

Using this device, direct tensile strength was measured on 30 different portland cement concrete slabs. Normally the average of three tensile tests was determined for each slab. These tensile strength measurements were found to be slightly better correlated with the compressive strengths of air dried core samples taken from the same slabs than any of the other measurement techniques investigated. In a linear regression analysis to estimate core strengths from the average tensile strengths the coefficient of variation was found to be 17.7 percent.

The test is somewhat time consuming because it requires a period of about an hour and a half for the epoxy to harden prior to testing. On a warm day about 40 tests could be made in an 8-hour day. Values obtained using this test would probably be more indicative of the general quality of the concrete slabs than any of the other tests investigated and the test is believed to be practical for bridge deck measurements.

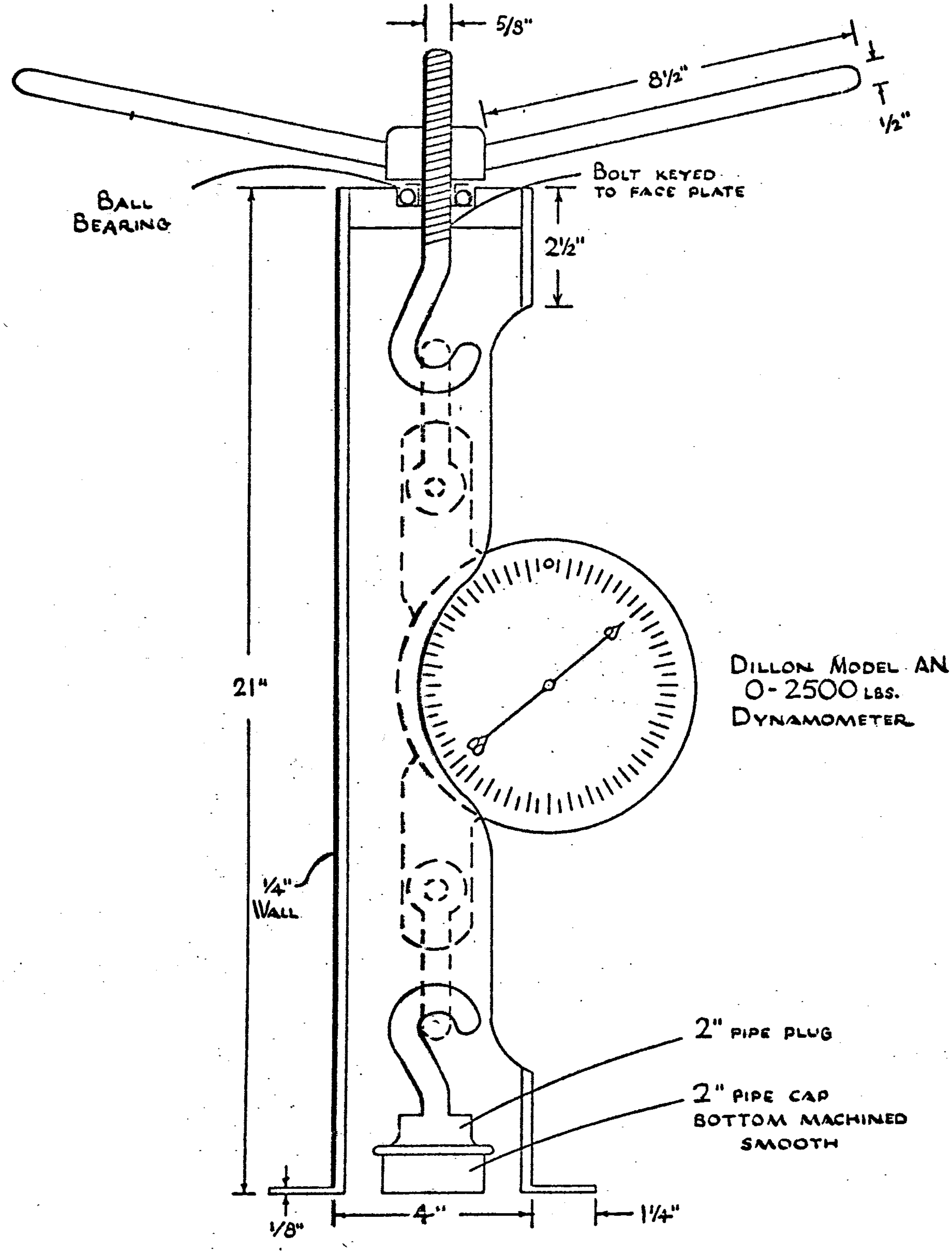


FIGURE 13: "Highway Tensile Tester" developed in 1956 by the Shell Chemical Corporation.

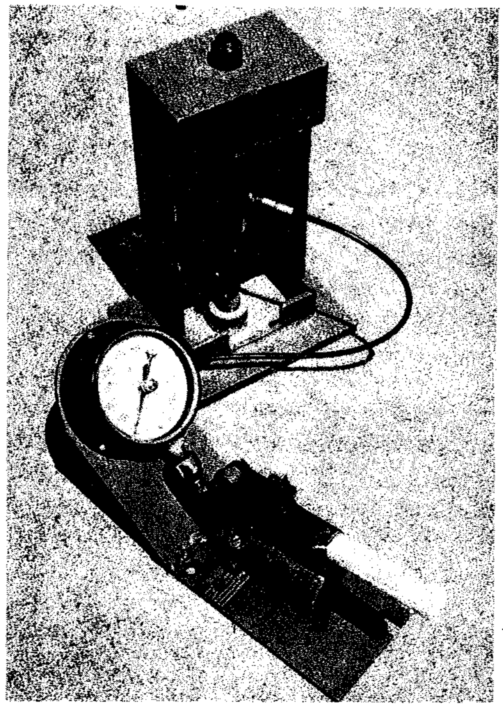


FIGURE 14: Two-inch diameter aluminum cylinders are epoxied to a smooth clean concrete surface. After about 90 minutes for curing, tension is applied to pull out a dome shaped piece of concrete.

8. CONCLUSIONS

1. The technique utilizing the delamination detector developed in this study has been found to be practical and effective for determining the extent of delamination in bridge decks.
2. It appears that all of the six measurement techniques investigated have merit and can be used to locate weak spots or deterioration in bridge decks; however, each one is designed to measure a different characteristic property.
3. The Direct Tensile Test, Velocity Meter, Windsor Probe and the Rebound hammer can each be used to estimate core compressive strength within about 20 percent.

9. REFERENCES

1. Freyermuth, Clifford L., Paul Klieger, David C. Stark, and Harry N. Wenke. "Durability of Concrete Bridge Decks-A Review of Cooperative Studies", Highway Research Record No. 328, pp. 50-60, 1970.

2. Spellman, Donald L. and Richard F. Stratfull. "Chlorides and Bridge Deck Deterioration," Highway Research Record No. 328, pp. 38-49, 1970.

3. Stark, David. "Studies of the Relationships Among Crack Patterns, Cover Over Reinforcing Steel, and Development of Surface Spalls in Bridge Decks," Highway Research Board Special Report No. 116, pp. 13-21, 1971.

4. Stewart, Carl F. "Deterioration in Salted Bridge Decks," Highway Research Board Special Report No. 116, pp. 23-28, 1971

5. Moore, William M., Gilbert Swift, and Lionel J. Milberger. "An Instrument for Detecting Delamination in Concrete Bridge Decks," Research Report 130-4, Texas Transportation Institute, Texas A&M University, College Station, Texas, pp. 1-29, 1970.

6. Gewertz, M. W., B. Tremper, J. L. Beaton, and R. F. Stratfull. "Causes and Repair of Deterioration to a California Bridge Due to Corrosion of Reinforcing Steel in a Marine Environment," Highway Research Board Bulletin No. 182, pp. 1-41, 1958.

7. Stratfull, R. F. "The Corrosion of Steel in a Reinforced Concrete Bridge," Corrosion, Vol. 13, No. 3, June 1957.

8. Krautkramer, J. and H. Krautkramer. "Ultrasonic Testing of Materials," Springer-Verlag, New York, 1969.

9. Breuning, S. M. and V. J. Roggeveen. "Soniscope Testing," Proceedings 34th Annual Meeting, Highway Research Board, Washington, D.C., pp. 379-386, 1955.

10. Whitehurst, E. A. "Pulse-Velocity Techniques and Equipment for Testing Concrete," Proceedings 33rd Annual Meeting, Highway Research Board, Washington, D.C., pp. 226-242, 1954.

11. Manke, Philip G. and Bob M. Gallaway. "Pulse Velocities in Flexible Pavement Construction Materials," Highway Research Record No. 131, pp. 128-153, 1966.

12. Popovics, Sandor. "Characteristics of the Elastic Deformations of Concrete," Highway Research Record No. 324, pp. 1-14, 1970.

13. Woods, K. B. and J. F. McLaughlin. "Application of Pulse Velocity to Several Laboratory Studies of Materials," Highway Research Board Bulletin No. 206, Washington, D.C., pp. 14-27, 1959.

14. Long, B. G., H. J. Kurtz, and T. A. Sandenaw. "An Instrument and Technique for Field Determination of Modulus of Elasticity of Concrete (Pavements)," Proceedings, American Concrete Institute, Vol. 41, pp. 217-231, 1945.

15. Leslie, J. R. and W. J. Cheesman. "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures," Proceedings, American Concrete Institute, Vol. 46, pp. 17-36, 1950.

16. Swift, Gilbert and William M. Moore. "An Investigation of the Applicability of Acoustic Pulse Velocity Measurements to the Evaluation of the Quality of Concrete in Bridge Decks," Research Report 130-7, Texas Transportation Institute, Texas A&M University, College Station, Texas, pp. 1-32, 1971.

17. Klotz, Robert C. "Field Investigation of Concrete Quality Using the Windsor Probe Test System," presented at the 50th Annual meeting of the Highway Research Board, Washington, D.C., 10 pp., 1971.

18. Gaynor, R. D. "In-Place Strength of Concrete -- A Comparison of Two Test Systems," presented at the 39th Annual Convention of the National Ready Mixed Concrete Association, New York, 13 pp., 1969.

19. "Concrete Compressive Strength Test by the Windsor Probe Test System," Windsor Probe Test Systems, Inc., Elmwood, Connecticut, 12 pp., 1970.

20. Boundy, C. A. P. and G. Hondros. "Rapid Field Assessment of Strength of Concrete by Accelerated Curing and Schmidt Rebound Hammer," Journal of the American Concrete Institute, Vol. 61, pp. 77-84, 1964.

21. Grieb, William E. "Use of the Swiss Hammer for Estimating the Compressive Strength of Hardened Concrete," Public Roads, Vol. 30, No. 2, pp. 45-50, June, 1958.

22. Zoldners, N. D. "Calibration and Use of Impact Test Hammer," ACI Journal, Proceedings, Vol. 54, No. 2, pp. 161-165, August, 1957.