AN INVESTIGATION OF THE APPLICABILITY OF ACOUSTIC PULSE VELOCITY MEASUREMENTS TO THE EVALUATION OF THE QUALITY OF CONCRETE IN BRIDGE DECKS

by

Gilbert Swift
Research Instrumentation Engineer

and

William M. Moore
Associate Research Engineer

Research Report No. 130-7
A Study of Reinforced Concrete Bridge Deck Deterioration:
Diagnosis, Treatment and Repair
Research Study 2-18-68-130

Sponsored by

The Texas Highway Department
In Cooperation with the
U. S. Department of Transportation
Federal Highway Administration

August, 1971

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

PREFACE

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

The authors wish to acknowledge their gratitude to all members of the staff of the Texas Transportation Institute who contributed to this research. Special thanks are expressed to Mr. L. J. Milberger and Mr. Frank H. Scrivner for their advice and assistance throughout the study, and to Mr. Rudell Poehl for his assistance in the data reduction.

The support given by Texas Highway Department personnel is also appreciated, especially that of Mr. M. U. Ferrari and Mr. Don McGowan who provided advice and assistance throughout the study and that of the personnel of District 2 who assisted during the preliminary field tests.

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation, Federal Highway Administration.

ABSTRACT

The compressional wave velocity was measured and compared with several other significant properties of concrete specimens, using a wide variety of concrete compositions. Measured velocities in concretes containing like coarse aggregates were found to decrease with loss of strength. In all concretes tested, the elastic modulus could be estimated satisfactorily from the measured pulse velocity and the unit weight.

A technique for measuring compressional wave velocities on bridge decks or other concrete structures having only one accessible surface was validated by measurements made on laboratory specimens. A portable field-type velocity measuring instrument utilizing this technique was developed. It was concluded that such an instrument appears suitable for the task of detecting the extent of deterioration of concrete in bridge decks.

Key Words: Pulse-Velocity, Concrete, Bridge Deck, Measurement, Instrument.

SUMMARY

Pulse velocity measurements were found to be indicative of deteriorated or poor quality concrete in bridge decks.

It was found that the measured velocity could be used together with the unit weight, to estimate the elastic modulus of the concrete. It was also found that the compressional wave velocity in concretes of similar composition was generally indicative of their quality or strength.

A portable field-type velocity measuring instrument was developed during this study, for use on bridge decks. It was concluded that this instrument appeared to fulfill its design objectives and to be applicable to the task of detecting the extent of deterioration of concrete in bridge decks.

IMPLEMENTATION STATEMENT

The work reported establishes the foundation for a practical method of evaluating the extent of deterioration of concrete in bridge decks. The method and apparatus developed for making in situ measurements of compressional wave velocity appear suitable and applicable for use in conjunction with the Delamination Detector previously developed in this study and now being implemented by the Texas Highway Department. Further field evaluations of the velocity measuring technique and instrument are needed before this system can be introduced into routine use in connection with bridge maintenance.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

This is the second progress report of Phase 1 of a research study entitled "A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment and Repair," 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 this phase of the research is the development of methods to evaluate the extent of deterioration in concrete bridge decks.

In this study, two defects have been considered to be of paramount importance. They are (a) delamination (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," describes the "Delamination" portion of the research. The present report is being written to describe the efforts directed toward the detection of poor quality or deteriorated concrete.

Laboratory measurements were made on a wide variety of concrete specimens to explore the applicability of acoustic pulse velocity measurements to the detection of poor quality concrete and to establish the feasibility of a technique for making such measurements conveniently on the accessible upper surface of bridge decks.

Compressional wave velocities were found to be strongly related to elastic moduli determined either by conventional resonant frequency testing or by standard stress-strain observations. Also velocities were found to generally increase as compressive strength increased for concretes having similar composition. Thus, comparisons of concrete quality based on observations of velocity tend to be valid for structures composed of similar concretes.

An instrument for measuring compressional wave velocities on the upper surface of bridge decks has been designed and constructed. The basic considerations for its design were portability, accuracy, and convenience of operation. Limited field and laboratory tests indicate that these design objectives have been met.

2. REVIEW OF LITERATURE AND SELECTION OF METHOD OF ATTACK

From the literature, acoustic pulse velocity measurements appeared to offer the most promising method for determining the quality of the concrete in bridge decks. Accordingly, as a first step, the relationship of acoustic wave velocity to other properties of concrete was explored.

The literature indicates the existence of a general relationship between concrete quality and acoustic velocity (1, 2, 3)* and a theoretically based relationship between velocity, density and the elastic constants of concrete (3, 4, 5, 6, 7, 8). A relationship has also been found between velocity and presence of certain cracks which lengthen the path and thus lower the observed velocity (1, 2, 3, 8).

A relationship between velocity and a subjective description of the quality of concrete is contained in reference 1 as indicated in the following table:

Table 1: Relation of Velocity to Concrete Quality
(after Krautkrämer)

Velocity in feet/sec	Quality of Concrete
above 15,100	Very Good
11,800 to 15,100	Good
9,850 to 11,800	Questionable to Moderate
6,900 to 9,850	Bad
below 6,900	Very Bad

---

* Numbers in parenthesis designate reference numbers in Section 8.

A somewhat similar table is given in reference 2. While these approximate relationships neglect many factors which can influence the results, they imply that the extent of deterioration of concrete in a bridge deck might be determined by surveying the deck with an instrument which measures the acoustic wave velocity.

The theoretical relationship between the compressional wave velocity, the density and the elastic constants of a homogeneous elastic material follows:

$$V_c = \sqrt{\frac{E}{\rho} \frac{(1-\mu)}{(1+\mu)(1-2\mu)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 1}$$

where V_c is the compressional wave velocity,

E = Young's modulus of elasticity,

μ = Poisson's ratio,

ρ = the mass density, or W/g,

W = the unit weight, and

g = the acceleration due to gravity.

While concrete is not perfectly elastic, nor homogeneous, this relationship has been reported by several investigators to be generally applicable to concrete (4, 5, 6). From it a value for Young's Modulus can be computed, given the compressional wave velocity, the unit weight, and the value of Poisson's ratio, viz:

$$E = \frac{V_c{}^2 W}{g} \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 2}$$

This relationship is such that in the vicinity of Poisson's ratio equal to 0.20 (the vicinity applicable to both good and inferior concretes), small changes in Poisson's ratio have very little effect on the value obtained for the elastic modulus. For example a 25 percent increase in Poisson's ratio changes the modulus by less than 7.5 percent. A decrease has less effect. Changes in unit weight have a directly proportional effect on the modulus value. Accordingly, one might expect to find that measurements of the compressional wave velocity could be used to compute a reasonable accurate value for the elastic modulus using estimated values for Poisson's ratio and unit weight. To the degree that a decrease in the derived modulus value is an indication of deterioration, the above relationship also implies that the extent of deterioration of concrete in a bridge deck might be determined by surveying the deck with a suitable compressional wave velocity measuring instrument.

The literature contains seemingly conflicting opinions as to the validity or the general applicability of these relationships between the pulse velocity and other attributes of concrete. The application of pulse transmission is not recommended by ASTM for determination of strength or modulus (ASTM C597)*. Manke and Gallaway (4) state that there appears to be some doubt as to the value of dynamic moduli calculated from measured pulse wave velocities. However, Manke and Gallaway also quote Whitehurst (3) who states in effect, that the pulse velocity itself is as good a criterion for comparison of concretes as any other property which might be calculated from it. Woods and McLaughlin (6) similarly conclude that in general no benefit is derived from calculating a modulus of elasticity value from velocity measurements. They note, however, that the use of the theoretical relationship, given above, to convert velocity to dynamic modulus is recommended by Long, Kurtz and Sandenaw (7) for mass concrete and is recommended by Leslie and Cheesman (8) for all concrete, including laboratory specimens.

* All referenced ASTM tests can be found in reference 11.

A highly informative survey by Jones and Facaoaru (9) shows widespread use of the pulse velocity technique for estimating in situ strength of concrete. However, considerable divergence of opinion and practice was revealed by answers to questions such as what analytical formula is used and what properties of the concrete should be varied in order to derive the correlation between pulse velocity and compressive strength of laboratory samples. A more positive finding is reported by Elvery and Din (10) who conclude that ultrasonic pulse testing provides a better correlation with beam strength than that given by control specimens. They are referring to comparisons of the flexural strength of reinforced concrete beams with pulse velocity in the critical zone of the beam and with laboratory crushing strength tests on cubes made of the same concrete.

In view of this range of opinion it was considered desirable to explore the underlying relationships between acoustic pulse velocities and other properties of concrete, in order to apply them to the problem of detecting deterioration of concrete in bridge decks. The investigation began with a laboratory comparison of measured wave velocities in a variety of concrete specimens having different compositions, strengths, and other physical properties.

Specifically, relationships among the following variables were explored for a wide variety of concrete compositions:

1. Compressional wave velocity
2. Dynamic modulus (from resonant frequency tests)
3. Elastic modulus (from stress-strain observations)
4. Unit weight
5. Compressive strength

The compressional wave was selected in preference to other acoustic waves because its velocity can be measured more conveniently and accurately. Its higher velocity insures that the first observed arrival of energy represents that of the compressional wave. The velocities of the later arriving waves usually cannot be determined precisely since their arrivals tend to be obscured by the earlier arrival and the duration of the compressional wave.

3. MEASUREMENT OF COMPRESSIONAL WAVE VELOCITY IN CONCRETE

Basically the compressional wave velocity of any material can be determined by initiating an acoustic impulse in the material and timing its travel over a known distance. In elastic solids several types of waves are generally produced in addition to the compressional wave. Fortunately, however, the compressional wave travels faster than the others. Hence the first arrival of energy at a point not too distant from the source may be identified safely as being due to the compressional wave.

The ability to time the arrival of a wave accurately is a function of the abruptness or rise-time of the wave. Accordingly the acoustic impulse and the received wave should rise as steeply as possible. Most sonic and ultrasonic transducers are inherently resonant devices which produce and receive impulses having the form of lightly damped wave trains which oscillate numerous times while building up to their maximum amplitude. With such transducers the attainable timing accuracy is generally proportional to the frequency of the wave train. Therefore, for accurate velocity measurements, it is desirable to use as high a frequency as possible and to time the travel of the wave over as large a distance as possible. However, the properties of concrete prohibit the use of the high frequencies which are normally employed for testing metals and other relatively homogeneous elastic substances. The granular nature of concrete causes scattering and attenuation of waves whose length is comparable to, or shorter than, the size of the coarse aggregate particles. These effects set a limit somewhat below 100 kilohertz for the highest frequency which can be employed satisfactorily in concrete, and a limit of a few feet to the practical distance range. Frequencies between 20 and 50 kilohertz are therefore generally chosen for use with concrete.

Compressional wave velocities in various concretes ordinarily range between 8,000 and 16,000 feet per second. The waves thus traverse a distance of one foot in about 60 to 120 microseconds. To determine their velocity with a precision in the order of one percent one must, therefore, be able to define the onset of the wave train to within 0.6 to 1.2 microseconds per foot of path length in the specimen. Such accuracy is not readily achieved with wave trains, each oscillation of which occupies 20 to 50 microseconds and whose first oscillation is substantially smaller than the succeeding ones. Judgment of the observer is thus a highly significant factor in the timing process.

4. LABORATORY INSTRUMENTATION AND TECHNIQUE

The apparatus used for the laboratory measurements of compressional wave velocities is shown in Figure 1 and is substantially the same as that described in reference 4. It consists of a pulse generator, a commercially available oscilloscope equipped with a calibrated delayed sweep, and a pair of piezoelectric transducers. The assembled transducers are resonant at approximately 40 KHz. A repetition rate of 60 impulses per second is employed to facilitate observation.

The simplest measuring technique, as shown in Figure 2, may be described as "timing through" the specimen. Velocity is determined by observing the time-interval between the occurrence of the driving impulse and the onset of the wave train received through the specimen, then subtracting the time-interval observed with the transducers coupled directly together in the absence of the specimen. In taking this difference it is assumed that no change of the time delay within the transducers or in the acoustic couplings occurs when the specimen is introduced or removed. Accordingly, for reliable measurements it is essential to insure good coupling. This is generally attained by applying a film of grease or starch which acts as a couplant between the transducers and the specimen, and by applying a substantial pressure during the measurement.

An alternative technique which is applicable to specimens which have only one accessible flat side may be described as "timing along" the specimen. As shown in Figure 3 this technique utilizes a series of two or more observations made with various distances between the transducers.

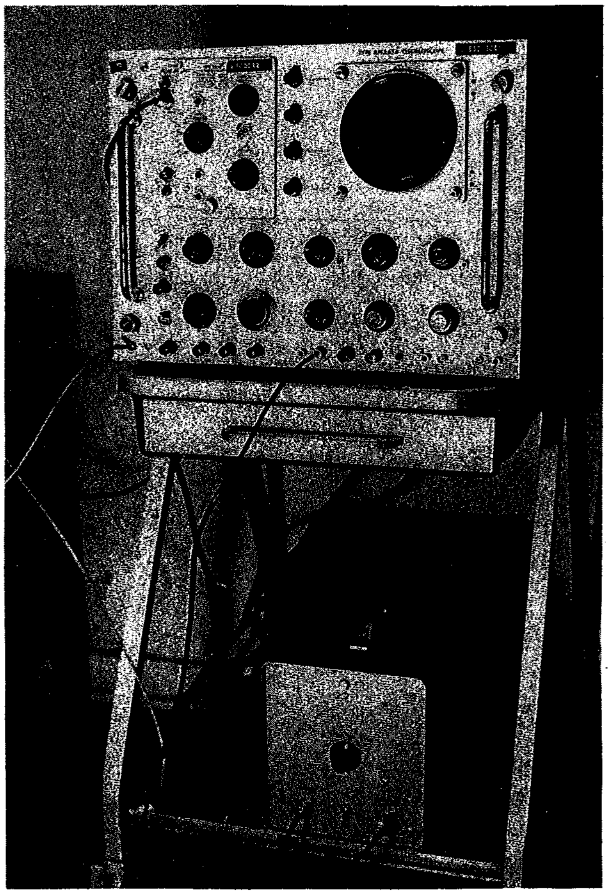


Figure 1: Timing oscilloscope and pulse generator used for measuring acoustic pulse velocities in concrete.

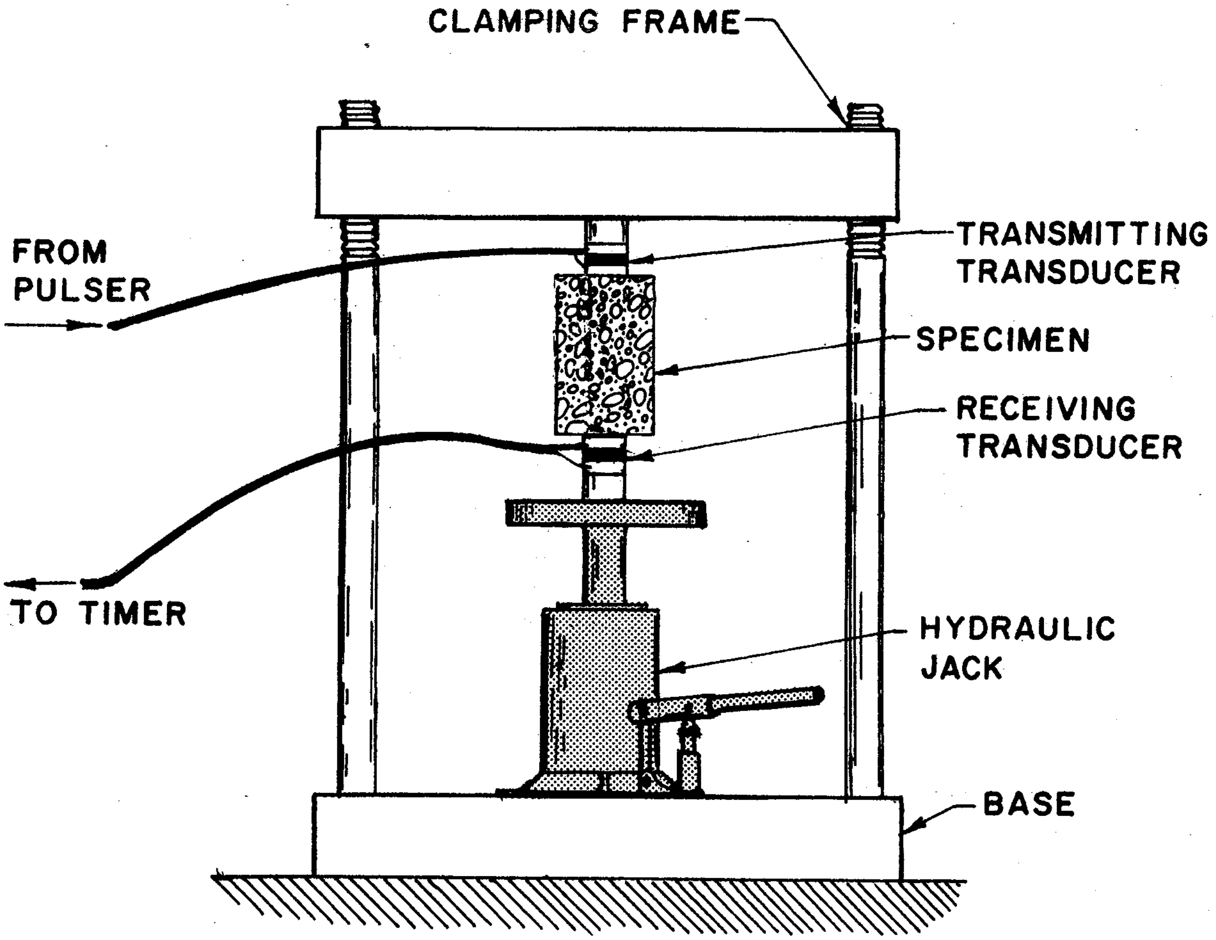


Figure 2: Concrete specimen in test position during measurement of acoustic pulse velocity by the "timing through" technique.

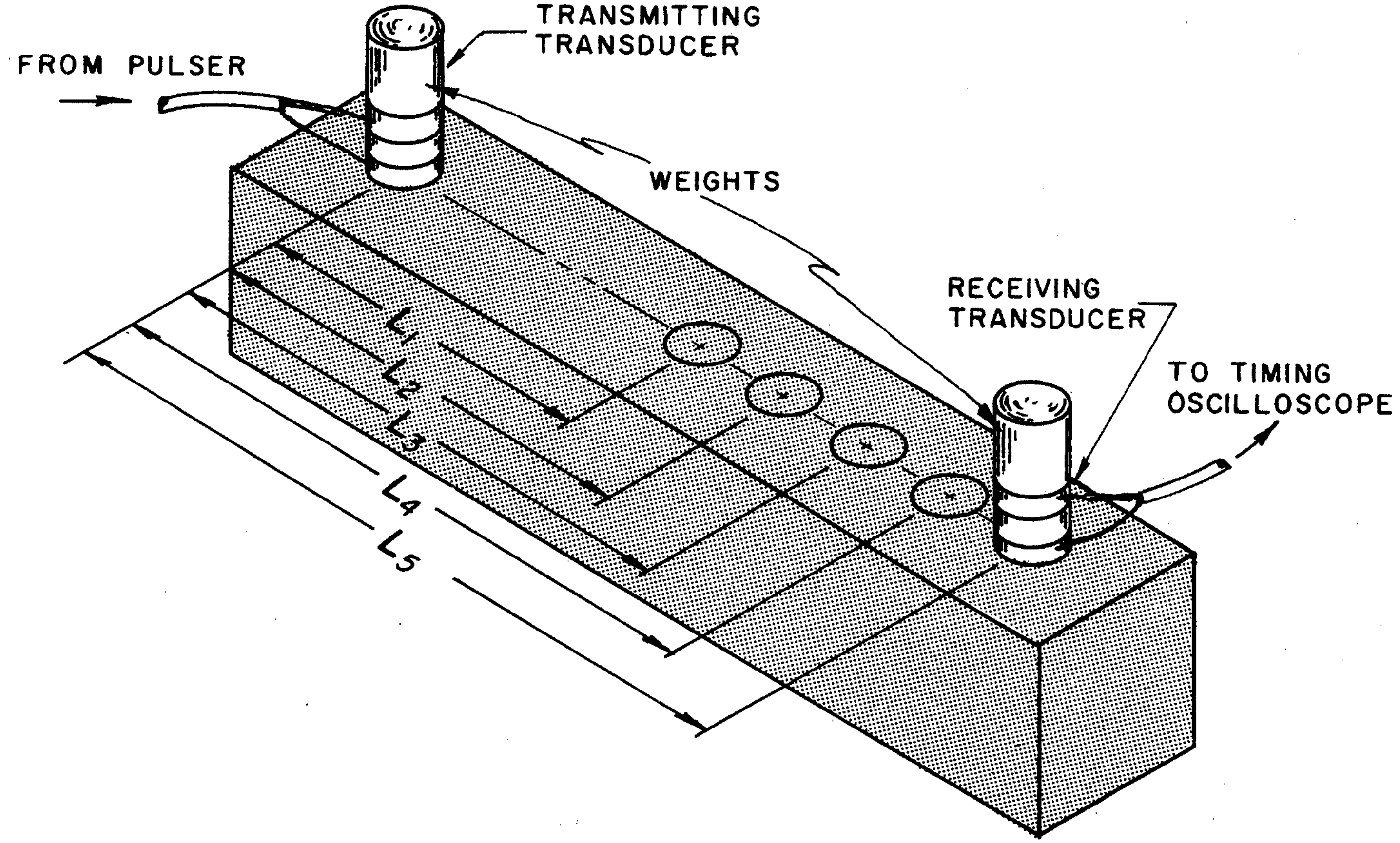


Figure 3: Representation of concrete specimen during measurement of acoustic pulse velocity by the "timing along" technique.

Velocity is obtained from the slope of the distance versus time plot of these observations. The intersection of this plot with the time axis is a measure of the time delay in the transducers and their couplings plus any time required by changes in the direction of the wave path. In this technique coupling delay remains an important factor affecting the accuracy of each individual observation but its effect tends to average out among the series of observations. Adequate contact is obtained by placing a weight of a few pounds on each transducer and by using a suitable coupling agent.

5. LABORATORY RESULTS

5.1 Comparison of "timing along" versus "timing through" Techniques

The accessibility of the upper surface of bridge decks makes it convenient to perform pulse velocity measurements there using the "timing along" technique. Accordingly, before developing an apparatus for such measurements on bridge decks, a series of laboratory tests was made to examine the validity of this technique.

Thirty-six 3 x 3 x 12 inch beams made during this study from twelve batches of concrete -- three replicate (i.e., as nearly identical as possible) beams from each batch -- were measured by both the "timing through" and the "timing along" methods. Descriptions of the twelve batches of concrete are given in Table A-1 of Appendix A. It is sufficient to say here that the batches contained three very different types of aggregate, and had widely varying cement factors. The results of the measurements made by the two methods are given in Table A-2 of Appendix A, and are plotted in Figure 4. This figure shows a satisfactory agreement between the two measurement techniques. Thus, either of the two techniques may be applied for comparison of various concretes and for estimation of their velocity-related properties. A small bias was noted in the comparison in that the velocities obtained by "timing through" a given specimen averaged about 3 percent greater than the velocities obtained by "timing along" the same specimen. The reasons for this bias have not been determined.

5.2 Relation of Velocity to Dynamic Modulus, E_r

The theoretically based relationship of velocity to the elastic modulus and the unit weight (Equation 2) was examined through measurements

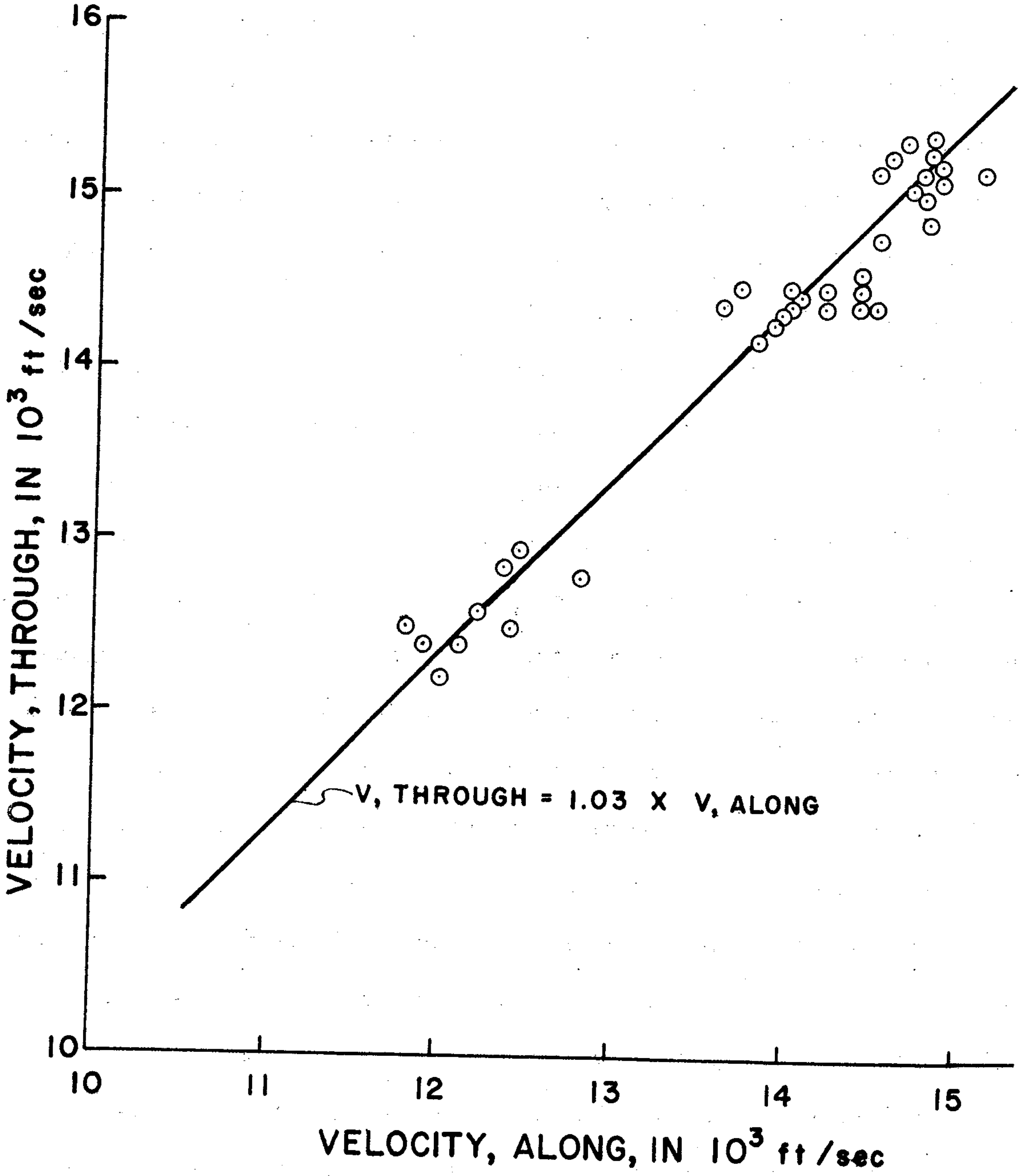


Figure 4: Comparison of velocities measured using the "timing along" technique with those measured using the "timing through" technique.

made on fifty-seven 3 x 3 x 12 inch beams. Thirty-six of these beams were the new beams described above and the remaining twenty-one were similar beams of unknown composition which had been deteriorated by freeze-thaw cycling in a research study conducted several years previously. Velocities were determined by the "timing through" technique, unit weights were determined from the weight and dimensions of the specimens, and the dynamic elastic moduli, E_r, were determined by the transverse resonant frequency method (ASTM C215). The results of these measurements, as well as computed values of $V_c{}^2\rho$ (i.e., $V_c{}^2W/g$), are given in Table A-2 of Appendix A.

A plot of the dynamic modulus versus $V_c{}^2\rho$ is shown in Figure 5. Also shown on this plot are theoretical lines for several values of Poisson's ratio, as computed from Equation 2. The line which best fits the plotted points is seen to coincide with the theoretical line for Poisson's ratio equal to 0.26. One can note from this plot that fairly reasonable estimates of the dynamic moduli could have been made from the values of $V_c{}^2\rho$ if 0.26 had been assumed for the Poisson's ratio of all beams. The standard deviation and the coefficient of variation for the prediction errors, assuming 0.26 for Poisson's ratio, are given in Table II.

Table II: Errors associated with Dynamic Modulus and the Quantity $V_c{}^2\rho$

	Number of Tests	Standard Deviation (10^6 psi)	Coefficient of Variation (percent)
Prediction Error (E_r - 0.817 $V_c{}^2\rho$)	57	0.411	9.7
Within batch replication error in E_r	36	0.334	6.5
Within batch replication error in $V_c{}^2\rho$	36	0.108	1.8

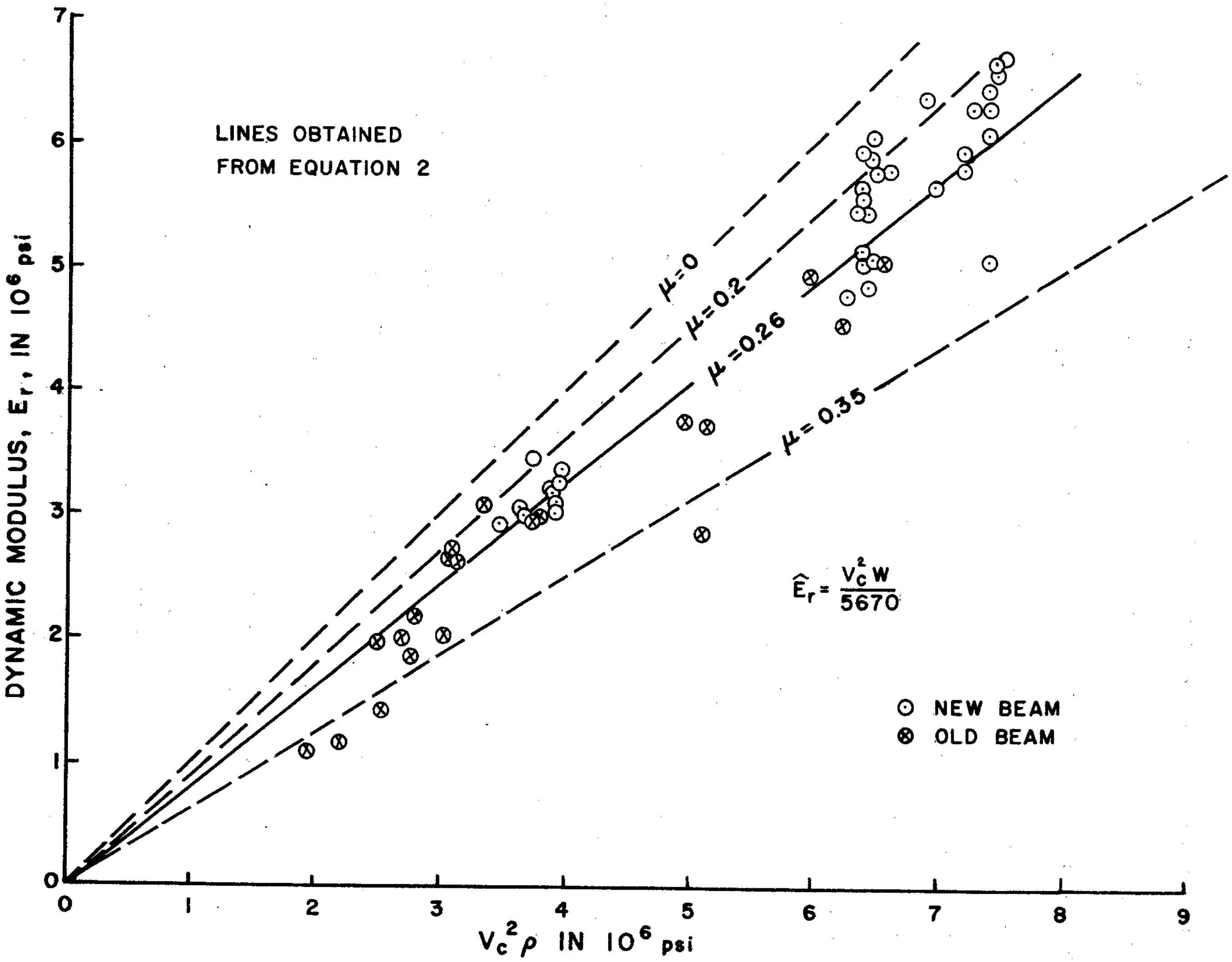


Figure 5: Relationship between the dynamic modulus, E_r, as measured by transverse resonant frequency method and the quantity $V_c{}^2\rho$ determined from laboratory measurements.

Variations in measured values obtained on replicate beams from the same concrete batch are due to both measurement errors and beam variations, and these variations might be considered a limiting value for any predicting technique. Thus, an analysis of variance was made for the values of dynamic modulus and the values of $V_c^2\rho$ for the thirty-six beams cast from the twelve different batches to determine the standard deviations and the coefficients of variation for these two parameters within a concrete batch. These values are also given in Table II.

From a comparison of the values shown in Table II one can note that the prediction errors are not excessively large. Thus, there is substantial agreement between the resonant frequency method of determining dynamic elastic modulus (ASTM C215) and values derived from velocity and unit weight measurements. From the following equation (Equation 2 with Poisson's ratio equal to 0.26), a compressional wave velocity observation, in combination with a corresponding value of unit weight, can be utilized to estimate the dynamic elastic modulus as would be measured using the transverse resonant frequency method:

$$\hat{E}_r = \frac{V_c^2 W}{5670} \quad \text{. . . . .} \quad \text{Eq. 3}$$

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

V_c = compressional wave velocity in ft/sec,

W = unit weight in pcf.

Since the dynamic modulus is generally thought to be indicative of deterioration due to freeze-thaw cycles (ASTM C290 and C291) it follows that dynamic modulus values estimated from observations of the compressional wave velocity should be similarly indicative of deterioration within a bridge deck.

5.3 Relation of Velocity to Chord Modulus, E_c

The theoretically based relationship of $V_c^2\rho$ to elastic (chord) modulus was also examined, from measurements made on 56 cylindrical specimens. Thirty-six of the specimens were 6 inch diameter x 12 inch high cylinders. Three replicate specimens were cast from each of the previously mentioned twelve batches of concrete. The remaining twenty specimens were cores of various origins, described in Table A-3, Appendix A. Velocities were determined by the "timing through" technique, unit weights were determined from the weights and dimensions of the specimens, and the chord moduli, E_c, were determined by stress-strain observations (ASTM C469). The results of these measurements, as well as computed values of $V_c^2\rho$, are given in Table A-3 of Appendix A.

A plot of the chord modulus versus $V_c^2\rho$ is shown in Figure 6. In this case the line which best fits the plotted points coincides with the theoretical line for Poisson's ratio equal to 0.32. One can note from this plot that fairly reasonable estimates of the chord moduli could have been made from values of $V_c^2\rho$ if 0.32 had been assumed for the Poisson's ratio of all specimens.* The standard deviation and the coefficient of variation for the prediction errors, assuming 0.32 for Poisson's ratio, are given in Table III. Also shown in this Table are similar values for the within batch replication errors for both the chord modulus and $V_c^2\rho$.

---

* The apparent increase in Poisson's ratio over the value of 0.26 previously found is attributed to the fact that the chord modulus, E_c, is usually found to be substantially smaller than the dynamic modulus, E_r.

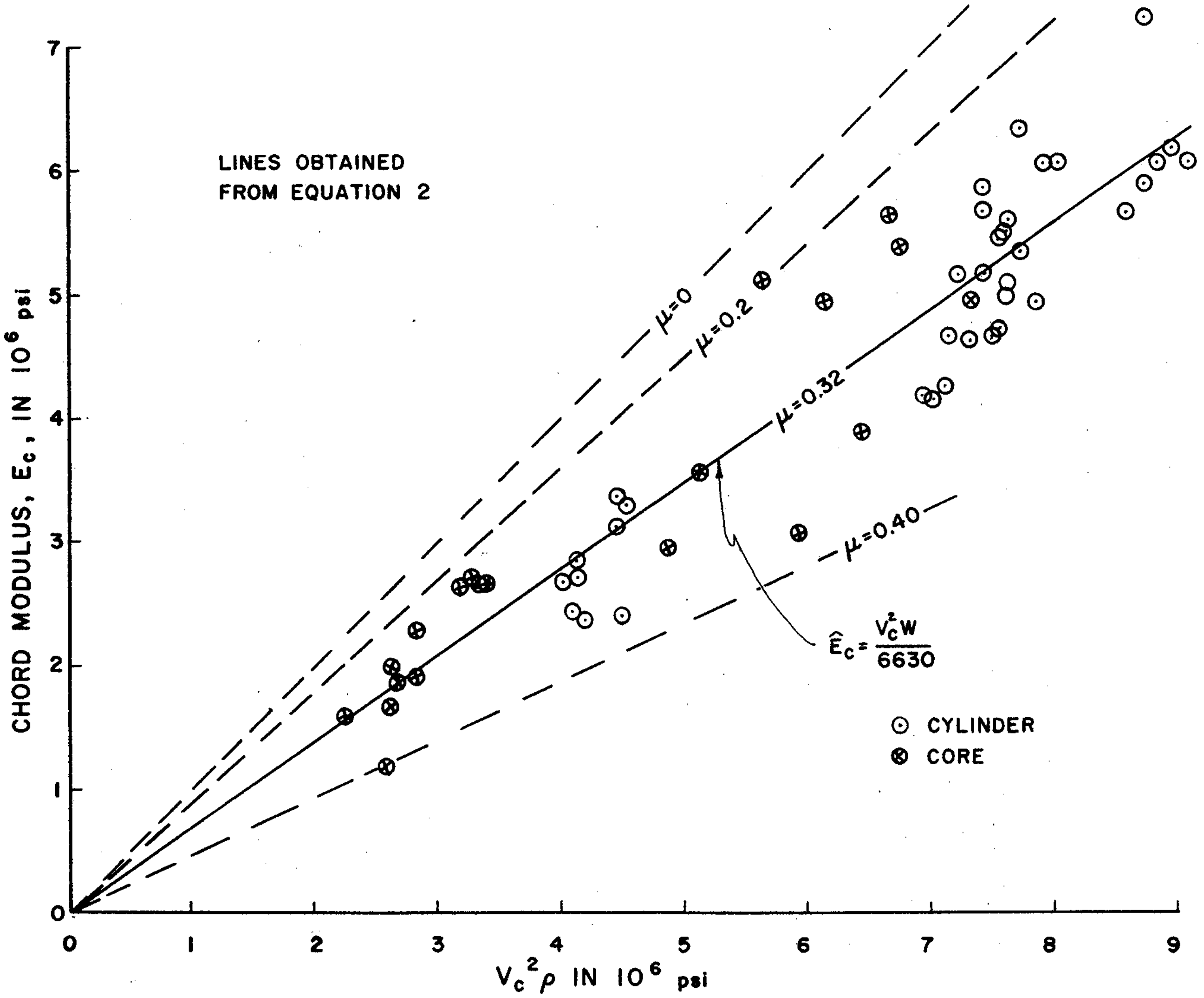


Figure 6: Relationship between the chord modulus, E_C, measured by stress-strain observations and the quantity $V_c^2\rho$ determined from laboratory measurements.

Table III: Errors associated with Chord Modulus and the Quantity $V_c^2\rho$

	Number of Tests	Standard Deviation (10^6 psi)	Coefficient of Variation (percent)
Prediction Error ($E_c - 0.699\ V_c^2\rho$)	56	0.503	12.0
Within batch replication errors in E_c	36	0.348	7.3
Within batch replication error in $V_c^2\rho$	36	0.164	2.4

Again there is substantial agreement between two methods of determining moduli. Velocity and unit weight can be used in the following equation (Equation 2 with Poisson's Ratio equal to 0.32) to estimate the chord modulus as would be determined with stress-strain measurements (ASTM C469):

$$\hat{E}_c = \frac{V_c^2 W}{6630} \quad \text{. . . . . Eq. 4}$$

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

V_c = compressional wave velocity in ft/sec., and

W = Unit weight in pcf.

Thus, observations of compressional wave velocities should make it possible to rank the concrete at a number of locations with respect to the chord modulus. To the degree that a decrease in chord modulus indicates the occurrence of quality deterioration, the velocity measurement can serve to locate the extent of this deterioration.

5.4 Relation of Velocity to Compressive Strength

The relationship between the compressional wave velocity and compressive strength was explored by measuring the ultimate compressive strength (ASTM C39)* of the 56 cylindrical specimens used for the chord modulus determinations. The compressive strength values are given in Table A-3 of Appendix A.

No consistent relationship was found among all the cylindrical specimens, but separate tendencies were noted for the velocity to increase with strength within each group of cast cylinders containing a given type of coarse aggregate. Cores taken from beams were consistently higher in strength than cylinders cast from the same concrete batch, although their modulus values and their velocities were substantially alike.

While no useable relationship could be established for estimating the strength of all the cylindrical specimens from the measured velocities, the consistent trends for velocity to increase with modulus for all concretes tested and to increase with strength within groups having similar composition, indicate that velocity measurements, utilized with discretion, are generally indicative of the quality of the concrete.

---

* Compressive strength of air-dried specimens was determined shortly after measuring the velocity.

6. PORTABLE FIELD-TYPE VELOCITY MEASURING INSTRUMENT

A velocity measuring system particularly adapted for use in the field was developed, utilizing the experience gained with the laboratory instrumentation described in Section 4. The basic considerations for its design were portability, accuracy, freedom from coupling errors and convenience of operation. Since the instrument is intended for use on bridge decks, pavement slabs and other concrete structures, of which only one flat surface may be accessible, it is based on the "timing along" principle. The effect of time delays within the transducers themselves, or in the coupling of the transducers to the concrete, is minimized in this system by using an array of two transmitters and two receivers as shown in Figure 7. This array permits waves to be propagated from left to right using the left transmitter or from right to left using the right transmitter. Time of travel, between the two receiving transducers, which are spaced one foot apart, is observed first for one direction of travel and then for the opposite direction. The two observed time-intervals are then averaged to obtain a value which is substantially independent of any time delay in the coupling of either receiving transducer. It can be seen that any excess delay in one of these couplings will lengthen the observed time-interval for waves travelling in one direction but will diminish the observed interval by a like amount for oppositely travelling waves.

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. The appearance of this

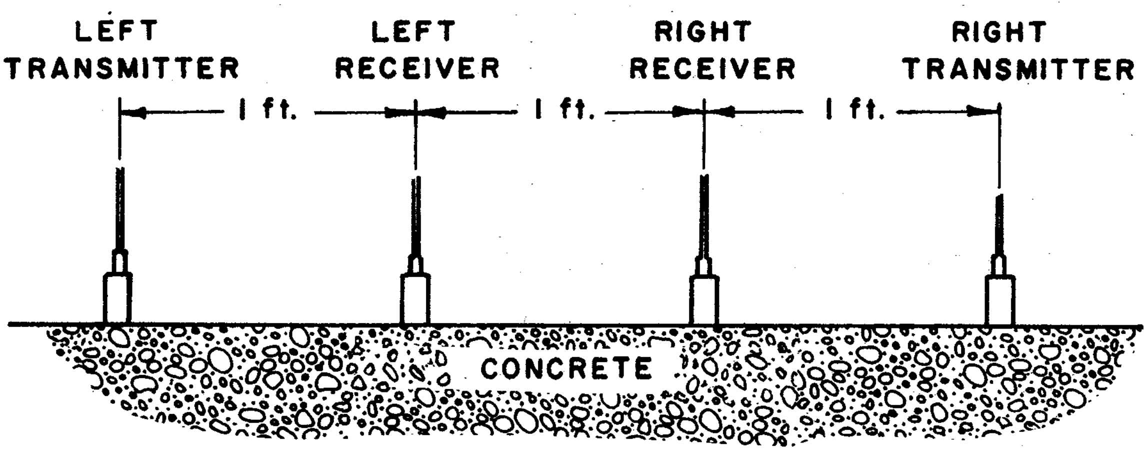


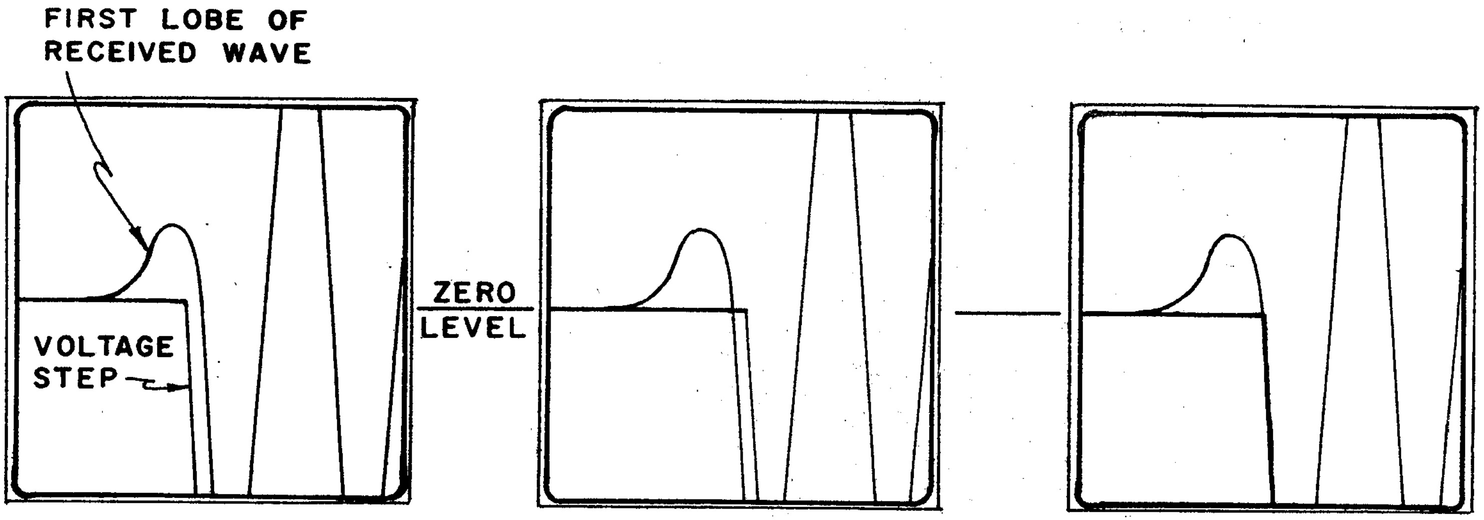
Figure 7: Array of four transducers for velocity measurement using the "timing along" technique. This array propagates waves alternately in two directions, thus minimizing coupling delay errors.

oscilloscope display is shown in Figure 8. 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. A single switch on the control panel determines the direction of wave travel and selects which of the received signals is displayed on the oscilloscope.

The complete instrument comprises the probe shown in Figure 9 together with the control unit and the oscilloscope shown in Figure 10. The apparatus is intended primarily for operation from the tailgate of a station wagon and is powered, through an inverter, from the vehicle battery.

The probe, which is weighted to 30 pounds to provide good coupling, is attached to the control unit through a flexible cable. Electrical coupling between the transmitting and receiving transducers is minimized by employing magnetostrictive transmitters with piezoelectric receivers. Individual pulse generators are mounted directly on the probe above each of the transmitting transducers, and receiving pre-amplifiers are mounted adjacent to the receivers. Acoustic coupling through the frame of the probe is made slow compared with the travel time in concrete by constructing the frame of low-velocity plastic material.

Coupling of the transducers to the concrete surface, particularly for somewhat rough or uneven surfaces, is facilitated by suspending the transmitting transducers from the frame in a flexible manner and by providing telescopic mountings for the receivers. Also, the receiving



VOLTAGE STEP ADJUSTED TOO EARLY

VOLTAGE STEP ADJUSTED TOO LATE

VOLTAGE STEP CORRECTLY MATCHED TO ZERO CROSSING OF RECEIVED WAVE

Figure 8: Representations of typical oscilloscope display showing received wave with three successive adjustments of a voltage step used for timing the wave arrival.

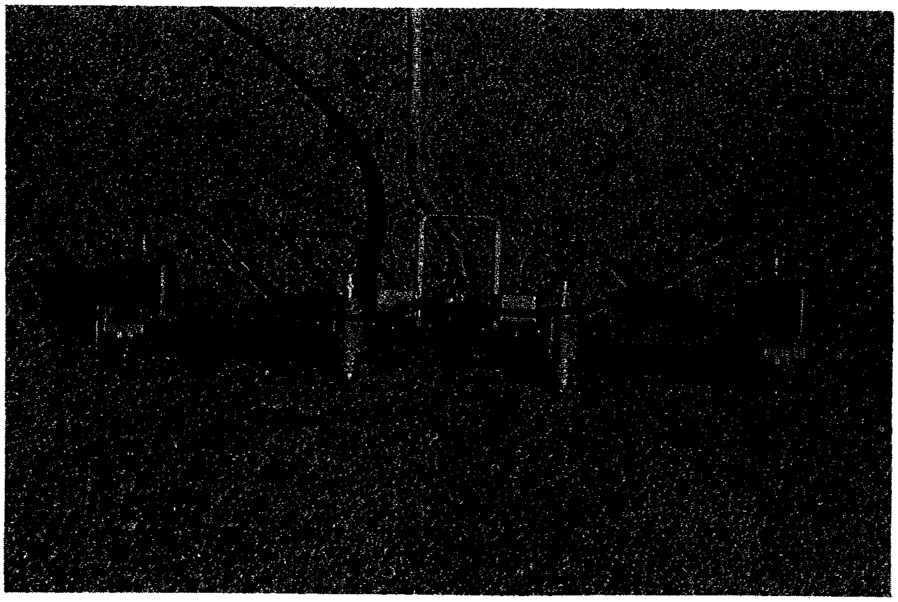


Figure 9: Measuring probe, employing four-transducer array, used in the portable field-type velocity measuring system.

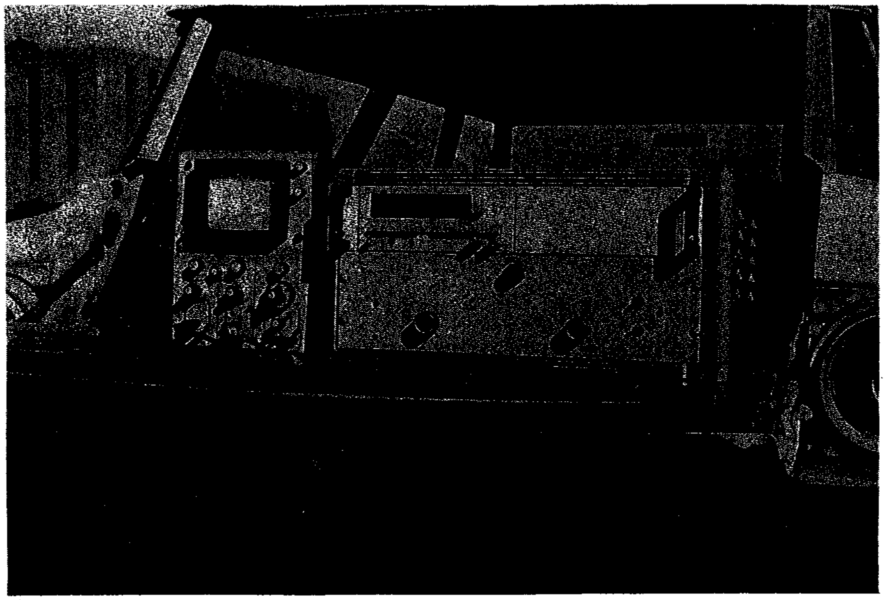


Figure 10: Timing unit and oscilloscope used with the measuring probe in the portable field-type velocity measuring system.

transducers themselves are permitted to swivel in ball joints at the bottom of their telescopic housings, and thus adjust themselves to the local surface irregularities. A grease or starch couplant is placed on the contact surfaces of the probe.

In operation it has been found that a second operator can usually reproduce the observed time-intervals to within about 0.4 microsecond with the probe remaining stationary. Much larger variations are generally encountered when the probe is moved a few inches, due to the inherent nonuniformity of the material. Variability of the time delay in the couplings of the two receivers has been found to range from zero to as much as four microseconds at some locations, but as mentioned, averaging the observations for two directions of travel cancels this effect. Accordingly, the accuracy of this velocity meter appears to be limited principally by its readability and by the variability within the concrete. For an observed travel time of 60 microseconds for one foot, which corresponds to a velocity of 16,700 feet per second the readability of 0.4 microsecond represents about 0.7% error and for a speed of 100 microseconds per foot which corresponds to 10,000 ft/sec it is 0.4%. It can be seen that the inaccuracy might be up to ten times larger if the coupling delays were not averaged out.

A limited number of measurements have been made with this instrument in the field on bridge decks. In general the system has proven fieldworthy and its measurements appear to have adequate accuracy and resolution. It appears to be stable, rugged and simple to operate. The velocities observed on the few bridges tested were all representative of good quality concrete. Further field evaluation of this instrument is planned together with supplementary strength tests at the same sites.

7. CONCLUSIONS

1. Compressional wave velocities measured by the "timing along" technique were found to be in substantial agreement with velocities measured by the "timing through" technique. Thus, the "timing along" technique, which is more conveniently applicable on bridge-decks and other concrete structures of which one flat surface is accessible, can be utilized, in connection with relationships established by either technique, to evaluate the velocity-related properties of concrete in situ.

2. The compressional wave velocity and unit weight can be used to estimate the dynamic modulus of concrete as it would be determined by the transverse resonant frequency method (ASTM C215).

3. The compressional wave velocity and unit weight can be used to estimate the chord modulus of concrete as determined from stress-strain measurements (ASTM C469).

4. No consistent relationship was found between velocity and strength among all concretes tested; however a trend was found for velocity to increase with strength within concretes containing like coarse aggregates.

5. Compressional wave velocity in concretes of similar composition is generally related to their quality. Slower velocities indicate poorer quality, lower modulus and diminished strength on a given bridge deck or other structure having a single concrete batch design.

6. The portable field-type velocity measuring instrument developed in this study appears to fulfill its design objectives and to be applicable to the problem of detecting the degree and the areal extent of quality deterioration of concrete in bridge decks.

8. REFERENCES

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

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

3. 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.

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

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

6. Woods, K. B. and J. F. McLaughlin. "Application of Pulse Velocity to Several Laboratory Studies of Materials", Highway Research Board Bulletin 206, Washington, D. C., pp. 14-27, 1959.

7. 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.

8. 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.

9. Jones, R. and I. Facaoaru. "An Analysis of Answers to a Questionnaire on the Ultrasonic Pulse Technique", Materiaux et Constructions, Vol. 1, No. 5, pp. 457-465, 1968.

10. Elvery, R. H. and N. M. Din. "Ultrasonic Inspection of Reinforced Concrete Flexural Members", Proceedings, Symposium on Concrete, Institution of Civil Engineers, London, pp. 35-42, June, 1969.

11. ASTM Standards, Vol. 10, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1968.

APPENDIX A

Included in this Appendix are tables of data pertaining to the concrete specimens tested. Beams and cylinders were cast from a variety of concrete batches which were designed to approximate the range of concrete properties typically found in Texas. Supplementary specimens were of various origins as noted in Tables A-2 and A-3. Most of these were of unknown composition which had been deteriorated by freeze-thaw cycling in a research study conducted several years previously.

Table A-1: Concrete Batch Design

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: Data from Tests of Beam Specimens

Specimen designation*	Velocity (V_c through) 10^3 ft/sec	Velocity ($V_c{}^1$ along) 10^3 ft/sec	Unit Weight (w) pcf	Dynamic Modulus (E_r) ASTM C 215 10^6 psi	$V_c{}^2\rho$ (computed) 10^6 psi
1PD-1	14.6	14.4	143	5.78	6.58
-2	14.4	14.5	144	6.05	6.45
-3	14.8	14.5	145	6.36	6.86
2PD-1	14.4	14.2	144	5.88	6.45
-2	14.4	14.0	143	5.43	6.40
-3	14.4	14.0	142	5.93	6.36
3PD-1	15.2	14.8	147	6.07	7.33
-2	15.3	14.6	148	6.69	7.48
-3	15.3	14.6	146	5.07	7.38
4PD-1	15.2	14.8	148	6.41	7.38
-2	15.4	14.8	145	6.62	7.42
-3	15.3	14.8	146	6.29	7.38
5PD-1	12.2	12.0	108	2.92	3.47
-2	12.4	11.9	110	2.99	3.65
-3	12.4	12.1	109	3.03	3.62
6PD-2	12.8	12.8	111	3.35	3.93
-3	12.9	12.4	112	3.44	4.02
-5	12.9	12.4	111	3.35	3.99
7PD-7	14.5	14.4	140	5.57	6.35
-8	14.5	14.0	141	5.44	6.31
-9	14.4	14.4	142	5.15	6.36
8PD-7	14.5	13.7	142	5.06	6.44
-8	14.4	13.6	142	5.62	6.36
-11	14.5	14.0	143	5.76	6.49
9PD-7	14.9	14.8	145	5.64	6.95
-8	15.1	14.8	146	5.78	7.19
-9	15.2	14.5	149	6.54	7.43
10PD-7	15.1	14.7	147	6.29	7.24
-8	15.1	14.8	146	5.92	7.19
-9	15.2	15.1	147	6.04	7.33
11PD-7	14.2	13.8	143	4.79	6.22
-8	14.3	13.9	144	5.01	6.36
-9	14.5	14.2	141	4.87	6.40

Table A-2 (continued): Data from Tests of Beam Specimens

Specimen designation*	Velocity (V_c through) 10^3 ft/sec	Velocity ($V_c{}^1$ along) 10^3 ft/sec	Unit Weight (w) pcf	Dynamic Modulus (E_r) ASTM C 215 10^6 psi	$V_c{}^2\rho$ (computed) 10^6 psi
12PD-7	12.5	12.4	116	3.09	3.91
-8	12.5	11.8	116	3.04	3.91
-9	12.6	12.2	115	3.24	3.94
C-4	12.9		142	2.82	5.10
D-42	14.0		145	4.56	6.22
D-43	14.3		146	5.06	6.54
DO-12	13.9		143	4.95	5.96
GB-1	12.8		107	2.98	3.78
GB-2	12.0		107	3.09	3.33
GB-3	12.6		109	2.95	3.74
1MID-1	11.4		98	1.85	2.75
1MID-3	11.4		99	2.19	2.78
3FTW-1	11.8		100	2.02	3.01
3FTW-2	10.9		97	1.99	2.49
3FTW-3	11.2		99	2.01	2.68
4FTR-2	11.4		108	2.79	3.03
4FTR-3	11.5		108	2.77	3.08
5FTH-2	13.1		138	3.71	5.11
5FTH-3	12.8		140	3.76	4.95
28R-1	9.8		105	1.18	2.18
28R-2	9.4		100	1.10	1.91
28R-3	10.5		106	1.43	2.52
237-2	11.4		109	2.64	3.06
237-3	11.6		107	2.61	3.11

* Specimens 1PD-1 through 12PD-9 were 3 x 3 x 12 inch beams cast from the concrete batches listed in Table A-1. The remaining specimens were similar beams of unknown composition which had been subjected to freeze-thaw cycling in a research study conducted several years previously.

Table A-3: Data from Tests of Cylindrical Specimens

Specimen designated*	Velocity (V_c through) 10^3 ft/sec	Unit Weight (w) pcf	Chord Modulus (E) ASTM C 469** 10^6 psi	Compressive Strength ASTM C 39** 10^3 psi	$V_c^2\rho$ (computed) 10^6 psi
1PD-8	15.6	145	5.10	3.91	7.62
-9	15.8	141	5.49	3.61	7.60
-10	15.6	144	5.45	3.98	7.56
2PD-8	15.5	143	5.85	3.79	7.42
-9	15.5	143	5.66	3.92	7.42
-11	15.6	144	4.72	3.39	7.56
3PD-2	16.7	147	6.05	4.61	8.85
-3	16.5	146	5.66	4.64	8.58
-4	16.7	151	6.07	4.95	9.09
4PD-2	16.8	147	6.18	4.52	8.96
-3	16.7	145	5.89	4.85	8.73
-4	16.6	147	7.22	4.50	8.74
5PD-3	13.7	111	2.39	4.57	4.50
-4	13.0	110	2.65	4.72	4.01
-5	13.2	110	2.70	4.42	4.14
6PD-2	13.5	113	3.36	5.69	4.45
-3	13.6	113	3.29	5.35	4.51
-4	13.6	112	3.10	5.41	4.47
7PD-2	15.2	143	4.65	5.36	7.13
-3	15.6	143	4.66	5.29	7.51
-4	15.4	141	5.17	4.78	7.22
8PD-2	15.4	143	4.62	5.63	7.32
-3	15.6	145	5.60	6.64	7.62
-4	15.7	145	5.36	6.64	7.72
9PD-2	15.5	147	4.98	2.65	7.62
-3	15.3	147	5.16	2.58	7.43
-4	15.7	148	4.94	3.03	7.87
10PD-2	15.8	147	6.04	3.01	7.92
-4	15.8	149	6.04	2.83	8.03
-5	15.6	147	6.31	2.79	7.72
11PD-1	15.2	143	4.26	2.45	7.13
-2	15.0	143	4.18	3.13	6.95
-3	15.1	143	4.14	2.96	7.04

Table A-3 (continued): Data from Tests of Cylindrical Specimens

Specimen designated*	Velocity (V_c through) 10^3 ft/sec	Unit Weight (w) pcf	Chord Modulus (E) ASTM C 469** 10^6 psi	Compressive Strength ASTM C 39** 10^3 psi	$V_c^2\rho$ (computed) 10^6 psi
12PD-1	12.9	115	2.82	1.77	4.13
-3	12.8	116	2.43	2.02	4.10
-4	12.9	117	2.36	1.93	4.20
1PD-3	14.1	143	4.94	4.17	6.14
2PD-2	13.6	141	5.10	4.64	5.63
12PD-12A	11.7	108	2.63	3.37	3.19
12PD-12B	12.1	108	2.66	3.39	3.41
FW-1	14.9	153	4.93	5.51	7.33
FW-2	14.5	147	5.62	4.41	6.67
FW-3	14.6	147	5.38	4.64	6.76
C-4	12.7	140	2.93	3.38	4.87
D-42	14.4	144	3.88	5.11	6.45
DO-12	13.9	143	3.07	4.54	5.96
GB-2	12.0	106	2.68	5.66	3.29
1MID-3	11.2	99	1.87	4.36	2.68
1KRFT-2	9.9	123	0.99	2.48	2.60
3FTW-2	10.8	100	1.66	3.10	2.52
3FTW-3	11.0	101	1.98	3.16	2.64
4FTR-3	11.1	106	2.29	4.34	2.82
5FTH-2	12.8	145	3.55	3.32	5.13
10D-1	11.4	101	1.90	4.57	2.83
28R-2	10.1	103	1.59	3.13	2.27
237-1	12.1	106	2.65	5.15	3.35

* Specimens 1PD-8 through 12PD-4 were cylinders, 6 inches in diameter by 12 inches long, cast from the concrete batches listed in table A-1. The next four specimens, 1PD-3 through 12PD-12B, were cores, 2-5/8 inches in diameter by approximately 5 inches long, taken from 3 x 3 x 12 inch beams cast from the concrete batches listed in table A-1. The next three specimens, FW-1 through FW-3, were cores 4-1/2 inches in diameter by approximately 6-1/2 inches long, taken from a bridge deck. The remaining specimens were cores, 2-5/8 inches in diameter by approximately 5 inches long, taken from 3 x 3 x 12 inch beams which had been subjected to freeze-thaw cycling in a research study conducted several years previously.

** Chord modulus and compressive strength of air-dried specimens were determined shortly after measuring the velocity.