PAVEMENT THICKNESS MEASUREMENT USING ULTRASONIC TECHNIQUES

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The development and field evaluation of an ultrasonic pulse-echo type of instrument for measuring the thickness of portland cement concrete pavements are described. The results show that the system was accurate to within ±3 percent at 78 of the 100 test locations. Results were checked by core measurements made by the Ohio Department of Highways. The thickness gage was also evaluated on plastic concrete. The results show that this instrument is not capable of measuring the thickness of plastic concrete and also suggest that it is unlikely that any method using ultrasound could perform this function with the desired degree of accuracy. Laboratory experiments on blocks of bituminous concrete indicate that this instrument can be used to measure the thickness of this material at moderate temperatures.

•THE PAVEMENT THICKNESS gage described uses ultrasonic pulse techniques to measure the thickness of portland cement concrete, in place, in highways. Efforts to develop ultrasonic methods for accurate (±2 percent) measurement of portland cement concrete thicknesses have been generally unsuccessful in the United States and in other countries. Significant advances were reported by Jones (1), Bradfield (2), and Muenow (3), but in all cases it was found that accuracies better than ±5 percent were difficult, if not impossible, to obtain.

Two of the critical basic difficulties that have been encountered include (a) the relatively coarse-grained aggregates within the concrete that scatter, reflect, and severely attenuate high-frequency sound waves and (b) the surface roughness (particularly of bottom surfaces on gravel or other subbase structures) that tends to destroy coherent ultrasonic reflections from these surfaces.

The first phase of the development of the pavement thickness gage has already been reported (4). Since that time the interpretation of the acoustic signal spectrum has been revised, and a number of modifications, including the use of an independent acoustic velocity measuring procedure, have been made to the system. These changes have led to a more accurate and reliable system for measuring highway pavement thickness.

THEORY OF OPERATION

The pavement thickness gage measures pavement thickness by monitoring the time it takes for an ultrasonic pulse to travel down through the concrete and back again. The distance the sound travels is related to the transit time and sound velocity by the expression

$$d = 2.04\ T - Vt$$

where

d = distance traveled, in.;
T = pavement thickness or $d/2.04$, in.;
V = velocity of sound propagation, in./sec; and
t = transit time, sec.

A measure of the velocity with which the ultrasonic pulse travels through the concrete is obtained by measuring the time required by an ultrasonic pulse to travel between

2 transducers separated by a known distance on the surface of the pavement. The factor 2.04 is used rather than 2 because the ultrasonic beam does not follow a path straight down and back but rather follows a triangular path from the transmitter to the receiver via the bottom of the concrete pavement.

DESCRIPTION AND OPERATION

The thickness gage system consists of the following individual units: 1 large-area, ring-shaped transmitter, one 5-MHz receiver, two 4.25-in. diameter transducers, 1 type-0 Tektronix operational amplifier, 1 type-453 Tektronix oscilloscope, and specially designed pulse power supply. A photograph of the complete thickness gage is shown in Figure 1. The component parts and their functions are described in the following.

Transit-Time Measurement

The large-area transmitter, shown in detail in Figure 2, is used to obtain the transit-time measurement. This unit has an outside diameter of 18 in. and an inside diameter of 6 in. The ultrasonic generator is a mosaic piezoelectric radiator composed of 14 segments of a modified barium titanate material (Channelite 300). It has a characteristic thickness resonance of 200 kHz to which it responds when excited with an electrical impulse. The mosaic, although composed of several independent elements, responds acoustically as a single radiator when it is excited electrically. This capability has permitted high-energy ultrasonic pulses distributed over a broad area to be introduced into pavement materials for thickness-measuring purposes. The piezoelectric elements are glued to a 3-in. plastic buffer plate that supplies sufficient weight to the assembly to ensure good contact with the pavement.

The radiation pattern from the transmitter has an intensity peak about 20 in. from the unit. A receiver placed in the center of the transmitter would detect this peak when the unit was operating on a 10-in. thick pavement. A functional drawing of the transit-time measurement system is shown in Figure 3. This transmitter is designed for operation on 8- to 12-in. thick pavements. For pavements less than 8 in., a smaller diameter transmitter would give higher amplitude signals. Ideally the transmitter should be designed to have an intensity peak in the radiation pattern at a distance from the unit equal to twice the average thickness of the pavement on which the gage is used.

The signal reflected from the bottom of the pavement is detected by a 2.25-in. diameter, 5-MHz, lithium sulfate receiver. Earlier studies revealed that a receiver of the same frequency as the transmitter distorted the wave shape of the acoustic pulse and made signal identification difficult. The 5-MHz unit was found to be optimum for detecting the 200-kHz signal.

The electrical system used in the thickness gage is representative of a typical A-scan configuration often found in ultrasonic nondestructive testing. Thys type of presentation displays ultrasonic signal amplitude as a function of time. The unit providing the timing as well as the pulse excitation for the ultrasonic system is a typical multivibrator and thyratron pulser configuration. This unit is capable of delivering 600 volts at 75 amperes to a 5-ohm capacitative load for 1-μsec pulses.

In operation the transmitter and receiver are coupled to the pavement by a layer of glycerine. The receiver is moved about on the surface of the pavement within the center hole of the transmitter to optimize the signal response. The typical signal spectrum received is shown in Figure 4. The signal reflected from the bottom of the pavement is easily distinguished from the surface waves that have traveled from the transmitter to the receiver along the surface of the concrete. The transit time of the acoustic pulse through the concrete is obtained by subtracting the system delay time from the time measurement. The delay time, or the length of time necessary for the pulse to traverse the plastic block of the transmitter, is obtained by placing the receiver in direct contact with the base of the transmitter and recording the time of the signal detected.

Velocity Measurement

The transducers used to obtain the acoustic velocity are two 20-kHz rochelle salt units manufactured by James Electronics, Inc. The 4.25-in. diameter housings are

Figure 1. Complete pavement thickness gage system.

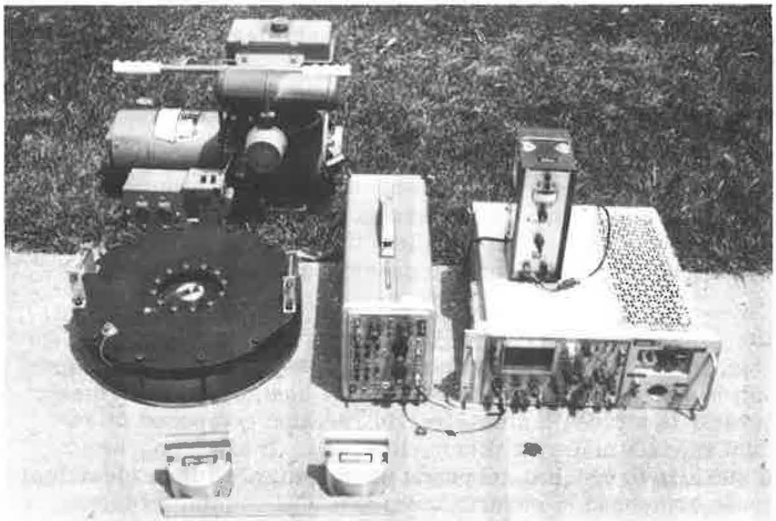


Figure 2. Disassembled large-area transmitter.

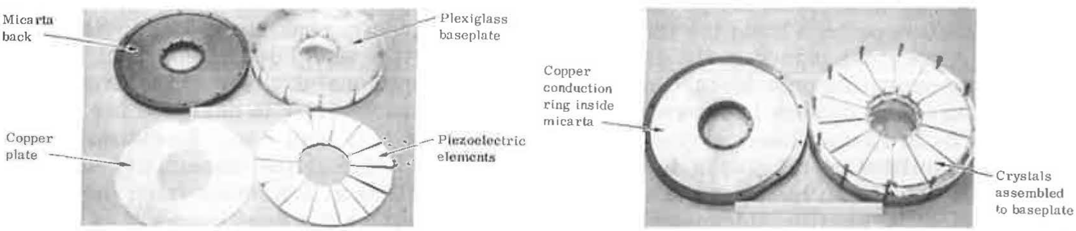


Figure 3. Functional drawing of the pavement thickness gage.

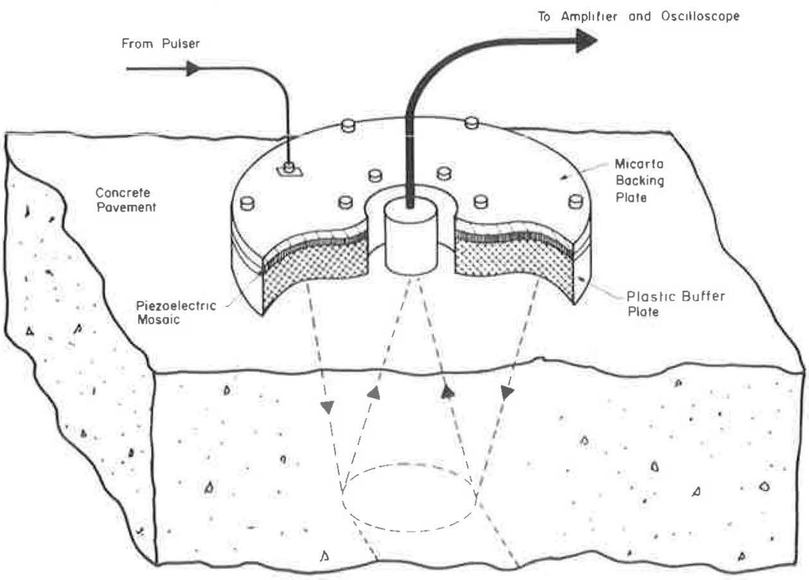
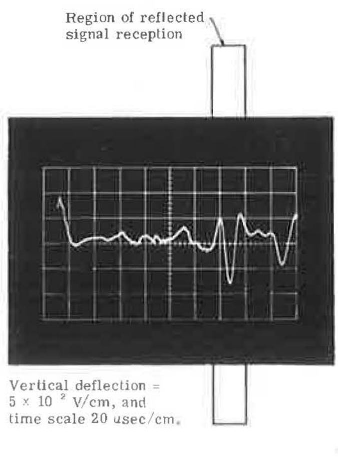


Figure 4. Response from tranmitter on 8-in. concrete.



filled with oil under pressure, thereby providing complete shock and vibration protection for the piezoelectric elements. The transducers are shown in the foreground in Figure 1. The pulse power supply and other electronic equipment is the same as those used for the transit-time measurement.

When the transducers have been placed a known distance on the surface of the pavement, one of the transducers is excited electrically and thereby transmits ultrasonic pulses into the concrete. The other transducer receives the pulses that are then displayed on the oscilloscope. The time of arrival of the pulses is recorded by noting the position of the first negative peak in the signal spectrum shown in Figure 5. The time required for the ultrasonic pulse to travel the known distance between the transducers is obtained by measuring the system delay time and subtracting it from the time measurement. This is obtained by holding the transducers in contact and noting the time of the signal displayed on the oscilloscope.

This technique samples the acoustic velocity in the concrete close to the surface of the pavement. If a velocity gradient exists through the thickness of the pavement, this method of measuring the acoustic velocity would be in error. However, laboratory experiments on test blocks, which permitted the placement of the receiver on the bottom of the concrete slabs, showed very good agreement with the surface method of obtaining the acoustic velocity. During these experiments the optimum separation between the transducers was found to be 18 in.

The complete thickness gage was evaluated under laboratory conditions on a number of test slabs in the 6- to 10-in. thickness range. The results showed that the gage was capable of consistently measuring the thickness of these blocks to within ±2 percent. The performance of the gage in actual highways is described in the following section. Improvements in the velocity measuring technique were made after the field tests and are described in a later section.

FIELD TEST RESULTS

Field tests were performed at each of the following locations in Ohio: Interstate 270, Columbus; Interstate 77, Cleveland; US-33, Athens; Ohio-48, Lebanon; and Interstate 90, Cleveland.

Approximately 100 core locations were examined. Fifty percent of all cores measured had accuracies of ±2 percent or better; 78 percent had errors less than ±3 percent. Greater accuracy would have been achieved if one core had been drilled from each section of highway to calibrate the thickness gage. Seventy-eight percent of the measurements would have had errors less than ±2 percent, and 94 percent would have had errors less than ±3 percent. The results of all the field tests are given in Table 1 and show the average thickness of the highway at each major test location as measured by both the acoustic and mechanical gages. The standard deviations of the acoustic measurements from the mechanical measurements are also given. The basic parameters of the highway, which could affect the quality and interpretation of the acoustic signal spectrum, are given in Table 2 for each test location.

Core measurements taken by a mechanical gage were provided by the testing laboratory of the Ohio Department of Highways. The results are shown in Figures 6 through 10 in a form that permits a clear comparison of the measurements made by the acoustic and mechanical gages at each core location. These plots show the difference between the acoustic and mechanical measurements. The results were also plotted with the use of a core calibration whenever this procedure significantly improved the accuracy of the results.

IMPROVED VELOCITY MEASUREMENT PROCEDURE

Transducer Orientation

Laboratory tests conducted after the field tests on the actual cored samples indicated that errors of as much as ±2 percent were encountered in the velocity measurements. Tests were performed to find the source of those errors. It was learned that, although the transducer housing is circular with a 4-in. diameter, the piezoelectric element is

Table 1. Summary of field test results.

Location	Number of Sites	Core Average (in.)	Gage Average (in.)	Standard Deviations (in.)
I-270	25	8.60	8.45	0.33
I-77	18	10.45	10.50	0.20
US-33	18	8.40	8.75	0.17
Ohio-48	20	9.30	9.20	0.26
I-90	18	10.70	10.35	0.13

Figure 5. Typical signal pattern received and used to measure local acoustic velocity.

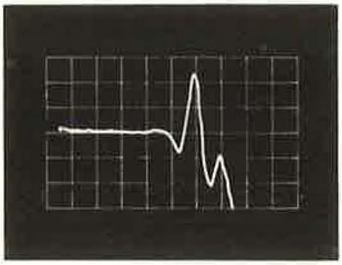


Table 2. Basic parameters at each test location.

Location	Aggregate Type	Top Surface Roughness	Subbase	Reinforcement
I-270	Gravel	Rough	Bituminous aggregate	0.725-in. longitudinal bars 6 in. apart and 0.5-in. transverse bars 34 in. apart
I-77	Slag	Smooth	Slag	Paving mesh
I-90	Slag	Smooth	Slag	Paving mesh
Ohio-48	Gravel	Smooth	Sand and gravel	Paving mesh
US-33	Gravel	Smooth	Sand and gravel	Paving mesh

Note: Paving mesh consists of 0.262-in. longitudinal bars 6 in. apart and 0.225-in. transverse bars 12 in. apart.

Figure 6. Field test results from I-270.

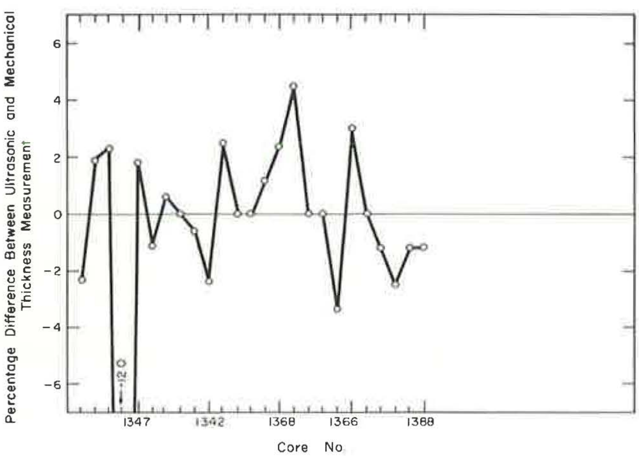


Figure 7. Field test results from I-77.

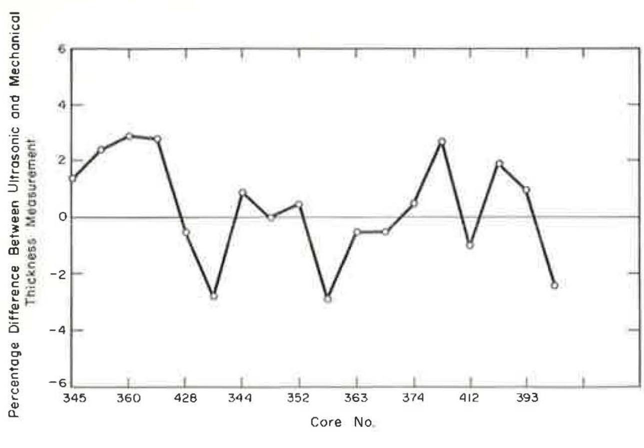


Figure 8. Field test results from US-33.

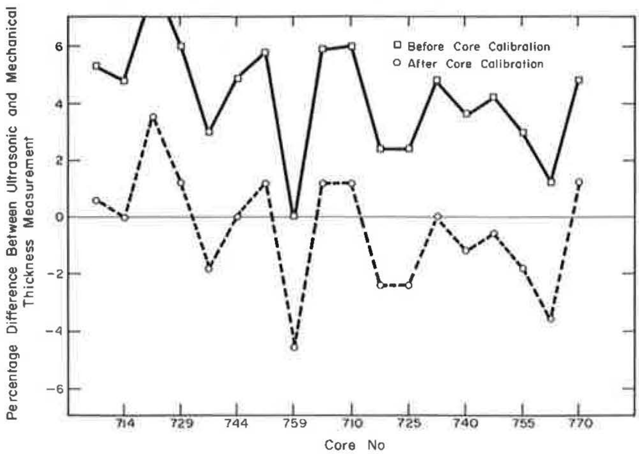


Figure 9. Field test results from Ohio-48.

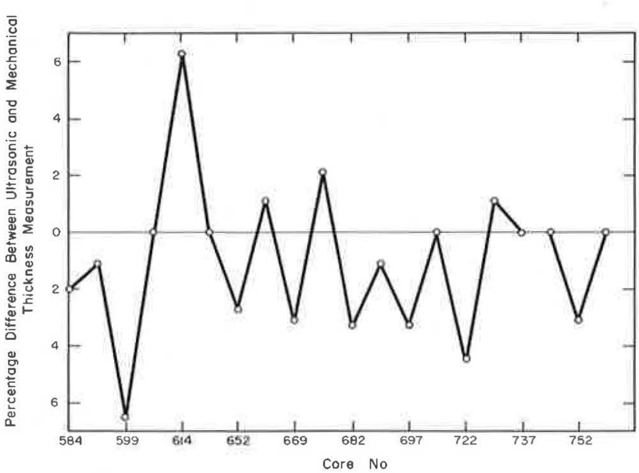
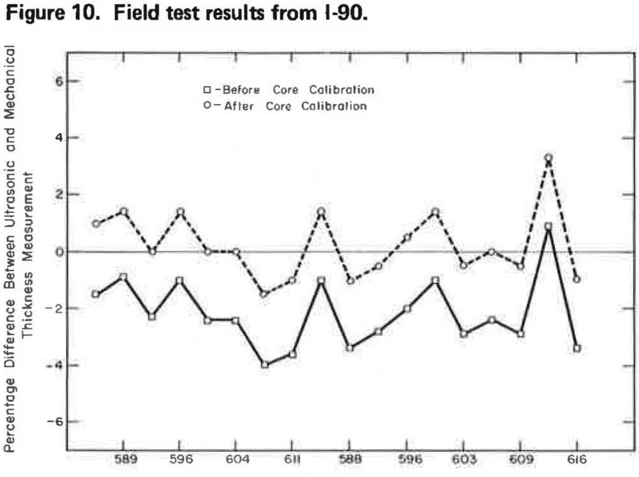


Figure 10. Field test results from I-90.



rectangular. The actual separation distance of the crystals, therefore, varies with the orientation of the transducers. Figure 11 shows 2 possible positions of the transducers, position B having been rotated 90 deg from position A. The tests showed that random orientation of the transducers could result in a maximum error of 1 percent in the velocity measurement.

Transducer Contact Pressure

The housing of the transducers used for the velocity measurement is filled with oil; the oil couples the acoustic output from the piezoelectric element to the highway through a rubber membrane at the base of the transducer. Because the oil is under pressure, the rubber membrane presents a convex surface to the highway. The actual contact area between the transducer and the pavement depends on the contour of the membrane surface and the force with which the transducer is pressed onto the pavement.

Analysis of the field measurements showed that the system delay time, obtained by pressing the transmitters and receiving transducers together, varied from 30 μsec (30×10^{-6} sec) to 35 μsec. This was shown to be mainly due to a variation in the pressure with which the transducers were held in contact. Because the transducers were also pressed by hand onto the pavement to measure the acoustic velocity, the value obtained was also subject to error due to pressure variations.

This problem was corrected by attaching 12.5-lb weights to each transducer. The oil pressure in the transducers was adjusted to achieve a 2-in. diameter contact area with the pavement. The delay time was measured by placing one transducer on top of the other and by taking the reading with no additional pressure applied by hand. Using this constant pressure showed that the delay time would not vary by more than 0.5 μsec. It is expected that the use of a constant transducer orientation and contact pressure will significantly improve the accuracy of velocity measurements.

PLASTIC CONCRETE STUDIES

A laboratory investigation was conducted to evaluate the capability of the pavement thickness gage to measure the thickness of plastic concrete pavements. If this instrument could measure the thickness of concrete immediately after pour, it could be used to monitor, and control, the laying of pavements by a slip-form paver.

The laboratory arrangement used in this investigation is shown schematically in Figure 12. Figure 13 shows the signals detected by the 2 receivers 1 hour after pour. The receiver R_1 received the signal marked R_1. The receiver R_2 received the signal R_2 after it was reflected from the bottom of the concrete. Receiver R_2 also detected signals reflected from the aggregate within the concrete.

The transmitted signal R_1 shows severe attenuation from its passage through the plastic concrete. The signal is also of very low frequency suggesting that only the lower frequency components of the acoustic pulse succeeded in penetrating the 4-in. plastic concrete. The reflected signal R_2 was expected to be of lower amplitude and frequency than R_1 because R_2 had traveled twice as far in the plastic concrete. However, the reflected signal R_2 contains comparatively high-frequency components and high-amplitude signal strength.

Figure 13 also shows the same signals 1.5 hours after pour and with a different time scale. The high-frequency components of R_2 are modulated by a much lower frequency wave form similar to R_1. The low-frequency component represents the acoustic signal reflected from the bottom of the concrete. The high-frequency components are reflections from the aggregate within the concrete.

The acoustic velocity was also monitored from the time of pour of the concrete. The results are shown in Figure 14. The acoustic velocity in plastic concrete (1,000 fps) is very low compared with that in hardened concrete (14,000 fps).

It was, therefore, concluded that the pavement thickness gage in its present form could not measure the thickness of plastic concrete immediately after pour. Because of the high degree of nonhomogeneity of plastic concrete, the acoustic signal is severely scattered and attenuated by reflections from the aggregate. The resulting signal is of comparatively low amplitude and low frequency (23 kHz) and is not detectable until about

Figure 11. The transducers in positions A and B, the 2 positions used during field tests.

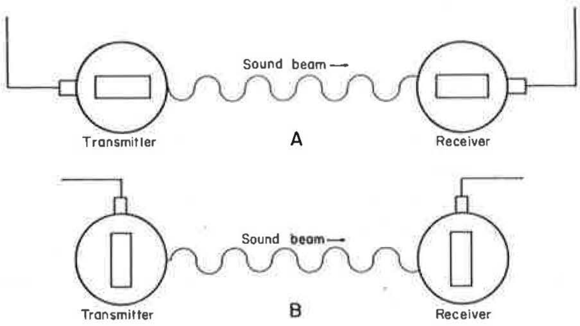


Figure 12. Experimental arrangement used to evaluate the capability of gage to measure plastic concrete.

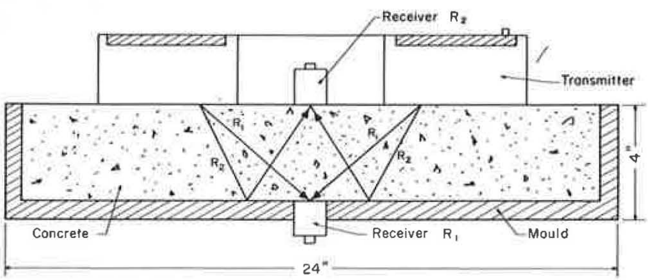
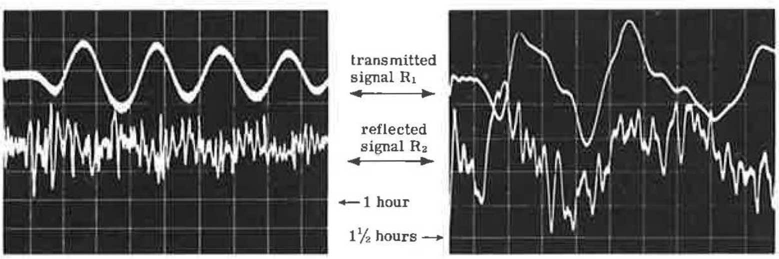


Figure 13. Transmitted and reflected signals through 4-in. plastic concrete 1 hour and 1½ hours after pouring.



Vertical deflection = 2×10^{-4} V/cm, and time scale = 0.2 μsec/cm.

Vertical deflection = 2×10^{-4} V/cm, and time scale = 0.1 μsec/cm.

Figure 14. Variation in acoustic velocity in concrete with 50 percent aggregate from time of pouring.

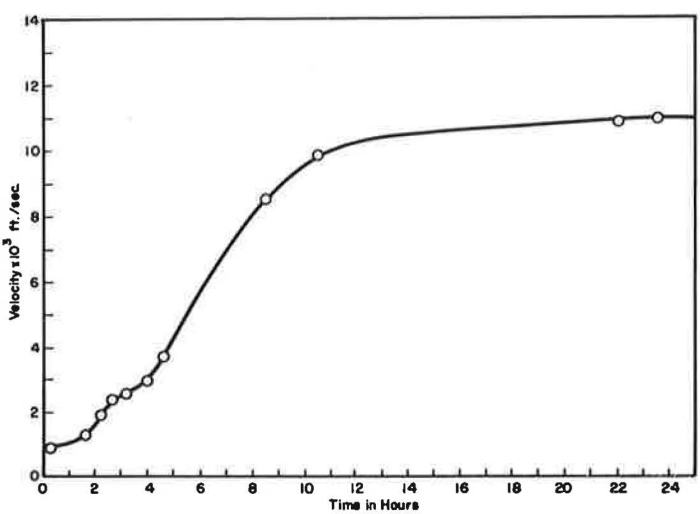
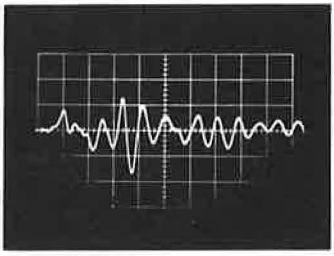


Figure 15. Typical transit-time signal recieved from 4-in. block of bituminous concrete.



Vertical deflection = 50 MV/cm, and time scale = 20 μsec/cm.

1 hour after pour of standard slip-form paver concrete. The low amplitude of the reflected signal, compared with that scattered back from the aggregate, suggests that electrical filtering techniques would have to be used to enable identification of the desired signal.

The results of the experiments described suggest that, even with a large area and low-frequency transmitter (20 kHz), it is very doubtful whether a usable signal could be obtained from plastic concrete immediately after pour. It is, therefore, concluded that the ultrasonic techniques on which the thickness gage is based cannot be used to measure the thickness of plastic concrete pavements.

THICKNESS MEASUREMENT OF BITUMINOUS CONCRETE

Tests were conducted on a 4-in. thick block of bituminous concrete to evaluate the capability of the gage to measure the thickness of this material. The transit-time signal received from the block is shown in Figure 15. The use of this signal, together with a velocity measurement, resulted in an acoustic measurement of the thickness to within 1 percent of the actual thickness.

The attenuation of the acoustic signal in bituminous material at room temperature (22 C) was found to be twice that experienced in portland cement concrete. The attenuation increased considerably with increasing temperature until no transit-time signal could be observed at 52 C. The gage could, therefore, be used to measure the thickness of bituminous concrete at moderate temperatures.

CONCLUSIONS

The pavement thickness gage has demonstrated its ability to measure the thickness of portland cement concrete pavements. Accuracies of ±3 percent at more than 90 percent of the test locations are expected with the use of the improved velocity measuring technique. That is probably the best agreement that can be expected with the mechanical measurement taken from cores.

It is expected that the ultrasonic gage would show much better agreement with the mechanical measurements if statistical methods were used to evaluate pavement thickness. Laboratory results have also demonstrated that the gage can measure the thickness of bituminous concrete provided the measurements are performed at moderate temperatures.

Tests on plastic concrete have shown the thickness gage to be incapable of measuring concrete immediately after pour. Depending on the properties of the mix, it is possible that a thickness measurement could be made about 3 hours from the time of pour, but by this time the concrete is generally in the transition region between the plastic and hardened states.

Additional field tests of the gage are now being performed in Ohio and in Pennsylvania.

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