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16. Abstract

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AN INVESTIGATION OF CONCRETE QUALITY EVALUATION METHODS

by

Rudell Poehl
Engineering Research Associate

Gilbert Swift
Research Instrumentation Engineer

and

William M. Moore
Associate Research Engineer

Research Report No. 130-10
A Study of Reinforced Concrete Bridge Deck Deterioration:
Diagnosis, Treatment and Repair
Research Study 2-18-68-130

Sponsored by

The Texas Highway Department
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U. S. Department of Transportation
Federal Highway Administration

November, 1972

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

Preface

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

9. "Detection of Bridge Deck Deterioration," by William M. Moore, Research Report 130-9, 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 authors wish to acknowledge their gratitude to all members of the staff of Texas Transportation Institute who contributed to this research. Special thanks are expressed to Mr. L. J. Milberger for his assistance in instrument development.

The support given by the Texas Highway Department personnel is also greatly appreciated, especially that of Mr. M. U. Ferrari and Mr. Don McGowan who provided advice and assistance throughout the study and that of the maintenance personnel of Districts 2, 4 and 7 who helped in the bridge deck investigations.

Abstract

Four techniques applicable to a field survey for detecting areas of poor quality concrete in concrete bridge decks were investigated and compared. Comparisons were also made between the measurements obtained using these four techniques and laboratory determinations of the compressive strength of cores taken from each bridge deck.

It was concluded that each of the techniques, acoustic velocity, Windsor probe, Schmidt hammer and direct tensile test can be applied to a survey procedure for detecting weak spots. The results imply that core compressive strength is not the only useable indicator of concrete quality and also that the several properties of concrete which determine its quality are largely independent. Each of the above techniques and the core strengths appear to be somewhat differently influenced by the effects which accompany deterioration.

KEY WORDS: Concrete Quality, Deterioration, Non-destructive Testing, Bridge Deck, Measurement.

Summary

Several non-destructive (or slightly destructive) techniques for detecting deteriorated or poor quality concrete in bridge decks were compared with each other and with measurements of core compressive strengths. Measurements made on 26 bridge slabs indicate that core compressive strength is not a complete measure of environmental deterioration or loss of quality of concrete. Each of the other measurement techniques, acoustic velocity, Windsor probe, Schmidt hammer and direct tensile test, was found applicable to a survey procedure for finding deteriorated or poor quality areas on bridge decks. The Schmidt hammer was found to provide the most rapid method, but, as ranked by the authors with respect to confidence in its ability to detect deteriorated concrete, the tensile test was superior. The results imply that each of the measurement techniques is differently influenced by the effects which accompany deterioration.

Implementation Statement

Any one of the four techniques investigated could be implemented to provide a rapid field survey method for detecting and delimiting areas in bridge decks which contain deteriorated or poor quality concrete.

The choice among the field instruments tested depends largely upon the purpose of the testing program and upon such factors as the required speed of operation and the level of operator training and skill available.

The most rapid and economical of the methods investigated (and the one requiring the least skillful operation) was found to be the Schmidt rebound hammer. This device, which has been available for a number of years and has been widely used in concrete testing, could be applied in a program of routine bridge deck survey measurements to accomplish the general objective of finding low quality areas. While somewhat greater confidence might be placed in measurements made by another technique, the simplicity and economy of the Schmidt hammer are such as to make it the most readily implementable one of the several methods tested.

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1. Introduction

This report describes the research effort directed at the detection of the accumulated gradual deterioration and loss of quality in concrete bridge decks. This research was a portion of the work in Phase 1 of the research study entitled "A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment and Repair" being 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 objective of Phase 1 was the development of methods to evaluate the extent of deterioration in bridge decks.

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 equipment development and initial testing directed toward the detection of poor quality concrete. Research Report 130-9, entitled "Detection of Bridge Deck Deterioration" summarized several different types of instruments applicable to the detection of several forms of bridge deck deterioration and the results of their use in this study. The present report deals only with the measurements aimed at determining concrete quality, the specific purpose of this research effort being the detection of poor quality concrete. Although emphasis was placed on non-destructive testing techniques, two slightly destructive evaluation methods were included in this investigation. The following quality determination techniques were investigated and evaluated:

(a) acoustic velocity

(b) Windsor probe, (slightly destructive),

(c) Schmidt rebound hammer, and

(d) direct tensile strength (slightly destructive).

The measurements made using these four techniques and the results obtained are presented in this report. Comparisons between the concrete properties indicated by each of these measurement techniques, and the compressive strengths of cores taken in the vicinity of the spot at which the measurements were made on each slab, are evaluated.

At the outset of this research it was believed that the best technique available to evaluate deterioration or the loss of quality in a concrete bridge deck would be the measured compressive strength of cores taken from the deck. The results of the investigation reported here imply that the core compressive strength is not clearly the best indicator of concrete quality. They indicate that the properties of concrete measured by the four instruments mentioned above also determine its quality and that these properties are largely independent.

2. Measurements Program

Initially, measurements were made with each of the four instruments on twelve 18x48x7.5 inch slabs made during this study from twelve different batches of concrete. Descriptions of the batches are given in Table A-1 of Appendix A. The batches contained three different types of aggregate and had widely varying cement factors.

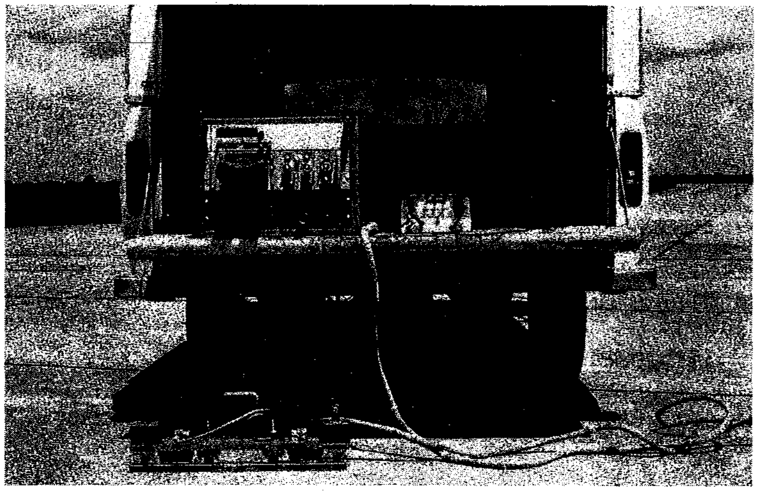
Additional measurements were made in the field on actual bridge slabs. The bridges were located in the Texas Highway Department Districts of Fort Worth, Amarillo, and San Angelo. Bridges were selected with the objective of obtaining a range of ages and strengths of the concrete. The bridges and the number of slabs tested on each bridge are listed in Table A-2 of Appendix A. Measurements were attempted with each of the four instruments on all of the bridges. However, on one bridge slab in the Amarillo District, readings could not be obtained with the acoustic velocity meter. Many of the velocity readings reported were difficult to obtain because of micro-cracking in the bridge decks. Although the wave velocity is substantially unaffected, these cracks tend to greatly attenuate the acoustic signals. Also, the measurements made of the direct tensile strength in the Fort Worth District have been discarded. The needle of the hydraulic gage was sticking during the time these tests were made, rendering these data inaccurate and therefore meaningless. The data taken on the twenty-six bridge slabs and the twelve test slabs are given in Table A-3 of Appendix A. Average values are shown for each instrument on each slab. The number of observations made on each slab differed with instruments. Fifteen were made with the rebound hammer. Three were normally made with the Windsor probe and velocity meter; however, on the laboratory slabs, only one reading was made with the velocity meter. Three tensile tests were made on the laboratory slabs and normally four on the bridge slabs. Also shown in Table A-3 are compressive strengths of 4" diameter cores taken from all thirty-eight slabs in the vicinity of the locations used for the other tests. One core was taken from each slab. All of the tests on each slab, other than the velocity tests were made within a one square yard area. Because of the need to avoid cracks, the velocity measurements could not always be made within the same area used for the remaining tests.

3. Operation of Instruments

A. Operation of the Velocity Meter

The velocity measuring system was basically the same as that described in a previous publication, Research Report 130-7[1] but was modified by reducing its transducer spacings from 1 foot to 8 inches. The operating procedure for its use is given in Section 1 of Appendix B. As shown in Figure 1, this apparatus consists of an array of four transducers placed in contact with the bridge deck for transmitting and receiving the propagated waves, and electronic equipment for determining the time-interval between the wave arrival at two receiving transducers spaced 8 inches apart. Waves are propagated from left to right using the left transmitter and from right to left using the right transmitter. The time of wave travel between the two receiving transducers is observed for each direction of travel and averaged. This procedure minimizes the effect of time delays in the acoustic couplings between the receiving transducers and the concrete surface.

Timing is accomplished by separately observing the first zero crossing of each received signal on one trace of a dual-trace oscilloscope and setting an appropriately shaped voltage step to occur at the corresponding instant on the second trace. When this matching has been done for both received signals, the time-interval between the two voltage steps has been set equal to the time-interval between the wave arrival at the two receivers. The two voltage steps are utilized respectively to start and stop a time-interval counter having a digital display readable to the nearest one-tenth microsecond.



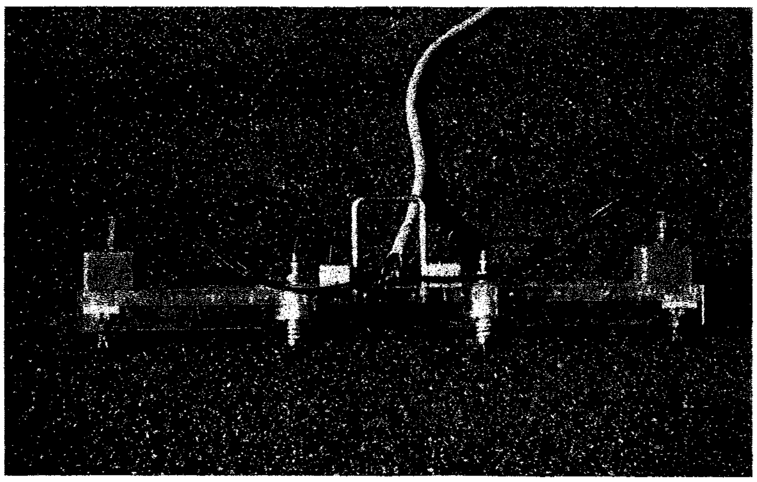


FIGURE 1: The control unit of the field-type velocity measuring instrument is conveniently operated from a pickup tail gate as the probe unit is moved to various points on the deck.

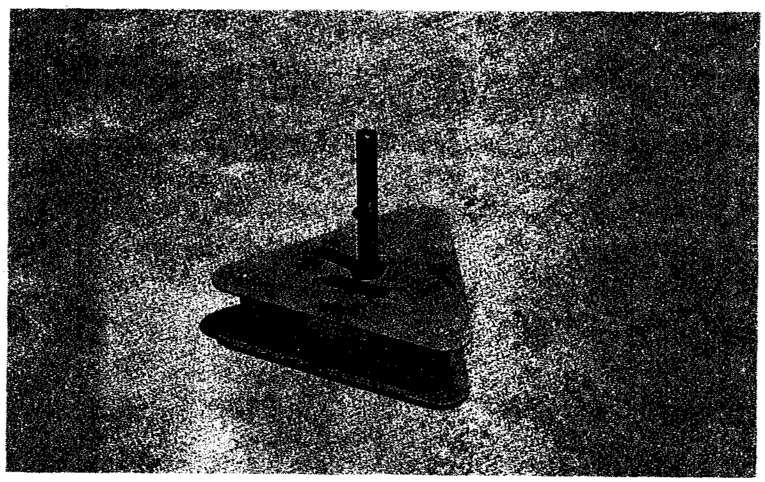


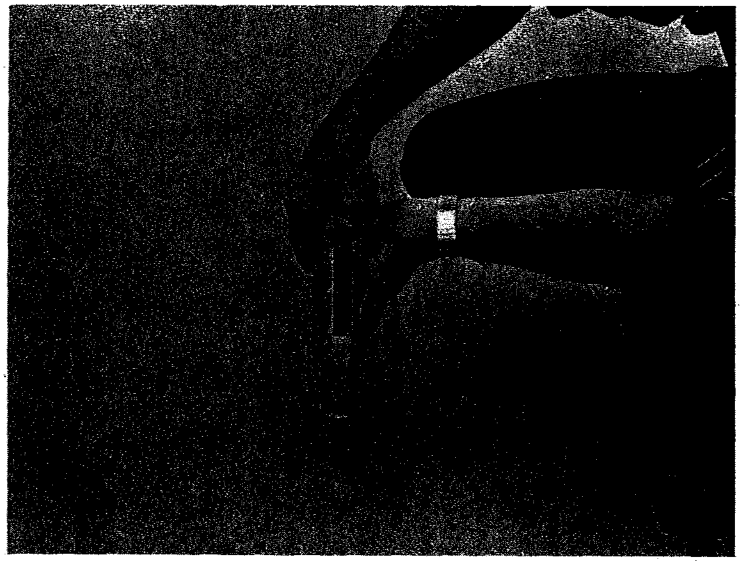
FIGURE 2: A standard probe is shot into concrete with the Windsor probe test system to determine concrete quality. The average penetration resistance of three shots is measured using a depth gage and special templates.

B. Operation of the Windsor Probe System

The Windsor probe, shown in Figure 2, is a device designed to provide estimates of concrete compressive strength by measuring the resistance to penetration of a probe driven into the concrete by a constant energy explosive cartridge (2). The probe penetration is considered to be inversely related to the compressive strength of the concrete. The procedure for the operation of the Windsor probe is given in Section 2 of Appendix B. In normal practice, three probes are shot into a bridge deck through a template having three equally spaced holes. The template is then removed and the average exposed height of the three probes is measured using the measuring plates and gage provided by the manufacturer, Windsor Probe Test Systems, Inc. The probes are pulled out of the bridge deck after the measurement is completed. The test is slightly destructive to the concrete surface being tested. 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. The Windsor scratch test set, containing minerals numbered from 1 to 10 on Moh's scale of hardness, is used to determine the hardness of the aggregate in the concrete. Using tables furnished by the manufacturer, an estimate can be obtained for the compressive strength of the concrete from the measured exposed height of the probes and the hardness of the aggregate.

C. Operation of Schmidt Rebound Hammer

The Schmidt rebound hammer is designed to provide an estimate of the concrete compression strength from its rebound readings. A Soiltest Model CT200 test hammer, shown in Figure 3, was used in this study. The procedure for its operation is given in Section 3 of Appendix B. Its plunger is pressed against a smooth area on the surface of the bridge deck, applying a gradual



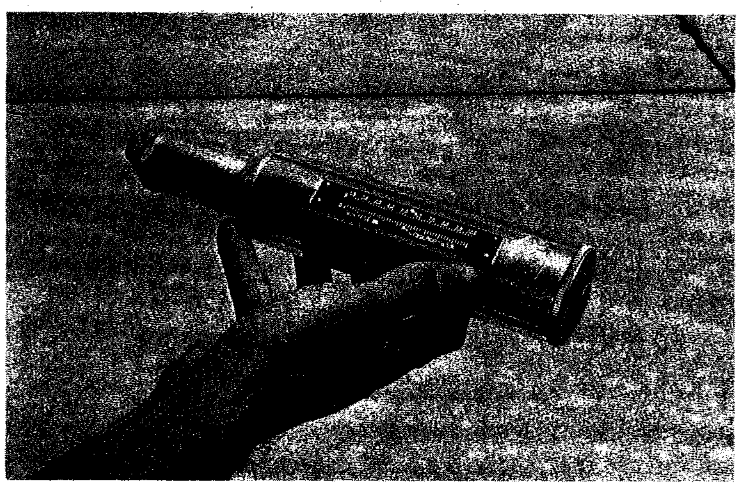


FIGURE 3: After smoothing the surface with a hand grinder a Soiltest Model CT200 concrete tester is used to obtain rebound readings.

increase in pressure until the hammer impacts. The rebound reading from the indicator scale can be used to make an estimate of the compressive strength of the concrete by means of calibration curves provided by the manufacturer. Rough spots, honeycombs and porous areas should be avoided. A number of readings -- 15 are recommended by Soiltest -- should be taken to get a good mean value of the rebound at a given location.

D. Operation of Concrete Direct Tensile Test

The direct tensile tests were made with the device shown in Figure 4. It was designed to provide a direct measurement of the tensile strength of in-place concrete. The operating procedure for its use is given in Section 4 of Appendix B. A two inch diameter aluminum disc is attached, by means of an epoxy adhesive, to the prepared surface of the bridge deck. The surface is prepared by grinding and then cleaning with toluene. After the epoxy has hardened, an hydraulic cylinder is used to pull the discs from the bridge deck, thereby breaking a dome shaped piece of concrete out of the deck. Thus, this test is also slightly destructive, producing approximately a two inch diameter spall about three eighths inch deep at the center. A gage in the hydraulic system indicates the force required to pull the concrete apart. The apparatus shown in Figure 4 was developed during this study, based on the design of a similar device developed in 1956 by the Shell Chemical Corporation.

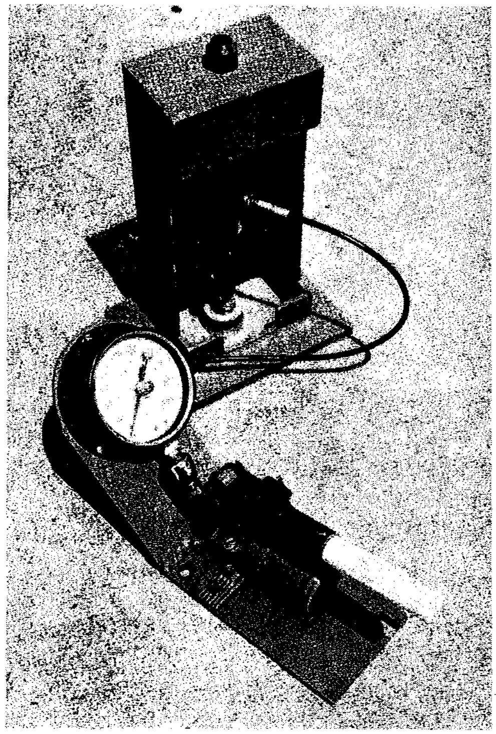


FIGURE 4: Two-inch diameter aluminum cylinders are epoxied to a smooth clean concrete surface. Tensile strength can be measured directly after approximately 90 minutes for curing.

4. Analysis of Data

As previously mentioned, the set of measurements pertaining to each locality on each tested slab comprised a laboratory determination of the compressive strength of a core, together with the readings obtained by each of the following instruments:

acoustic velocity meter
Windsor probe
Schmidt rebound hammer
direct tensile tester

Since poor quality concrete is generally thought to be concrete having inferior compressive strength, one approach to evaluating the applicability of these instruments to the detection of poor quality concrete is to compare their readings with the compressive strength of representative cores. Accordingly, both in the laboratory and on the bridge decks, a core was taken from each concrete slab on which the several instruments were used, at a point as near as possible to the location at which the instrument readings were obtained. The compressive strengths of the air dried cores were determined in the laboratory at the loading rate recommended in ASTM C39.[3]

Comparisons were made between these measured strengths and the estimated strengths obtained using the Windsor probe tables and the Soiltest hammer chart. The estimated strengths in both cases were generally higher than the measured strengths of the air dried cores. This is believed to be due principally to the manufacturers' estimating relationships having been developed from testing moist cured cylinders; whereas, in this study the cores were tested as taken, in the dry state.

In all analyses, the basic output data of the Windsor probe and rebound hammer were used rather than the compressive strengths estimated from manufacturers' tables and charts.

Four linear regression analyses were made in which the readings of each of the four instruments were used to determine the best fit estimating equations for the compressive strengths of the dry cores. Table 1 summarizes these particular analyses. The intercepts and slopes of the resulting regression equations given in the table can be used to estimate core strengths, but, as can be seen from the coefficient of variation shown for each analysis, the estimates will be somewhat rough. It can be concluded that, of the four techniques, the direct tensile test is the one which best correlates with compressive strength of the cores, however, none of the comparison measurements can be said to be very well correlated with core strengths.

Table 1: Linear Regression Analysis of Core Compressive Strength Versus Reading of Designated Instrument

Instrument	Intercept	Slope	Correlation Coefficient	Coefficient of Variation
Velocity Meter	-0.31	0.365	0.40	19.9
Windsor Probe	-4.71	4.49	0.32	20.3
Rebound Hammer	2.81	0.0391	0.15	21.2
Direct Tensile	2.31	4.06	0.56	17.4

Core Strength (ksi) = Intercept + (Slope x Instr. Reading)

Instrument Readings are in the following units:

velocity: 1000 ft/sec
Windsor probe: inches of exposed probe
rebound hammer: rebound reading
direct tensile: ksi

Intercomparisons of the same data among all the measurements techniques reveal other correlations of almost equal magnitude. As seen in Table 2, the velocity meter data is more strongly related to the direct tensile test than to the core strengths; the Windsor probe data correlates better with either the rebound hammer or direct tensile measurements than with the core strengths.

Table 2: Correlation Coefficient Matrix
All Slabs

	Velocity Meter	Windsor Probe	Rebound Hammer	Direct Tensile	Core Strength
Velocity Meter	--	0.21	0.01	0.45	0.40
Windsor Probe	0.21	--	0.51	0.51	0.32
Rebound Hammer	0.01	0.51	--	0.45	0.15
Direct Tensile	0.45	0.51	0.45	--	0.56
Core Strength	0.40	0.32	0.15	0.56	--

Since none of the relationships can be classified as very well correlated, each of the measurements appear to be largely independent. Each must respond to a somewhat different set of characteristics of the concrete. For example, the Windsor probe is obviously influenced by the hardness of the aggregate, as well as by that of the cement matrix, but it seems quite reasonable to expect strength and stiffness to be somewhat independent of the aggregate hardness. Similarly, it can be expected that the direct tensile test, which operates by failing the concrete in tension, will not be as influenced by the shear strength of the concrete as would the compression test. The observed acoustic velocities were found to be substantially unaffected by micro-cracking of the concrete, while the compressive and tensile strength are influenced by this factor. It was found earlier in this research that measurements of acoustic velocity could be used to estimate both the dynamic modulus and the chord modulus of concrete. As reported in Research Report 130-7, the coefficients of variation for these estimates were found to be 9.7 and 12.0 percent respectively. Upon comparison of these figures with the 19.9 percent listed in Table 1 for strength estimation, it is seen that the velocity meter is more directly affected by changes in the modulus value of the concrete than by changes in its compressive fracture strength.

A highly significant factor affecting the correlation shown in Table 2 is believed to be the state of aging and weathering of the concrete. The laboratory slabs, although covering a wide range of compositions and strengths, had never been subjected to the environmental influences of weather and traffic to which the bridge decks were exposed. The effect of this factor on the correlations may be seen upon comparing the data in Table 3 in which only the laboratory slabs appear, with that of Table 2, representing all the tests.

Table 3: Correlation Coefficient Matrix
Laboratory Slabs Only

	Velocity Meter	Windsor Probe	Rebound Hammer	Direct Tensile	Core Strength
Velocity Meter	--	0.21	0.70	0.82	0.69
Windsor Probe	0.21	--	0.32	0.38	0.58
Rebound Hammer	0.70	0.32	--	0.81	0.81
Direct Tensile	0.82	0.38	0.81	--	0.67
Core Strength	0.69	0.58	0.81	0.67	--

The notably higher correlation coefficients shown in Table 3 are believed to result from the relatively undeteriorated state of the laboratory slabs. This implies that, while the several instruments may be better correlated with the compressive strength of undeteriorated concrete, they, and the core strengths, are all differently influenced by the effects which accompany deterioration.

Analyses of variance were made of the rebound hammer readings, the direct tensile strengths and the velocities to determine whether the instruments used to make these measurements could distinguish variations which exist between slabs from variations within slabs. The method used to arrive at such a measure of the effectiveness of each instrument is a comparison of the variability of the measurements between slabs to the variability within slabs. The higher the ratio of the between-slab variability to the within-slab variability, known as the "F-ratio", the more capable is the instrument of sensing differences in the concrete. The analyses showed that the rebound hammer, tensile tester and velocity meter could distinguish differences between slabs from measurement variability within slabs with a confidence of at least 0.9995. Table 4 summarizes these analyses. Analyses such as these could not be made of the core strengths and Windsor probe data since only one core was taken from each slab and only one average measurement was made of the penetration resistance of the three probes shot into each slab. However, the authors believe that any of the five measurement techniques can be used with confidence to detect areas of deteriorated concrete.

Table 4: Determination of Instrument Sensitivity by Analysis of Variance

Instrument	No. sets	Obs. per set	F-Ratio (Calculated)	F-Ratio (Confidence level of 0.9995)	Significant
Velocity Meter	23	2-3	3.65	3.24	YES
Rebound Hammer	38	15	22.13	2.11	YES
Direct Tensile	30	2-4	12.01	2.66	YES

Note: When analyzing data taken from a number of areas with a given instrument, it may be said with a confidence at least equal to a given confidence level that the areas are significantly different as measured by the instrument if the calculated F-ratio is equal to or greater than the F-ratio for the given confidence level. The F-ratio for a given confidence level is taken from published tables and is dependent upon the number of areas measured and number of data points taken within each area[4].

5. Implications of Results

Core compressive strength is not, per se, a complete measure of quality or deterioration, and thus every satisfactory indicator of quality need not show a high degree of correlation to core compressive strengths. In other words "quality" is not compressive strength alone and "deterioration" is not solely loss of compressive strength. Accordingly, the question of which instrument best measures loss of quality or detects deterioration is not answered by merely determining which provides the best basis for predicting compressive strength.

Each one of the techniques used, including the core compressive failure tests, appears to respond strongly to one or more significant characteristics of the concrete. These several characteristics of the material appear to affect each technique in differing degrees, thus impairing their correlations. However, each technique appears to be capable of distinguishing variations which exist from place to place within a given bridge deck. Each would be applicable to a survey procedure for detecting and delimiting deteriorated areas or weak spots in a single concrete batch design subjected to the same environmental influences. A choice among the field instruments tested would depend largely upon the purpose of testing program and upon such factors as speed of operation, level of operator training and skill available.

In the opinion of the authors the procedures can be ranked in order of speed and economy of operation as follows:

rebound hammer, most rapid and economical

Windsor probe, good rapidity, less economy

velocity meter, requires most training and operator skill

direct tensile test, least rapid of the field techniques

core test, least rapid and most expensive of all.

With respect to confidence in the ability of the test to indicate deteriorated concrete the authors would rank the measurement techniques as follows:

tensile test,

core test,

rebound hammer,

Windsor probe,

velocity meter.

The largest environmental influence which was seen during the field tests was that of attenuation of the acoustic waves caused by micro-cracking of the concrete. This is a factor which affects the operation of the velocity meter but is not measured by it. It is considered likely that if an instrument designed for measuring this attenuation had been available its readings would have been the most indicative of environmental deterioration or the loss of quality in concrete and be superior to any of the techniques tested.

Analysis of the properties of the four-transducer array used in the velocity meter, developed earlier in this study, indicates that such an array offers an attractive solution to a basic problem involved in the measurement of attenuation. This problem is caused by the large and unpredictable attenuation which occurs in the coupling between any acoustic transducer and the surface of the material whose attenuation it is desired to measure. As explained in Research Report 130-7, the 4 transducer array, when used to measure velocity in two directions, cancels out the effect of any inequality between the time delays associated with the couplings of the individual transducers to the material. A similar analysis, with respect to the attenuation observed between the signals produced by the two receiving transducers, shows that averaging the attenuations observed for two directions of wave travel likewise cancels any inequality between the attenuation characteristics of the transducers themselves or of their coupling to the material. Accordingly, it is suggested that an instrument, employing this type of array, represents a practical basis for the direct measurement of acoustic attenuation and that such measurements might provide a more trustworthy and economical technique for detecting poor quality and deteriorated concrete in bridge decks.

6. Conclusions

1. The compressive strength of dry cores taken from bridge decks can be estimated to within about 20% with the regression equations given in Table 1 using any one of the measurement techniques investigated. About two-thirds of the time the accuracy of estimates should be better than the indicated coefficient of variation and about one-third of the time larger errors can be expected.
2. Each of the measurement techniques investigated responds to a somewhat different set of properties of the concrete. These characteristic properties of concrete appear to be largely independent.
3. Each of the measurement techniques investigated appears to be capable of distinguishing variations which exist from place to place within a given bridge deck. Each would be applicable to a survey procedure for detecting weak spots in a single concrete batch design subjected to the same environmental influences.
4. Core compressive strength is not a complete measure of environmental deterioration or loss of quality in concrete. Such deterioration appears to affect several other significant material characteristics in differing degrees.
5. The largest environmental influence observed during the field tests on in-service bridge decks was the attenuation of acoustic waves caused by micro-cracking of the concrete. An instrument designed to measure this acoustic attenuation might be a superior detector of deterioration than any of the techniques investigated.

7. References

1. 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. 24-30, 1971.

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

3. ASTM Standards, Vol. 10, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 27-29, 1968.

4. Dixon, W. J. and F. J. Massey, "Introduction to Statistical Analysis," second ed., McGraw-Hill, New York, pp. 390-403, 1957.

Appendix A

Included in this Appendix are tables of information on concrete batch design for the laboratory slabs, description of bridges tested for the bridge slabs, and data pertaining to the concrete specimens tested with the four non-destructive instruments.

Table A-1: Concrete Batch Design for Laboratory Slabs

Batch Designation	Type of Coarse Aggregate*	Design Cement Factor Sacks/C. Y.	Actual Water Cement Ratio** Gal/Sack
1PD	River Gravel	5	5.6
2PD	River Gravel	5	5.8
3PD	River Gravel	6.5	3.9
4PD	River Gravel	6.5	3.9
5PD	Str. Lightweight	5	6.9
6PD	Str. Lightweight	6.5	5.3
7PD	Crushed Limestone	5	7.2
8PD	Crushed Limestone	6.5	5.3
9PD	River Gravel	4	7.5
10PD	River Gravel	4	7.5
11PD	Crushed Limestone	4	9.2
12PD	Str. Lightweight	4	8.8

* Natural sand was used in all batches for fine aggregate.

** The quantity of water estimated in mix design was adjusted during mixing to obtain a 3 inch slump in all batches.

Table A-2: Description of Bridges Tested

Bridge Number		District	No. of Slabs Tested
1	I.H. 35 north, over Trinity River	2	2
2	I.H. 35 north, over Cowen Road	2	2
3	U.S. 287 and 81 north, over F.M. 156	2	2
4	S.H. 121 business north, over U.S. 183	2	2
5	U.S. 83 north, over S.H. 29	7	1
6	U.S. 67 north, over U.S. 277	7	2
7	U.S. 67 north, over Crows Nest	7	1
8	U.S. 67 north, 0.5 mile north of Tom Green-Runnels County line	7	2
9	U.S. 87 south, (Grape Creek Bridge)	7	2
10	U.S. 66 east, over I.H. 40	4	2
11	U.S. 87 north, over Cherry Street	4	2
12	U.S. 87 frontage road, south of Buffalo Gap Road, over creek	4	2
13	Adkisson Road south, over I.H. 40	4	2
14	Buffalo Gap Road east, over U.S. 87	4	2

Table A-3: Comparative Measurements made on Slabs

Slab No.	Aggregate Hardness	Velocity Meter (fps)	Windsor Probe (inches)	Rebound Hammer Reading	Tensile Strength (psi)	Compressive Strength (psi)
			Laboratory Slabs			
1PD	6	13700	1.875	46.1	470	4030
2PD	6	13900	1.985	45.4	630	4120
3PD	6	14400	2.125	46.8	640	5830
4PD	6	15400	2.020	46.7	660	4690
5PD	(3)	11700	2.080	42.5	460	3250
6PD	(3)	12800	2.005	44.7	420	4740
7PD	4	13200	2.085	43.9	390	4480
8PD	4	13800	2.085	47.6	540	5870
9PD	6	13500	2.065	41.1	440	4050
10PD	6	13700	2.005	41.4	550	4210
11PD	4	12700	2.025	38.5	300	3590
12PD	(3)	11700	1.885	36.7	200	2570
			Bridge Slabs			
1-1	4½	12100	2.025	47.3	--	4900
1-2	4½	10800	2.020	47.3	--	4570
2-1	4	13400	2.050	41.6	--	3790
2-3	4	12800	1.920	38.8	--	3650
3-1	3½	12600	2.110	45.9	--	4530
3-3	3½	13600	2.110	46.5	--	6730
4-1	4½	13400	2.120	49.7	--	3360
4-3	4½	14100	2.170	53.5	--	3750
5-1	4½	13300	2.075	43.9	740	6620
6-1	5	14300	2.130	44.6	800	4430
6-2	5	15000	2.150	45.9	710	5330
7-1	5½	13800	2.130	43.6	670	3880
8-1	5	12000	2.110	43.7	490	3070
8-2	5	11600	2.075	45.4	480	3450
9-1	4½	14600	2.120	40.5	580	6110
9-2	4½	15000	2.035	35.9	620	5920
10-2	7	13900	2.050	46.9	590	5040
10-3	7	11500	2.040	43.2	580	4290
11-1	7	14100	2.040	43.4	590	4000
11-3	7	15000	2.065	43.7	540	4490
12-1	7	13100	2.160	50.3	540	5430
12-2	7	12500	2.135	50.6	710	4630
13-1	7	13100	2.075	42.7	610	5160
13-2	7	13000	2.045	42.0	640	5230
14-1	7	12400	2.100	48.5	710	4600
14-2	7	--	2.150	46.5	560	4810

Note: Velocities listed are normally averages of 3 readings.
Windsor probe penetrations are normally averages of 3 probes.
Rebound hammer readings are averages of 15 repetitions.
Tensile strengths normally are averages of 4 measurements.
Compressive strengths are measurements of a single core.

Appendix B

Included in this Appendix are the operating procedures for the four following instruments:

1. acoustic velocity meter
2. Windsor probe
3. Schmidt rebound hammer
4. direct tensile tester.

B-1: OPERATING PROCEDURE FOR ACOUSTIC VELOCITY METER USED ON CONCRETE SURFACES

1. Select a location on the concrete surface that is relatively free of cracks.
2. Grease the four transducer bases to insure good coupling to the concrete surface.
3. Place the transducer assembly in the selected location with the four transducers firmly in contact with the concrete surface.
4. Turn on the electronic equipment for measuring the time interval between transducers.
5. Place the selector switch to position 1 so that the left transducer is transmitting acoustic waves and the waves received by the nearest receiving transducer are displayed on the oscilloscope.
6. Observe the first zero crossing of the received signal on one trace of the dual-trace oscilloscope and adjust the left adjustment knob so that the downward abrupt voltage step occurs at the same instant on the second trace.
7. Place the selector switch to position 2 so that the left transducer is transmitting acoustic waves and the waves received at the far receiving transducer are displayed on the oscilloscope.
8. Again observe the first zero crossing of the received signal but this time adjust the right adjustment knob so that an abrupt downward voltage step occurs at the same instant on the second trace.
9. The time-interval between the two voltage steps has been set equal to the time-interval between the wave arrival at the two receivers and is displayed on the digital counter. Record this time.

10. Place the selector switch to position 3 so that the <u>right</u> transducer is transmitting acoustic waves and the waves received by the nearest receiving transducer are displayed on the oscilloscope.

11. Repeat step 6. (Align step, using <u>left</u> knob).

12. Place the selector switch to position 4 so that the <u>right</u> transducer is transmitting acoustic waves and the waves received by the far receiving transducer are displayed on the oscilloscope.

13. Repeat step 8. (Align step, using <u>right</u> knob).

14. Repeat step 9. (Record time interval).

15. Average the two times recorded.

16. Calculate the velocity of the wave using the following equation:

$$V(\text{fps}) = 670 \;/\; \text{Avg. time in milliseconds.}$$

B-2: OPERATING PROCEDURE FOR WINDSOR PROBE USED ON CONCRETE SURFACES

1. Select an area on the concrete surface for testing. Surfaces rougher than a broom finish should be ground smooth prior to testing.
2. Place the triangular probe locating template on the surface of the area to be tested.
3. Load the driver gun with a probe and explosive cartridge.
4. Position the gun over one of the three holes in the locating template and fire the probe into the concrete.
5. Repeat steps 3 and 4 until three probes have been fired, through the locating template into the concrete, in a triangular pattern.
6. Remove the probe locating template.
7. Tap each probe with a hammer to insure that it has not bounced back from its deepest penetration position.
8. Sweep the loose concrete away from the probes.
9. Place the base gage plate over the three probes, setting it firmly on the concrete surface.
10. Place the top gage plate on top of the three probes.
11. Place the depth gage thru the appropriate hole in the middle of the top gage plate. Hold the flange of the gage firmly against the top plate, release the gage plunger allowing it to snap against the base plate, lock the plunger in place, and then remove the depth gage.
12. Read and record the average exposed height of the three probes in inches, as measured with the depth gage.
13. Remove the two gage plates and jack the probes out of the concrete.

Note: The manufacturer's operating procedure included a determination of the hardness of the aggregate in the concrete using a mineral scratch test kit containing minerals numbered from 1 to 10 on Moh's scale of hardness. The compressive strength of the concrete may then be estimated from the exposed height of the probes, corrected for aggregate hardness, by using tables furnished by the manufacturer. The estimated strengths were generally higher than the measured strengths of air dried cores (See Section 4, page 12). The correction for aggregate hardness did not improve the correlation between the Windsor probe penetration data and core compressive strength. Thus, the average exposed height of the three probes in inches, obtained in Step 12, was used in all analyses.

B-3: OPERATING PROCEDURE FOR SCHMIDT REBOUND HAMMER USED ON CONCRETE SURFACES

1. Select an area on the concrete surface avoiding rough spots, honeycombs and porous areas.
2. Grind the area to be tested to prepare a smooth surface.
3. Place the plunger of the rebound hammer in contact with the concrete surface applying a light pressure to release it from the locked position and allow it to extend to the ready for test position.
4. Press the plunger against the concrete surface keeping the instrument perpendicular to the test surface while applying a gradual increase in pressure until the hammer impacts.
5. Hold the instrument firmly against the concrete and read the scale. If it is not convenient to read the scale in this position, press the button on the side of the instrument _after_ the hammer has impacted and remove the instrument from the test position for reading. Do _not_ touch the button while depressing the plunger.
6. Record the rebound number read from the scale on the side of the instrument.
7. Repeat steps 3 through 6 until 15 readings of the rebound have been obtained in the test area.
8. Average the 15 readings to obtain a mean rebound number for the test area.

Note: The manufacturer's operating instructions included on estimation of the compressive strength from the mean rebound number. Calibration curves for this purpose were furnished by the manufacturer. The estimated strengths were generally higher than the measured strengths of air dried cores (See Section 4, page 12). The possibility of this occurrence in old and dry concretes had been stated in the operating instructions, together with a suggestion that a special correlation between the rebound number and the compressive strength be determined and a new curve plotted. For this reason, the average rebound number, calculated in step 8, was used in all analyses.

B-4: OPERATING PROCEDURE FOR DIRECT TENSILE TESTER USED ON CONCRETE SURFACES

1. Smooth the concrete surface, upon which the two-inch discs are to be placed, with a grinder.
2. Clean the surface after grinding with toluene or xylene (toluene is believed to leave less residue) using a clean rag for rubbing. Rub the cleaned surface after it has dried to remove any residue left by the cleaning solution.
3. Clean the surfaces of the discs, to be epoxied to the concrete, with toluene or xylene using a clean rag.
4. Mix the two part epoxy according to specifications. A small amount of kaolinite (mineral filler) is then mixed in with the epoxy to give it a thicker consistency so that it will not run out from between the disc and the concrete. Mix only enough epoxy at one time to stick approximately four fairly close spaced discs. (The working life of mixed epoxies is influenced by temperature and amount of mixed epoxy. Higher temperatures and larger bodies of mixed epoxy accelerate the set-up time and shorten the working life.) The type of epoxy found suitable for use with the tensile tester is Shell Chemical Company EPON 828 resin and EPON Curing Agent U. The mix ratio is four parts resin to one part curing agent by weight.
5. Spread an even layer of the epoxy on the face of the disc and also on the concrete where the disc is to be stuck. Ice cream sticks or similar objects are suitable for this purpose. Push the disc firmly on the concrete. The excess epoxy that comes out around the side of the disc should be removed so as not to increase the effective area of the disc. Ice cream sticks are also applicable for this purpose.

6. Heating the stuck discs with a hand torch for approximately 15 minutes will accelerate the set-up time. Heat should be applied only to the top of each disc, as heat applied directly to the epoxy will cause it to break down. Do not overheat the discs; they should only be heated to "finger touch warm".

7. Allow approximately 90 minutes for curing. As previously stated, the set-up time varies with ambient temperature.

8. Screw the coupler into the disc and attach it to the tensile tester. The screw valve on the hydraulic jack must be loosened so that the piston of the hydraulic cylinder may be pulled down for attachment.

9. Operate the hydraulic jack, after closing the screw valve, to pump up the cylinder until the disc breaks loose pulling out a chunk of concrete. The hydraulic jack should be operated in such a manner as to provide for a slow and fairly constant increase in pressure as indicated by the gage. Before beginning this step be sure the red follower needle of the gage is set to zero. (If a chunk is not pulled out of the pavement, for example, the break is between the epoxy and the disc or concrete, the test should be rerun. These type breaks could result from poorly mixed epoxy or inadequate curing time.)

10. Observe and record the gage reading indicated by the red follower needle. The gage reading is the pressure exerted on the piston in the hydraulic cylinder. The tensile force is 0.375π times the gage reading. The tensile stress acting on the concrete is calculated by dividing the tensile force by the area of the disc (πr^2). Thus the Concrete Breaking Stress = (0.375 x Gage Reading)/r^2. For the two-inch diameter discs the radius is equal to unity and the equation reduces to Concrete Breaking Stress (psi) = 0.375 Gage Reading.