Pavement Thickness Measurement Using Ultrasonic Pulses

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A pulse-echo type of ultrasonic pavement thickness measuring system is described. The system's performance on newly constructed concrete pavements is reviewed. Recommendations for future system development are made along with design criteria for advanced versions of the present system.

The thickness measurements are based on ultrasonic pulse transit time measurements in pavements of known sound velocity. Accuracies of ±2 percent in better than half of the measurements taken were obtained during a testing program involving more than 350 measurements. Results were verified by core measurements made by the testing laboratory of the Ohio Department of Highways. This accuracy was attained through the use of large-area ultrasonic transmitters, high pulse powers, and high frequencies of operation (300 kHz).

During the evaluation program it was found that an assumed constant velocity of propagation over a finite area of pavement did not seriously impair the test results. Once velocity information was obtained for a given section of highway, it was found reasonably safe to consider that the velocity remained the same for considerable distances around the specific velocity measurement site.

•THE thickness gage described uses ultrasonic pulse techniques to measure thickness of portland cement concrete, in place, in highways. The need for accurate, nondestructive means of pavement thickness measurement is well known to highway engineers and contractors as well as to state and national agencies supporting highway construction and maintenance. Thus, it is not detailed here.

Efforts to develop ultrasonic methods for highly accurate (±2 percent) measurement of portland cement concrete thicknesses during the past 20 years have been generally unsuccessful in the United States and in other countries. Significant advancements were reported by Jones (1), Bradfield (2), and Muenow (3), but in all cases it was found that accuracies better than ±5 percent were very 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 pavement thickness measurement program described was specifically designed to compensate for these known difficulties through the use of novel transducer designs. The unusual features of the final design were specifically:

1. The use of unusually high ultrasonic power levels to compensate for signal attenuation in concrete due to the presence of coarse aggregate.
2. The use of large-diameter transducers that permitted averaging of bottom surface roughness.

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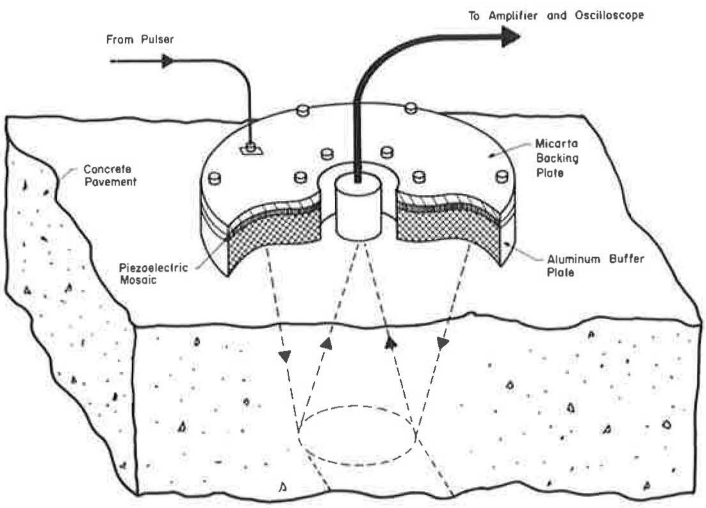

Figure 1. Functional drawing of the OSU/ODH Pavement Thickness Gage.

3. The use of high-frequency receiver systems to permit signal identification through wave shape observation.

By using these techniques, high-frequency operation for improved resolution of bottom surface location was obtained. The details of the gage are reviewed in the following discussions of theory and practice.

THEORY OF PAVEMENT THICKNESS GAGE OPERATION

The OSU/ODH Pavement Thickness Gage* measures pavement thicknesses by monitoring the amount of time it takes 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:

$$d = 2T = Vt \tag{1}$$

where

- d = distance traveled (in.),
- T = pavement thickness = $d/2$ (in.),
- V = velocity of sound propagation (in./sec), and
- t = transit time (sec).

Figure 1 shows the organization of the system.

Once the transit time is measured, then the thickness can be readily calculated, given the speed of sound for the material. For example, a pavement 9 in. thick having a sound velocity of 144,000 in./sec (12,000 ft/sec) would have a measured transit time $125(10)^{-6}$ sec (125 μsec). A pavement 10 in. thick with a velocity of 16,000 ft/sec would have a transit time of 104 μsec. Thus, the technique for measuring the pavement thickness is to establish the sound velocity for the local pavement material and to measure the transit times throughout the area.

The sound velocity can be obtained in various ways. One way is to take a transit time measurement for a pulse traveling down and back through the pavement. When

*The abbreviations represent the developmental and sponsoring agencies, i.e., Ohio State University and Ohio Department of Highways, in conjunction with the Bureau of Public Roads.

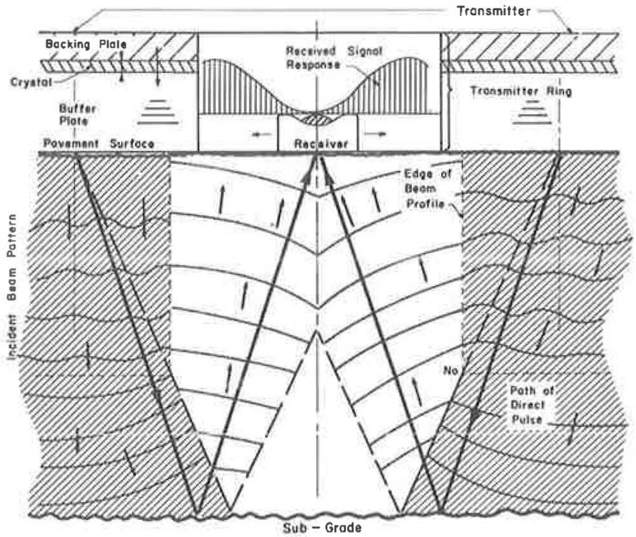

Figure 2. Schematic drawing of the sound field in the vicinity of the OSU/ODH Pavement Thickness Gage.

this time is compared to a core's length taken from the same area, the velocity can be computed by using Eq. 1. Although this technique was the one used for the initial evaluation of the OSU/ODH Pavement Thickness Gage on sections of Interstate highway systems near Columbus, Ohio, it was found that thickness accuracies within ±2 percent could be attained by assuming an average velocity throughout the 351 tests.

Due to the geometry of the transmitter and the location of the receiver, the ultrasonic beam path is not straight down and back, but rather follows a triangular path. The actually measured transit times are therefore slightly longer than those obtained by a pulse traveling straight down and back. This extra time corresponds to approximately 4 percent of the total transit time for the geometry used. However, it was found that an effective velocity could be used to describe the thickness of the pavement (effective signifying the velocity needed to describe the actual thickness given the measured transit time). Errors introduced by using this procedure are less than 1 percent in 8- to 10-in. pavements.

The Ultrasonic System

The detection system of the pavement thickness gage is based on the divergence of sound from an ultrasonic radiator. As a pulse of ultrasound propagates down through the concrete, it spreads out. Thus, the receiver, located at the geometrical center of the large transmitting radiator, obtains a useable signal. Although the large-area transmitter tends to concentrate the sound beam for better conservation of ultrasonic power density, it does not destroy the effect of the receiver's capability. Figure 2 shows the approximate ultrasonic profile of the sound beam within the concrete developed by such a large-area transmitter arrangement.

Note that in this configuration the receiver is physically removed from the transmitter area. This permits better isolation of transmitter noise from signal returns. The transmitter is in the form of a disc with a hole in its center for positioning of the receiver. Most effective was a transmitter with an outside diameter of 16 in. and an inside diameter of 4 in. The ultrasonic sound generator is a mosaic piezoelectric radiator composed of 20 segments of a modified barium titanate material (Channelite 300). It has a characteristic thickness resonance frequency of 400 kHz to which it responds when excited with an electrical impulse. When mounted in the assembly, this drops to about 300 kHz. The mosaic, although composed of several independent elements, responds acoustically as a single radiator when excited electrically. This capability has permitted high-energy ultrasonic pulses distributed over a broad area to be introduced into pavement materials for thickness gaging purposes.

The aluminum buffer plate located between the piezoelectric element and the pavement serves as a 3-in. protective layer between the ceramic-like element and the highly abrasive concrete surface. Due to multiple reflections within the buffer plate, a second transmitted pulse approximately 30 μsec behind the initial pulse is transmitted and often assists in identifying the bottom reflection signals in the presence of excessive background noise. The buffer plate also supplies sufficient weight to the assembly to assure good contact between the transmitter assembly and the pavement material.

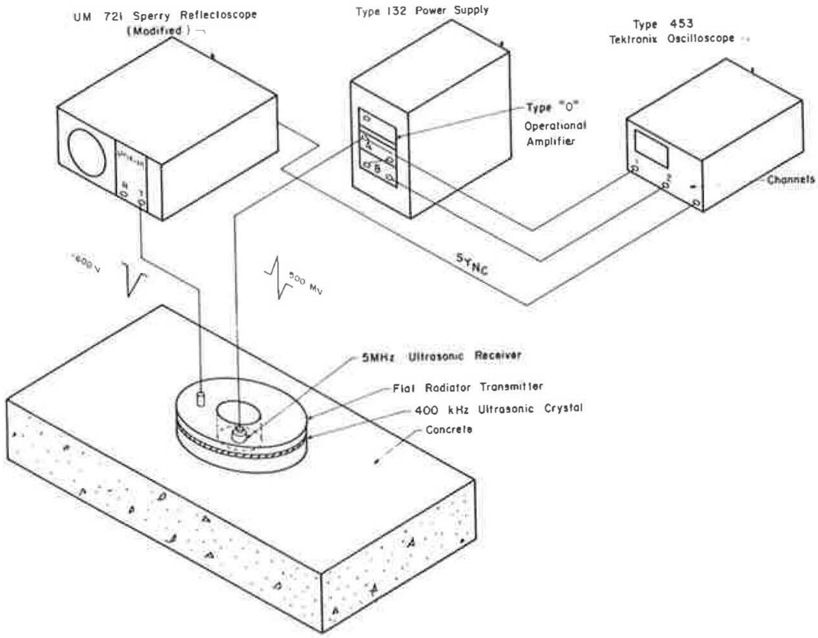

Figure 3. Block diagram of the OSU/ODH Pavement Thickness Gage.

Mathematical analysis of the theoretical sound fields showed that the main or central lobe of the transmitter (and therefore reflected) energy covers a radius of $^3/_4$ in. Thus, in order to maximize the response of the system, the receiver transducer was especially designed to be at least 1.5 in. in diameter. Experimental evidence showed an increase in receiver output of 10 times that previously available using smaller area receivers.

When a receiver is frequency-matched to an ultrasonic oncoming signal, the true shape of the received pulse is usually lost, although the output is high. Since it was found that bottom surface signals were identified by a characteristically high-frequency pulse, a receiving transducer with natural resonant frequency well above the frequency of the incoming signal was chosen. For a 200 to 400 kHz input signal, a 5 MHz receiver was found to be best. Thus, the special purpose receiver is 1.5 in. in diameter with a natural thickness resonance of 5 MHz.

The Electrical System

The electrical system used in the Pavement Thickness Gage is representative of a typical A-scan configuration often found in ultrasonic nondestructive testing. This type of presentation displays ultrasonic signal amplitude as a function of time. A block diagram of the system is shown in Figure 3. The unit providing the timing as well as the pulse excitation for the ultrasonic system is a typical multivibrator and thyratron pulser configuration. Signals corresponding to reflected ultrasonic pulses from the bottom surface of the concrete are detected by the high-frequency receiver located at the geometrical center of the transmitter. The received pulses may be amplified and/or modified in the operational amplifier and are then displayed by the type 453 Tektronix oscilloscope. The pulser unit is capable of delivering 600 volts at 75 amperes to a 5 ohm capacitive load for 1 μsec pulses.

Placement of the receiver probe in direct contact with the transmitter yields pulses of 6 volts peak amplitude. Since the receiver probe has a surface area equal to $^1/_{75}$ that of the transmitter's area, the drop from 600 volts excitation to 6 volts reception is to be expected. The wave-shape of this received signal is shown in Figure 4.

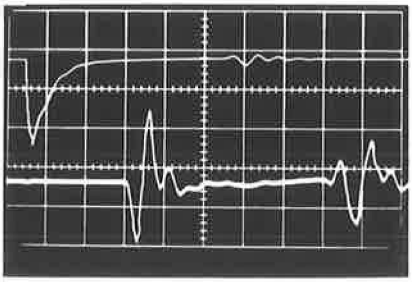

Figure 4. Excitation and received signals through 3-in. aluminum buffer plates.

Use of Operational Amplifiers

The operational amplifier is usually used for direct amplification of low-level signals. When identification of the received pulse is difficult, differentiation and amplification of the input signal may supply a uniquely clear indication of the received pulse. This follows since identification of the received signals is done through observation of a signal with a steeper slope than that of the background noise.

Under good conditions, the signal to noise (S/N) ratio was of the order of 2. When these signals are differentiated, their derivative is substantially larger than that of the background. The S/N ratio is improved to 5 or better.

FUNCTIONAL OPERATION OF THE OSU/ODH PAVEMENT THICKNESS GAGE

The usual technique of testing uses two operators. One operator handles the transmitter and receiver on the road surface while the other records the transit times measured from the oscilloscope. The transmitter and receiver are ultrasonically coupled to the pavement by a bentonite and water paste. The receiver in the center of the transmitter is moved about to assist the recorder in absolutely identifying the reflected signal. When a reflection from the base of the pavement is clearly visible on the oscilloscope, its exact transit time is recorded.

In most cases, the oscilloscope has sufficient signal amplification capabilities to give a satisfactory presentation of signal shape on the screen. For those cases in which the received signal is weak and very close to the background noise level, additional amplification can be supplied by an external operational amplifier.

The positive identification of the bottom surface reflected pulse (in the presence of background noise) is made by recognizing its unique high-frequency shape. Noise signals received in addition to the bottom surface signals are mostly at a frequency of about 10 kHz as opposed to the 300 to 400 kHz bottom reflection signal.

Signal Identification

Signal identification and interpretation are relatively simple using the Pavement Thickness Gage. Nearly every signal will show a low-frequency pulse at and around the time corresponding to the bottom thickness. Superimposed on the low-frequency waveform is the characteristic high-frequency bottom echo signal. The oscilloscope adds these two signals. The result is shown in Figure 5.

The labels in Figure 5 refer to the main factor for consideration in the pavement depth calculation:

T_{tt} = total transit time from pulse initiation to received signal display.

T_d = delay time, or the length of time necessary for the pulse to traverse the aluminum block of the transmitter.

T_{ta} = actual transit time, or the length of time necessary for the pulse to traverse the distance from pavement top surface to bottom surface and back to the receiver.

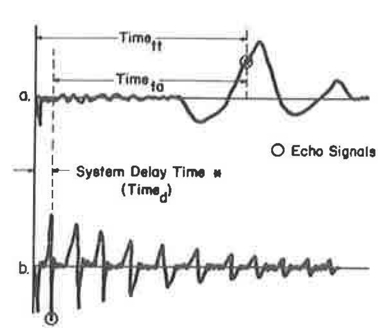

Figure 5. Oscilloscope display of satisfactory received signal.

There are occasions when the waveform completely "covers" the high-frequency echo pulse. In such instances, the signal display has the appearance of Figure 6a. In this situation the operator can usually improve the signal and make it more intelligible

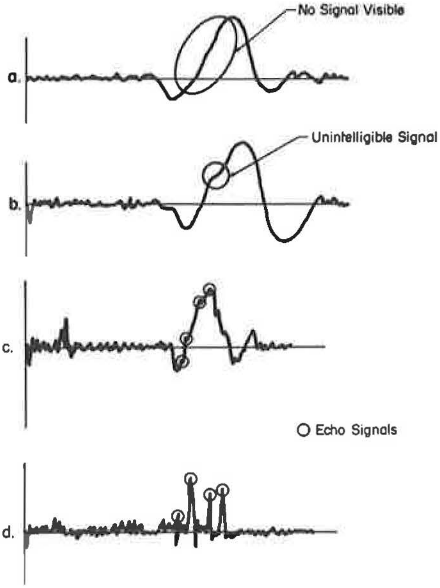

Figure 6. Oscilloscope display of unsatisfactory but informative signals.

by repositioning the transmitter and/or receiver. He can also make significant improvements by recoupling the transducer assemblies to the pavement. Figure 6b is another example of the same kind of signal; in this case the echo is visible, but not intelligible—i.e., the operator is unable to determine with precision where the peak of the pulse lies on the waveform.

Ordinarily, the signals obtained in the field vary between the types of signals shown in Figures 5a, 6a, and 6b. Whenever signals of types 5a and 6b are present, clarity and intelligibility can be improved by repositioning either the transmitter or receiver, or both, or by improving the coupling of the transducers to the pavement.

Sometimes a waveform such as shown in Figure 6c and 6d is displayed on the oscilloscope. Each of the points is an intelligible signal. The signal generally indicates to the operator either honeycomb on the bottom surface or lack of bonding at the subbase surface. Because this type of trace indicates a flaw in the integrity of the concrete, it is useful as a nondestructive test of pavement; but in order to establish a true depth, a good bottom echo must be obtained. In other words, when a signal trace of this type is encountered, the presence of the honeycomb can be recorded, but the transducer must be moved until a good echo is obtained before the true depth can be determined.

The Pavement Thickness Gage was evaluated by taking a series of transit times over a given testing area of pavement from which a single core had been removed. The core was used to find the effective velocity for the region. With this velocity information, it was possible to predict the thickness of remaining locations through the region by measuring the corresponding transit times.

A program of field testing was carried out using the flat-radiator version of the Pavement Thickness Gage during the late autumn of 1966 and the summer of 1967. The program that was followed and the results of the testing are outlined next.

FIELD TESTING PROGRAM

The field testing program was conducted on several unopened sections of Interstate highway throughout Ohio. Thickness measurements were taken both at sites which had been previously cored by the ODH testing laboratory personnel and at untested locations. Velocity data were initially obtained from transit time readings taken at a site which was subsequently cored and measured. With this information as a basis for testing, the remaining core locations were tested ultrasonically.

Core site locations were made available to the testing program through the cooperation of the ODH. During ultrasonic testing, the center of the area measured was marked with paint to assist the core driller in locating the site and to assure that identical test sites were used.

General Observations

Seven thickness measurements using ultrasonic techniques could usually be taken each hour. The present ODH rate is 20 cores a day, plus the time in the laboratory required to mechanically measure the cores.

There were some sections of pavement where the reflected signal was consistently hard to read. In these areas, the operating rate could be cut to only four measurements an hour plus extra care required in setting up equipment. Under favorable

TABLE 1

Site	No. of Comparisons	Avg. Thickness* ODH	Avg. Thickness* OSU	Discrepancy* ODH-OSU	% Accuracy (ODH/OSU) × 100
IR 75	45	9.12	9.03	-0.09	100.97
IR 77	52	9.02	8.95	-0.07	100.82
IR 70	60	9.08	9.47	+0.39	95.88
IR 270	86	9.09	9.20	+0.11	98.80
IR 275	20	9.02	9.40	+0.38	95.95
US 30	23	9.07	8.96	-0.11	101.22
IR 70	42	9.04	9.08	+0.04	99.55
	328	9.07	9.17	+0.10	98.90

* Thickness and discrepancy in inches.

operating conditions, rates of ten or more measurements an hour were maintained. For the hard-to-read regions, subsequent testing has revealed that these conditions are indications of such pavement characteristics as honeycombing, cracking, and general degradation of the pavement.

TEST RESULTS

More than 350 thickness measurements were taken by using the Pavement Thickness Gage during 1967. Of these, 150 were taken after the core had been cut. ODH and the ultrasonically measured pavement thicknesses agreed with ±2 percent in better than half of the measurements taken. For 9-in. pavement, ±2 percent is equivalent to an average difference of ±0.18 in. Perfect agreement between the two measuring systems occurred in 17 percent of the total readings. Comparative results of typical job sites and a major sampling of the type of results obtained by the Pavement Thickness Gage are given in Table 1. Accuracies on a job basis were mostly within 2 percent with two exceptions. The averages of the total program are within 1 percent, even though the two exceptions are both positive deviations.

The variances are attributed primarily to (a) the inherent averaging procedures used in the tests, (b) the differences in operating personnel, and (c) the acoustic characteristics of the pavement materials. Since the effective velocities used and the measure-

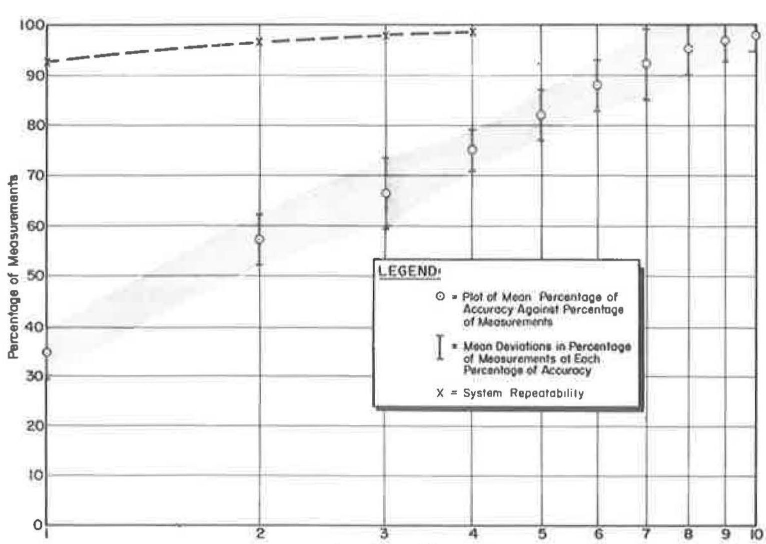

Figure 7. Average accuracy of the OSU/ODH Pavement Thickness Gage.

ments are based on the averaging of the ultrasonic pulse transit times representing pulse paths distributed over a 16-in. diameter ring, the ultrasonic gage is measuring an area four times the size of the ODH core. Thus, all of the variations within this larger area are also being compared to the core measurement. The figures also represent the training of three people in the operation of the equipment and all of the potential variations inherent in such a procedure. The velocity of sound in concrete throughout a given paving job was assumed constant. This was found true over modest segments of highway.

Figure 7 shows the results of the first 351 measurements made using the Pavement Thickness Gage. It shows the agreement of the OSU and ODH measurements for the total testing program and the duplication uncertainty found in the system. The results are expressed as the percentage of times the results fell within the specified ratios. For example, 35 percent of the measurements taken were within 1 percent of the ODH readings. The upper curve represents the variations found in merely trying to duplicate previous readings and is considered the best possible system performance.

Some of the more gross disagreements between OSU and ODH readings have been attributed to the varying characteristics of the concrete pavements. By examining cores that were cut at the same site at which ultrasonic gage results were incorrect, obvious problems in the concrete have been observed. Large pebbles, air pockets or uncommonly rough bottoms have usually been prevalent in these sample cores. Some of the cores inspected were found to be so bad that they broke apart during the coring process. Pavements in such condition can make the thickness gage ineffective for thickness measurement, but then it signals the presence of poor concrete by its noticeable lack of detectable signal. No effects were found present due to steel reinforcing rods in the pavements.

The degree of reproducibility of results and the system's inherent uncertainty are also shown in Figure 7. This curve was made from the normalized results of four separate readings taken at one site. The readings were normalized with respect to their average value. This is equivalent to the consistency of the system at a single core site. Figure 7, therefore, shows the highest performance which can be expected from this system. The graph indicates that about 92 percent of the results are consistent within ± 1 percent.

A similar plot constructed from data taken from typical mechanical tests made by the ODH testing laboratory has the same shape and value distributions. For the data obtained from ODH, 91 percent consistency was obtained within the ± 1 percent deviation, indicating that the ultrasonic system's reproducibility is equivalent to that of the mechanical testing procedure.

While poorly laid concrete does make the taking of measurements difficult, it is not the only road problem. Initial investigations showed that ridges in the top surface of the pavement of $\frac{1}{8}$ in. or more produce sufficient distortion in the incident and received pulses to make interpretation difficult. In addition, when the ridges are this deep it is difficult to maintain sufficient ultrasonic coupling between the transmitter and the road surface.

Measurements have been made on samples ranging from $7\frac{1}{2}$ to 10 in. thick. When samples are smooth on both sides, this range doubles. Beyond approximately 15 in., the signal attenuation is too large for reception of detectable signals. Below 5 in., the signal distortion makes interpretation of return signals impossible in many cases. These limits should cause little problem in highway testing, however, since the average pavement thickness of 9 in. is well covered.

Nominal velocity values were calculated from the transit time measurements resulting from field tests. The distributions of ultrasonic agreements with ODH measurements were observed using progressively higher velocities until an optimum in agreement was reached. The velocity yielding the optimum correlation was taken as the characteristic velocity for that section of pavement. The velocities obtained thus were later used to predict the pavement thickness throughout each given job.

In general, the gage characteristics can be summarized as follows:

1. It supplies data on pavement thickness with accuracies of ±2 percent or better in more than half of the recorded measurements.

2. It is operable in the field as well as in the laboratory.
3. It can detect high-frequency sound pulses in concrete throughout a range of 5 to 15 in.
4. It requires operator interpretation of signal readout and data reductions.
5. It is nondestructive to the pavement.

CONCLUSIONS

The OSU/ODH Pavement Thickness Gage has demonstrated its ability to measure pavement thickness. Because this ultrasonic device is nondestructive during each test, significantly larger numbers of thickness samplings can be made when evaluating the thickness of pavements. The accuracy of the system is attributed to the use of high-frequency and high-power transducer elements. The program has demonstrated the extreme usefulness of ultrasonic technology to the highway industry.

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