FINAL REPORT

USE OF THE IMPACT-ECHO METHOD IN NONDESTRUCTIVE MEASUREMENTS OF THE THICKNESS OF NEW CONCRETE PAVEMENTS

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16. Abstract

The non-destructive impact-echo (IE) method offers a simple means for introducing compressional stress waves into a concrete element or slab and measuring the resonance frequencies associated with the reflections of the waves from any internal voids and the bottom of the slab. It is relatively effective for detecting internal voids or delaminations in concrete, which is the application for which it was developed. It may also be possible to use the method for indirect measurement of the thickness of a slab if the wave propagation velocity in the concrete is known. This study was conducted to determine whether the IE method, by itself, could replace the use of coring for quality-assurance measurements of the thickness of concrete slabs in newly built pavements. The results from tests conducted on three pavements indicated that the wave velocity varied so much, not only between pavements but also within a pavement, that unacceptable errors can result when an average velocity is determined (through limited coring) for a pavement and subsequently assumed for the entire pavement. To reduce the error to an acceptablelevel, the wave velocity at a test location must be measured to within an acceptable accuracy by another independent method. In pursuit of this approach, an indirect-transmission procedure based on ultrasonic (UT) measurement was incorporated and tested. This combined IE/UT preocedure was able to measure thickness with absolute errors of 5 mm in one pavement and 7 mm in another, at a 90% probability. These results can be considered encouraging since the current procedure requires that the length of a core—reported to the nearest 3 mm—be the average of several measurements around the core and, in some cores, these measurements can have a spread of as much as 13 mm. In addition, it is expected that these errors can be reduced easily with the use of a transducer with a smaller contact face that would be less sensitive to roughness on the surface of grooved concrete pavements.

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(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

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INTRODUCTION

The eventual service life of a concrete pavement is influenced not only by the quality of the concrete mixture used in building the pavement, but also by the thickness of the concrete slab built into the pavement. Therefore, as part of the quality-assurance inspection before a newly built pavement is accepted, the thickness of the concrete slab throughout the pavement is measured to determine the extent of the contractor's compliance with the thickness specification. When the average actual thickness is found to be less than that required by the specification, an adjustment in payment is made according to the degree of deficiency found.[1]

At present, this measurement is performed in accordance with AASHTO T 148 (or ASTM C 174), which involves extracting cores (at specified intervals) from each lane and measuring the average length of each core with a proper calipering apparatus. This procedure is undesirable because coring is time-consuming and destructive—it leaves discontinuities that can weaken the pavement. Further, whenever a destructive inspection procedure is the only option, concerns with the cost and the potential adverse effect of the procedure on the structure being inspected probably often lead to a tendency to compromise the thoroughness of the inspection. Therefore, there is a need for an alternative inspection method that is rapid, inexpensive, nondestructive, and of adequate accuracy—probably to within 3 mm, which is the smallest unit by which core length is currently reported.

As part of a continuous effort to find a method that can fulfill this need, the new impact-echo (IE) method was examined for use in the nondestructive measurement of concrete thickness in new pavements—an application that had not yet been reported in the literature. As with any sounding method to measure the distance or thickness traveled by a probing electromagnetic or stress wave, it is necessary to know the propagation velocity of the wave in the material. When the IE method is used to measure the thickness of a concrete slab, it is necessary to know the velocity of the stress waves in the concrete to within a sufficient accuracy in order to obtain an acceptable accuracy in the resulting thickness measurement. Unfortunately, as will be discussed, stress wave velocity in concrete can vary considerably—not only between different mixture compositions but also within a project. This large variation makes the seemingly simple application of the IE method challenging.

BACKGROUND

Principle of the Impact-Echo Method

The IE method was originally developed at the National Institute of Standards and Technology (formerly National Bureau of Standards) for the detection of voids or delaminations in concrete structures.[2] It involves the introduction of a transient stress pulse into the concrete structure being tested by mechanical impact on the surface of the concrete (Figure 1). Radiating away from the point of impact, this stress pulse consists of compressional (P) and shear (S) waves that propagate into the concrete along spherical fronts and Raleigh (R) waves that propagate along the surface of the test object in circular fronts. The P and S waves are reflected to the surface by the external boundaries of the test object and any internal defects. Upon arrival at the surface, these waves are re-reflected back into the concrete, thereby creating periodic reflections (resonance) between the top surface and the bottom surface or any internal defects. These processes continue until all the energy created by the mechanical impact is dissipated.

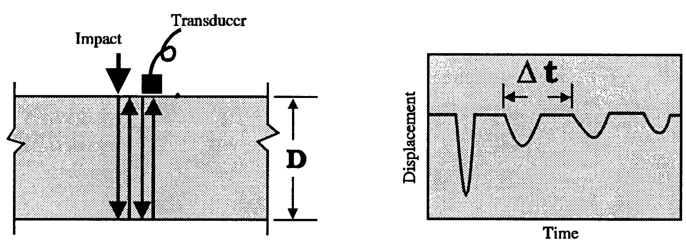

FIGURE 1 . Impact-Echo Method

The arrival of the reflected waves at the surface of the concrete structure produces corresponding displacements that can be measured by a piezoelectric transducer coupled to the surface. If the transducer is placed close to the point at which the stress pulse is introduced, the surface displacements observed will be predominantly caused by the arrival of P waves. Therefore, if the velocity of the P wave *(C_p)* is known, the depth *(D)* of an internal defect or a boundary can be related to the round-trip travel time *(Δt)* between the introduction of the waves and the reception of the corresponding P-wave echo, i.e.,

$$D = \frac{\Delta t C_p}{2}. \qquad [1]$$

However, in practice, it is often difficult to determine precisely the travel time from the time-domain displacement waveform, $x(t)$, detected by the receiving transducer. This can be circumvented by taking advantage of the periodic nature of or resonance in the reflections arriving at the surface. Each resonance has a characteristic frequency, f, that can be related to the corresponding Δt by the following relationship

$$\Delta t=\frac{1}{f}. \qquad [2]$$

Thus, equation 1 becomes

$$D=\frac{C_p}{2f}. \qquad [3]$$

The frequencies of the various resonances can be determined readily by performing a fast Fourier transform (FFT) analysis of the time-domain displacement waveform.[3]

Application in Thickness Measurement

Equation 3 implies that if the C_p of the concrete at any randomly selected test location in a concrete pavement is known, it is possible to measure indirectly the thickness of the concrete slab (T) at *that* location by measuring the resonance frequency corresponding to the P-wave reflections from the bottom of the slab (f_b), i.e.,

$$T=\frac{C_p}{2f_b}. \qquad [4]$$

This relationship is the basis for the possible use of the IE method for nondestructive measurement of the thickness of the concrete slabs in new pavements.

The accuracy of such thickness measurements would, of course, depend on the accuracy with which f_b at each inspection location could be measured and the accuracy with which C_p at the same location was known. As shall be shown, the former can be optimized to approximately 1% by the proper selection of operational settings on the instrument. The latter is quite uncertain, since C_p is a function of concrete mix proportions, the specific gravities of the mix ingredients, etc. It has been reported that C_p can vary in a wide range—from 3,000 to 4,500 m/s, presumably between concretes of different mixture designs and ingredients.[4]

However, the variability of C_p between different locations along the same pavement construction project was unknown until this study. It is this variability that would determine whether the IE method, by itself, could provide sufficient accuracy for thickness measurements. If C_p varies too much in a pavement, it would be necessary to devise another independent, nondestructive method that could measure C_p so that it could be used in combination with the IE method to provide reasonably accurate thickness measurements. It was, therefore, the primary purpose of this study to shed light on the extent to which C_p can vary in a pavement.

EXPERIMENTAL PROCEDURES

Instrumentation

An integrated IE field system (Figure 2) made by Germann Instruments of Chicago, Illinois, was used in this study. This system consists of a hand-held impactor/receiver unit and a computer-based data acquisition system (DAS).[4]

The top of the impactor/receiver unit has a handle that, when depressed gently, pulls back one of the six spherical steel impactors and then releases it to strike the test object. Each impactor is sized differently (from 4.8 to 12.7 mm in diameter) to create a different impact duration, i.e., contact time with the surface of the test object. The impact durations range from 25 to 75 μs. The selection of an impact duration is made by turning a knob (in the front), which is connected to each spherical steel impactor through a thin steel rod.

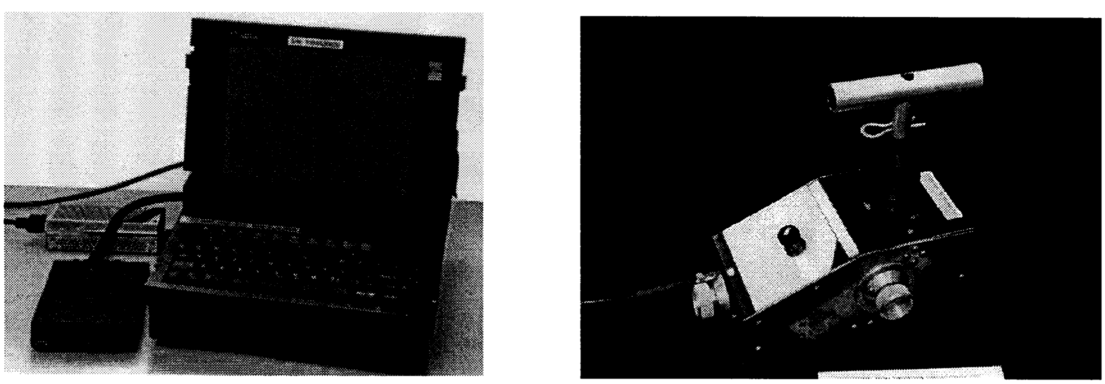

FIGURE 2. Integrated Impact-Echo Field System

The receiver is located 52 mm away from the impactor. It is a conically shaped piezo-electric element that has a resonance frequency of approximately 1 KHz. In contact with this transducer is a thin lead disk that serves as a coupler to the surface of the test object. Each reflection-induced displacement on the surface of a test object creates a pressure on the piezo-electric element, which, in turns, produces a voltage that is proportional to the magnitude of the pressure. This voltage, or electrical signal, is amplified by a battery-powered amplifier housed in the unit before it is fed to the DAS.

The data acquisition is accomplished by a MetraByte DAS-50 circuit board installed on a portable Grid 386 computer. This board automatically samples and digitizes the analog wave-form signals from the transducer for storage and processing, at a sampling rate of 1 mega-sample/s and with a 12-bit resolution. This system uses a custom software that allows automatic FFT and neural-network analyses of the recorded displacement waveforms. The system can be operated by either AC power or, at a project site, DC power from either an automobile cigarette lighter (through an adaptor) or a 12-volt battery.

Methodology

The methodology used in assessing the accuracy obtainable with the IE method consisted of (1) conducting IE measurements to measure the f_b at each of a number of test locations on each of three selected test concrete pavements where cores were extracted for measurement of the thickness of the concrete slab by the present standard procedure (AASHTO T 148); (2) calculating the thickness of the concrete at each test location; and (3) comparing the calculated slab thickness at each location with that obtained by measuring the length of the extracted core.

Measurement of Resonance Frequency

The IE measurement of f_b at each test location was conducted in accordance with the general procedure described in the manual for the system.[4] Initially, operational parameters for the field system, particularly the impact duration and record length of the signal, had to be set appro-priately for the application being investigated. Afterward, each measurement typically required only several seconds from the moment the impact was applied to the moment the time-domain displacement waveform and the spectra were displayed on the computer screen. If the results of a measurement were not satisfactory, the measurement was repeated immediately.

Duration of Impact

In general, it is desirable to use an impact duration *(t_c)* that is approximately equal to the expected round-trip travel time *(t)* of the compressional wave in the concrete pavement slab, i.e.,

$$t_c = t = \frac{2T}{C_p}. \quad [5]$$

Since the nominal thickness of the concrete pavements to be tested in this study was expected to range between 216 and 241 mm (8.50 and 9.50 in) and the C_p was expected to be between 3,500 and 6,000 m/s, the impact time used was between 60 and 75μs.

Length of Record

It was mentioned earlier that one of the two expected sources of errors in thickness measurement by the IE method is the uncertainty in the measurement of the resonance frequency (Δf_b). It is possible to minimize this uncertainty in each test by conducting the test for an adequate duration (or record length). Since Δf_b is inversely dependent on the total duration of a test, which is a product of the number of sample data points collected in a test *(n)* and the duration or sampling interval between consecutive sample points *(r)*, i.e.,

$$\Delta f_b = \frac{1}{nr} \qquad [6]$$

it can be shown from equation 4 that

$$\Delta T = -\left[\frac{2T^2}{C_p}\right]\Delta f_b = -\left[\frac{2T^2}{C_p}\right]\left[\frac{1}{nr}\right] \qquad [7]$$

i.e., this source of error in the thickness measurement can be minimized by increasing the total sample duration. Therefore, a sampling interval of 5 μs and 2,048 data points were used in this study to provide a record length that corresponded to a frequency resolution of ±0.10 KHz, which is the best the IE field unit provides. Thus, the resonance frequency for reflection of P waves from the bottom of the concrete slab, f_b, was read to the nearest 0.10 KHz. An example of the results of an IE measurement is illustrated in Figure 3.

As indicated in equation 7, the magnitudes of the actual thickness of the concrete slab *(T)* and C_p at a test location also have some effects on the error in thickness measurement at that location. For C_p*'s* ranging from 4,000 to 5,500 m/s in concrete slabs with a thickness ranging from 216 to 241 mm (8.50 to 9.50 in), the selected resolution in f_b of 0.10 KHz would result in an error in the thickness measurement that ranged from 1.7 to 2.8 mm (see Figure 4).

Calculation of Concrete Thickness at Each Test Location

After $f_{b,i}$ at a test location *i* was measured, the thickness of the concrete slab (T_i) at that location was calculated using

$$T_i = \frac{[C_p]_i}{2[f_b]_i} \qquad [8]$$

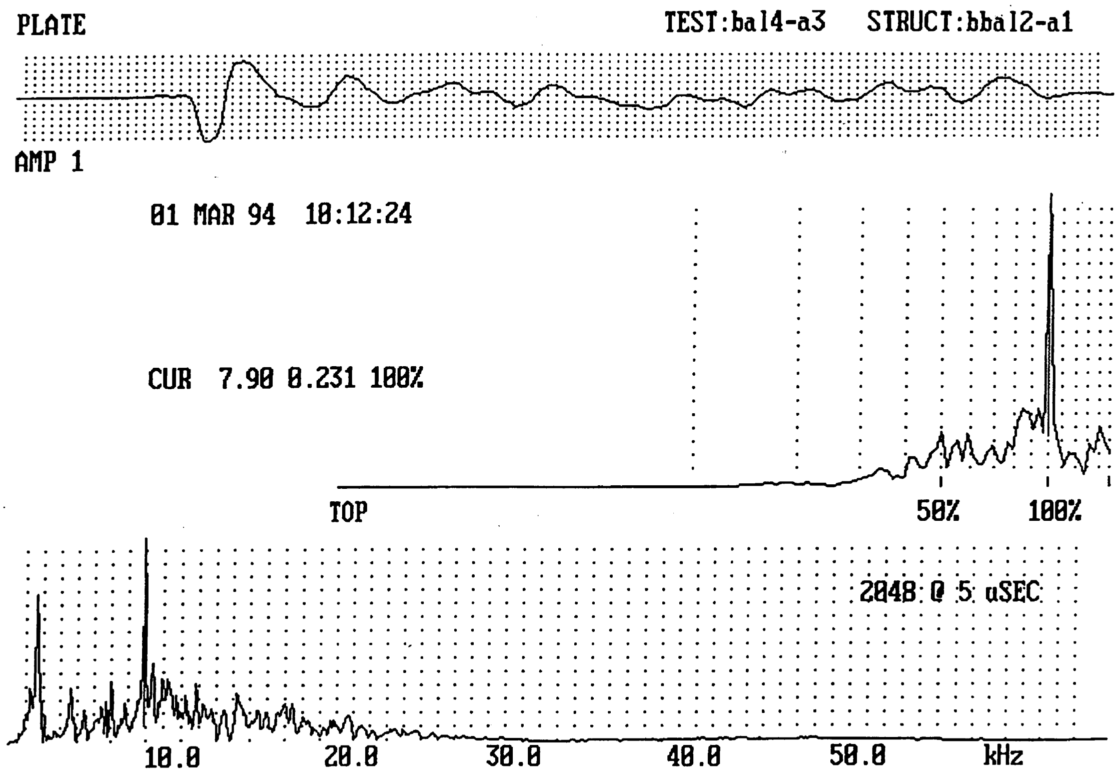

FIGURE 3. Impact-Echo Results Obtained from Test on Concrete Pavement. *Top,* a surface displacement waveform; *middle,* a normalized depth spectrum; *bottom,* an amplitude spectrum resulting from FFT analysis of the displacement waveform. The 7.90-KHz peak in the amplitude spectrum corresponds to the resonance frequency (f_b) of the reflection from the bottom of the slab.

where $[C_p]_i$ is, as will be discussed, assumed to be either the mean C_p of the particular pavement being tested or that measured at each location by an independent method.

Comparison of the Calculated Thickness with Coring

The error (E_i) associated with the estimated thickness (T_i) of the concrete slab at each test location was determined by comparing it with the length of the core (T_{ci}) extracted from the same location, i.e.,

$$E_i = T_i - T_{ci} \qquad [9]$$

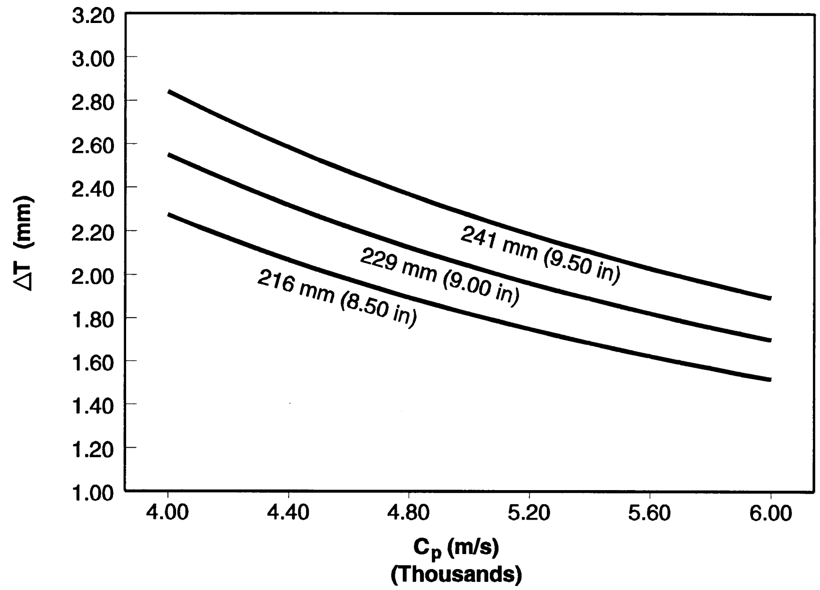

FIGURE 4. Effect of C_p on Thickness Measurement Error for Concrete Slabe of Various Thickness and a Selected Rsolution of 0.10 KHz in the Measurement of f_b

RESULTS AND DISCUSSION

Relationship Between Thickness and Resonance Frequency

To confirm the validity of equation 4 or 8, IE tests were made on two 2.7-m by 11.0-m concrete slabs that were built to simulate concrete pavements on dense-graded aggregates and compacted soil (see Figure 5). As illustrated, each of the slabs had five contiguous 0.91-m sections, each with a different thickness. The thickness increased from 152 mm for the section at one end of a slab to 254 mm for the section at the other end, in 25.4-mm increments. The slabs were constructed with the same concrete ingredients and practically the same mix proportion, except for the water/cement ratio (W/C)—one was 0.45 and the other was 0.54. During their construction, extreme caution was taken so that the concrete and, therefore, the C_p across each slab would be as uniform as possible.

The subsequent IE measurements conducted across each slab confirmed that if C_p is reasonably constant, the resonance frequency is strongly dependent only on thickness as expressed in equation 4 or 8 (see Figure 6). In fact, from the respective slopes of the relationships shown, the C_p for the concrete in each of the two slabs was estimated to be

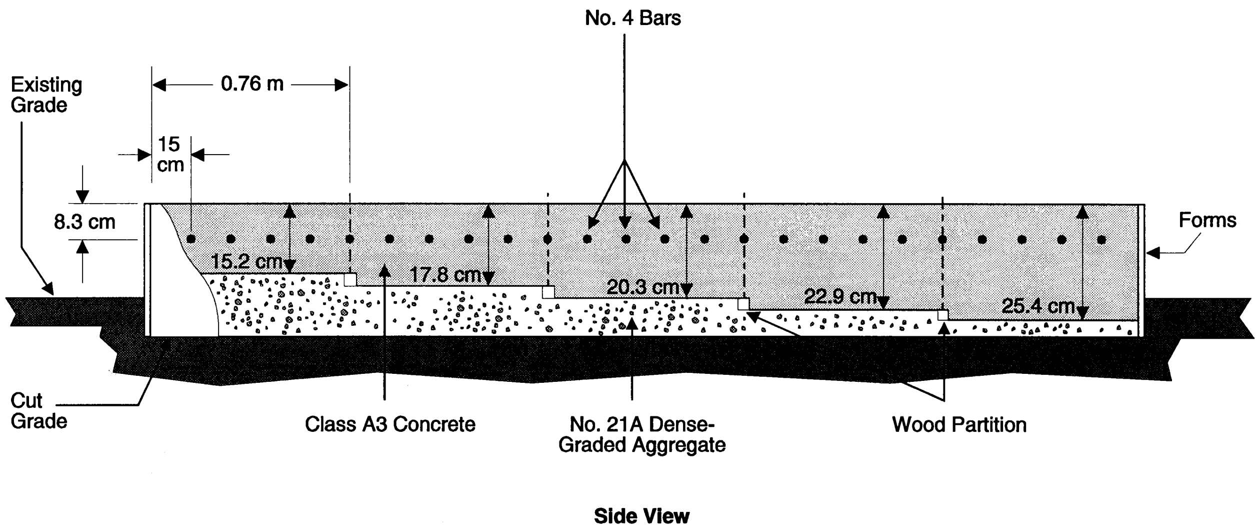

FIGURE 5. Reinforced Concrete Test Slabs Built Over Layer of Dense-Graded Aggregate

3,360 and 2,740 m/s for the concretes with a W/C of 0.45 and 0.54, respectively. This general direct relationship between C_p and the quality of concrete was expected.

Effect of Grooved Concrete Surfaces on Impact-Echo Measurements

Three concrete pavements were used in the investigation (see Table 1). Two pavements were new and had grooves on their surface that were 12 to 18 mm apart and 3 to 5 mm deep to prevent skidding during wet conditions. Since grooving usually results in a rough surface on a concrete pavement, which may prevent adequate contact of the impactor and the transducer (of the hand-held unit) with the pavement, the presence of grooves on the two pavements was a concern before the investigation.

To assess the possible adverse effect of grooves on IE testing, the bottoms of several extracted cores were cut with a saw to provide a smooth surface. Then IE tests were made on each core, on both the grooved top surface and the saw-cut bottom. Comparison of the resulting

TABLE 1. CONCRETE PAVEMENTS USED IN THE INVESTIGATION

	Route 664	Route 64	Route 460
Type of base	Asphalt treated	Cement treated	Asphalt treated
Type of surface	Grooved	None	Grooved
Lane kilometer tested	38	20	22
Number of test locations	53	21	22

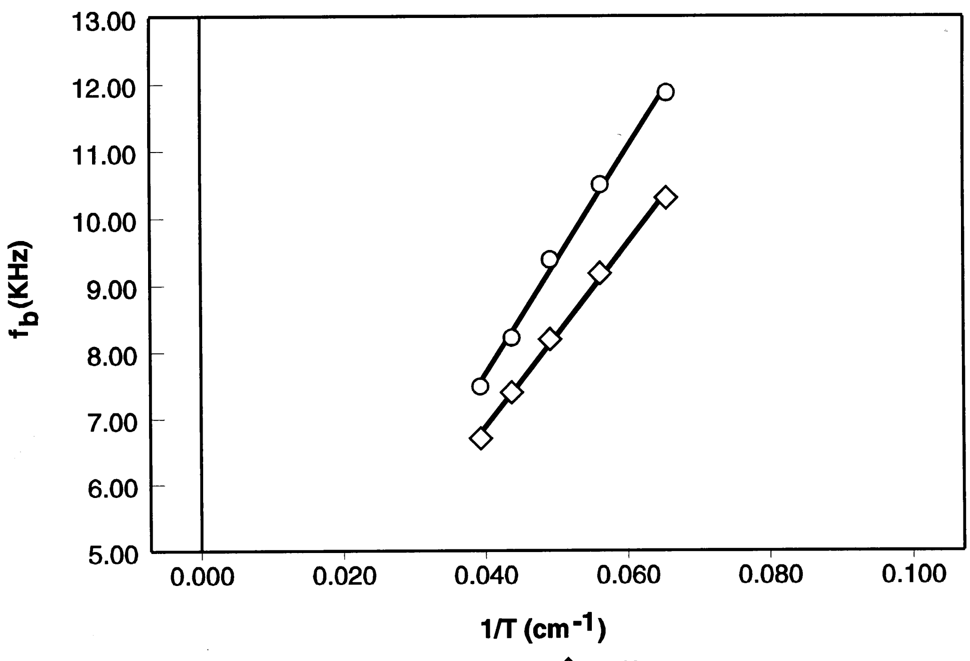

FIGURE 6. Relationship Between f_b and $1/T$ for Two Concrete Test Slabs with Different Water-Cement Ratios

pair of spectra for each core, as exemplified by Figure 7, indicated that the grooves per se did not noticeably affect the IE tests, since the f_b in both spectra were identical. However, the presence of grooves made it necessary to make repeated tries at some locations, by slightly shifting the position of the hand-held unit, before a satisfactory waveform could be obtained. Fortunately, it was not much trouble to make repeated tries, since each one does not require more than several seconds.

Measurement of SlabThickness in Test Pavements

Before the thickness of the concrete slab at any location can be calculated from the measured f_b, using equation 8, it is also necessary to know the C_p at the location. As discussed earlier, it is not possible, unfortunately, to know *a priori* the exact C_p for any location in a pavement, since the composition of a concrete and, therefore, the C_p, may vary even within the same construction project. However, if the variation is very slight, then it is possible to determine the mean C_p for the project and use it throughout all test locations for the project.

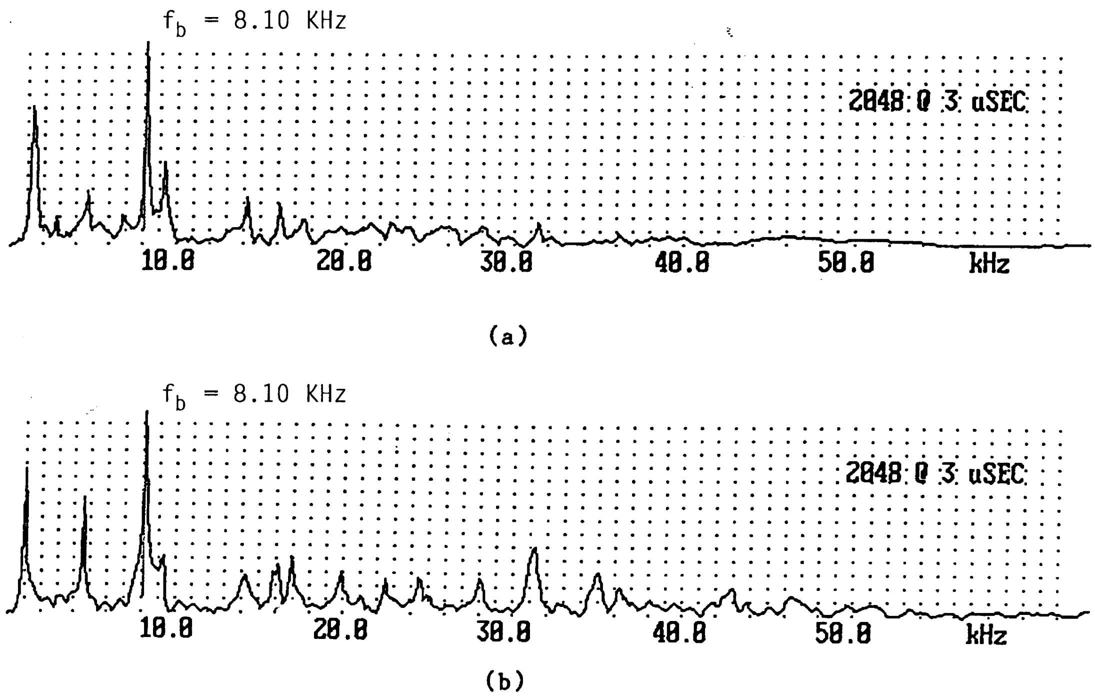

FIGURE 7. Amplitude Spectra from Concrete Core Obtained by Impacting on Its *(a)* Grooved Top and *(b)* Saw-Cut Edge. Notice that f_b in both spectra are identical.

Using a Mean Stress Wave Velocity Throughout a Test Pavement

It is possible to assume that the C_p at any location in a pavement approximates the mean C_p of the pavement and use the latter throughout the pavement without adversely affecting the accuracy of the calculated thickness if the C_p in a pavement has a sufficiently small standard deviation. Probably less than 1% would be needed.

The mean C_p can be easily estimated by taking cores from a relatively limited number of randomly selected "calibration" locations in a pavement. At each calibration location, the resonance frequency is measured, and then the actual thickness of the slab is measured from the extracted core. Afterward, the compressional wave speeds at all n calibration locations and their average are calculated as follows:

$$\overline{C_p} = \frac{\sum C_p}{n} = \frac{\sum 2 T_c f_b}{n} \quad [10]$$

where C_p is the wave velocity in meters per second, T_c is the core length in millimeters, and f_b is the resonance frequency in kilohertz at each location. By substitution in equation 8, the resulting mean C_p can then be used for the entire pavement to estimate the thickness of the concrete slab (T_i) at any other location i:

$$T_i = \frac{[C_p]_i}{2[f_b]_i} = \frac{\overline{C_p}}{2[f_b]_i} . \qquad [11]$$

The first concrete pavement on which this procedure was tested was a section of Route 664, from which the data presented in Table 2 were collected. When the C_p of the concrete at each of the 53 test locations was calculated from the f_b and core length, it was indicated that C_p varied considerably in this pavement, from 4,470 to 5,330 m/s (see Figure 8). This set of 53 samples had a mean of 4,870 m/s and a standard deviation of 210 m/s (or 4.3%).

After this procedure, in an exercise to determine the mean C_p for the pavement as if an actual quality-assurance inspection was being attempted with only limited coring, six calibration locations (i.e., 1 per 10 test locations) were randomly drawn from the total sample population of 53 locations. Averaging the wave velocities determined for this subset yielded a mean C_p of 4,810 m/s, which deviated from the true mean of the sample by only 1.2%. (Four other sets of random draws were made and yielded slightly different means that ranged from 4,720 to 4,970 m/s.)

When the mean C_p of the first set of six calibration locations (4,810 m/s) was used subsequently (as in equation 11) to estimate the thickness of the concrete slab at all 53 test locations, the resulting thickness estimates ranged from 227 to 251 mm, with a mean of 236 mm and a standard deviation of 5 mm (Table 3). In contrast, the true mean thickness (as obtained by measurement of core lengths) was 240 mm, with a standard deviation of 9 mm. Using IE measurements, the slab thicknesses at 21 test locations were overestimated, and those at the other 32 locations were underestimated. The mean absolute error was 8 mm, with 90% of the samples showing errors between 1 and 9 mm (Figure 9). Use of the four other averaged Cp's yielded mean absolute errors ranging from 8 to 10 mm.

Similar measurements were made on a section of the second concrete pavement (Route 64), on which 21 locations were tested (Table 4). As Figure 10 shows, the C_p of this entire sample population varied from 3,540 to 4,100 m/s, with a mean of 3,840 m/s and a standard deviation of 130 m/s (3.3%). Following the same random sampling procedure, the mean C_p for this pavement was estimated to be 3,870 m/s, which deviated from the true mean of 3,840 m/s for the entire sample population by only 0.8%. Using this average C_p on all 21 test locations yielded a mean slab thickness of 209 mm, with a standard deviation of 9 mm; in contrast, the mean core length was 208 mm with a standard deviation of 6 mm. As in the case of the first pavement, the observed absolute errors in the IE results varied between locations, with a mean of 6 mm and 90% of the samples showing absolute errors between 0 and 13 mm (Figure 11).

TABLE 2. IMPACT-ECHO AND CORING DATA COLLECTED FROM CONCRETE PAVEMENT ON ROUTE 664

Test Location	IE Measured f_b (KHz)	Core Length T_c (mm)	Wave Velocity (C_p)(m/s)
1	10.4	249	5178
2	10.3	249	5128
3	10.4	241	5019
4	10.0	241	4826
5	10.0	239	4775
6	10.0	251	5029
7	10.0	236	4724
8	10.0	244	4877
9	10.0	236	4724
10	10.0	236	4724
11	10.0	236	4724
12	10.4	236	4913
13	10.4	234	4861
14	10.4	226	4702
15	10.5	234	4907
16	10.6	246	5223
17	10.6	236	5008
18	10.0	249	4978
19	10.0	244	4877
20	10.0	236	4724
21	10.0	244	4877
22	10.0	239	4775
23	10.0	236	4724
24	10.0	234	4674
25	10.0	241	4826
26	10.0	231	4623
27	10.5	239	5014
28	10.5	236	4961
29	10.5	231	4854
30	10.5	241	5067
31	10.5	234	4907
32	10.5	231	4854
33	10.5	254	5334
34	10.5	234	4907
35	10.6	249	5277
36	10.1	259	5218
37	10.1	239	4823
38	10.1	229	4604
39	10.0	239	4775
40	10.0	257	5131
41	10.0	226	4535
42	10.1	224	4502
43	10.0	259	5197
44	10.0	229	4586

continues

TABLE 2. (CONTINUED)

Test Location	IE Measured f_b (KHz)		Core Length T_c(mm)	Wave Velocity (C_p)(m/s)
45	10.0		224	4484
46	10.2		246	5026
47	10.3		229	4695
48	10.0		224	4470
49	9.60		254	4877
50	10.0		259	5197
51	10.1		236	4757
52	10.1		249	5003
53	10.0		241	4826
		Mean	240	4870
		SD	9	210
		Minimum	224	4470
		Maximum	259	5330

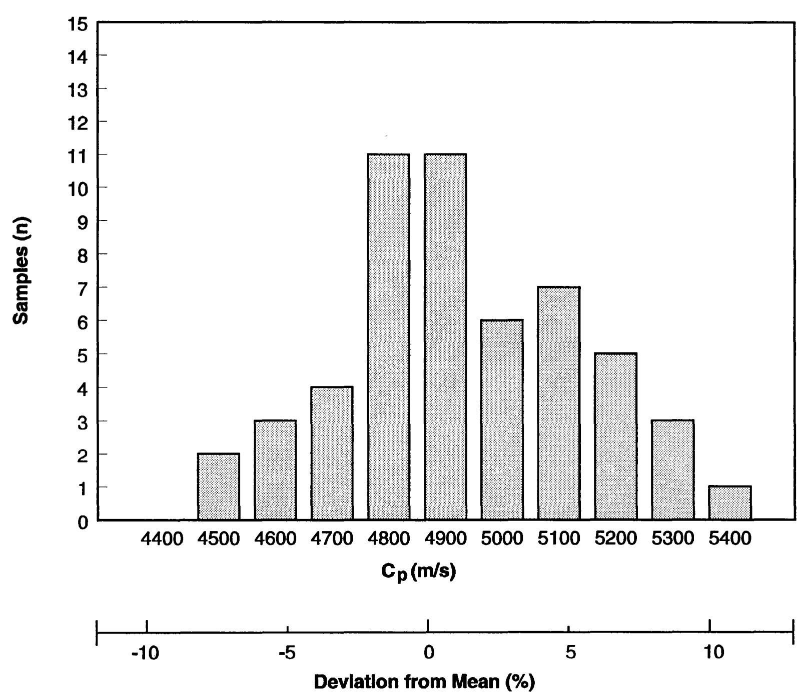

FIGURE 8. Compressional Wave Velocity in Concrete Pavement on Route 664

TABLE 3. ERRORS IN MEASUREMENT OF SLAB THICKNESS ON ROUTE 664 USING A RANDOMLY DETERMINED MEAN C_P

Test Location	IE Measured f_b (KHz)	Assumed Mean C_p (m/s)	Calculated Thickness (T_i) (mm)	Core Length (T_c) (mm)	Absolute Error (mm)
1	10.4	4810	231	249	18
2	10.3	4810	233	249	15
3	10.4	4810	231	241	10
4	10.0	4810	241	241	1
5	10.0	4810	241	239	2
6	10.0	4810	241	251	11
7	10.0	4810	241	236	4
8	10.0	4810	241	244	3
9	10.0	4810	241	236	4
10	10.0	4810	241	236	4
11	10.0	4810	241	236	4
12	10.4	4810	231	236	5
13	10.4	4810	231	234	2
14	10.4	4810	231	226	5
15	10.5	4810	229	234	5
16	10.6	4810	227	246	19
17	10.6	4810	227	236	9
18	10.0	4810	241	249	8
19	10.0	4810	241	244	3
20	10.0	4810	241	236	4
21	10.0	4810	241	244	3
22	10.0	4810	241	239	2
23	10.0	4810	241	236	4
24	10.0	4810	241	234	7
25	10.0	4810	241	241	1
26	10.0	4810	241	231	9
27	10.5	4810	229	239	10
28	10.5	4810	229	236	7
29	10.5	4810	229	231	2
30	10.5	4810	229	241	12
31	10.5	4810	229	234	5
32	10.5	4810	229	231	2
33	10.5	4810	229	254	25
34	10.5	4810	229	234	5
35	10.6	4810	227	249	22
36	10.1	4810	239	259	20
37	10.1	4810	238	239	1
38	10.1	4810	239	229	10
39	10.0	4810	241	239	2
40	10.0	4810	241	257	16
41	10.0	4810	240	226	14
42	10.1	4810	239	224	15

continues

TABLE 3. (CONTINUED)

Test Location	IE Measured f_b (KHz)	Assumed Mean C_p (m/s)	Calculated Thickness (T_i) (mm)	Core Length (T_c) (mm)	Absolute Error (mm)
43	10.0	4810	240	259	19
44	10.0	4810	240	229	11
45	10.0	4810	240	224	16
46	10.2	4810	236	246	11
47	10.3	4810	234	229	6
48	10.0	4810	241	224	17
49	9.60	4810	251	254	3
50	10.0	4810	240	259	19
51	10.1	4810	239	236	3
52	10.1	4810	239	249	10
53	10.0	4810	241	241	1
		Mean	236	240	8
		SD	5	9	6
		Minimum	227	224	1
		Maximum	251	259	25

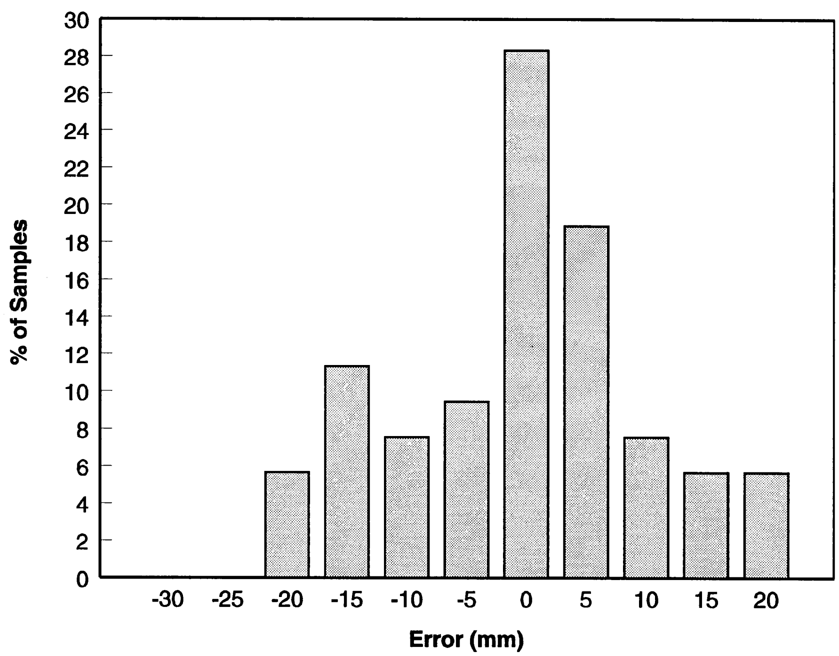

FIGURE 9. Errors in Thickness Measurements Made by Impact-Echo Method on Route 664

TABLE 4. ERRORS IN MEASUREMENT OF SLAB THICKNESS ON ROUTE 64 BY IMPACT-ECHO METHOD

Test Location	IE Measured f_b (KHz)	Core Length (T_c) (mm)	Calculated C_p (m/s)	Assumed Mean C_p (m/s)	Calculated Thickness (T_i) (mm)	Absolute Error (mm)
64-01	9.60	207	3974	3870	202	5
64-02	8.60	217	3732	3870	225	8
64-03	9.40	218	4098	3870	206	12
64-04	9.50	206	3914	3870	204	2
64-05	9.20	207	3809	3870	210	3
64-06	9.00	215	3870	3870	215	0
64-07	8.90	211	3756	3870	217	6
64-08	9.40	203	3816	3870	206	3
64-09	8.40	211	3545	3870	230	19
64-10	9.40	203	3816	3870	206	3
64-11	9.50	194	3686	3870	204	10
64-12	8.70	210	3654	3870	222	12
64-13	9.20	211	3882	3870	210	1
64-14	10.10	198	4000	3870	192	6
64-15	9.30	206	3832	3870	208	2
64-16	9.40	209	3929	3870	206	3
64-17	9.40	204	3835	3870	206	2
64-18	9.60	200	3840	3870	202	2
64-19	9.10	204	3713	3870	213	9
64-20	9.10	217	3949	3870	213	4
64-21	9.60	207	3974	3870	202	5
	Average	208	3839		209	6
	SD	6	127		9	5
	Minimum	194	3545		192	0
	Maximum	218	4098		230	19

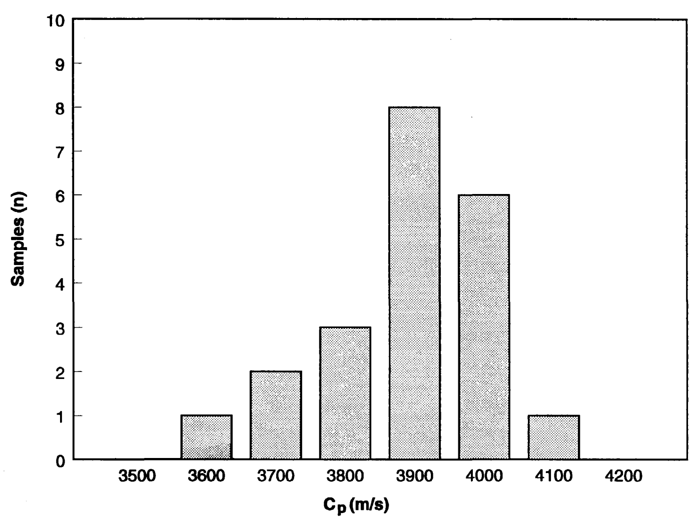

FIGURE 10. Compressional Wave Velocity in Concrete Pavement on Route 64

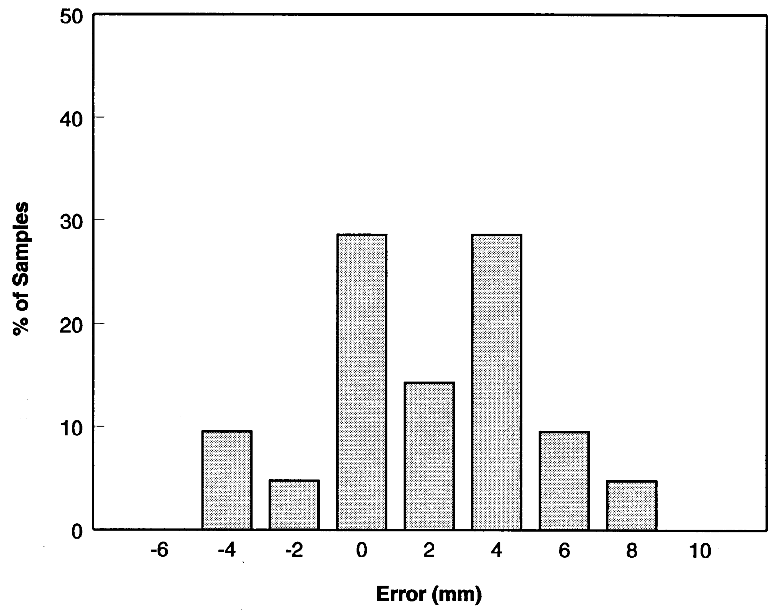

FIGURE 11. Errors in Thickness Measurements Made by Impact-Echo Method on Route 64

A similar exercise was conducted with the data collected from the third concrete pavement (Route 460). This resulted in absolute errors in thickness estimates that ranged from 1 to 23 mm for 90% of the samples, with a mean of 11 mm (Table 5). Again, the distribution of C_p in this pavement, as in the other two, was considerably wide, with a standard deviation of 220 m/s (5.2%), around a mean of 4,300 m/s (Figure 12). As was observed with the other pavements, the resulting absolute errors in thickness measurements with IE, when a mean C_p was assumed for the entire pavement, were distributed in the same manner as the observed wave speeds (Figure 13).

Table 6 summarizes the results of the thickness measurements made on the three test pavements. In general, these results indicated that C_p in each pavement varied considerably so that when the true C_p at each single inspection location was substituted by a mean C_p (that approximated the true mean of the pavement), the resulting slab thickness calculated from the measured f_b would be in error. As also indicated, the extent of error varied between pavements tested—the larger the distribution of C_p in a pavement, the larger the observed distribution of errors.

As discussed earlier, the error in each IE measurement is the result of a combination of two possible sources of errors: the measurement of f_b and the C_p assumed for each test location. The first source of error (Δf_b) was minimized, as described earlier, by using the longest record length available in the field unit to record each IE measurement. This record length provided a resolution of $\pm$10 KHz in the measurement of f_b, which, according to equation 7, would translate into a maximum error in thickness measurements of approximately $\pm$3 mm, based on the worst combination of T and C_p observed for each of the pavements.

TABLE 5. ERRORS IN MEASUREMENT OF SLAB THICKNESS ON ROUTE 460 BY THE IMPACT-ECHO METHOD

Test Location	IE Measured f_b (KHz)	Core Length (T_c) (mm)	Calculated C_p (m/s)	Assumed C_p (m/s)	Calculated Thickness (T_i) (mm)	Absolute Error (mm)
1	8.50	248	4216	4255	250	2
2	8.80	254	4470	4255	242	12
3	9.10	248	4514	4255	234	14
4	9.40	241	4531	4255	226	14
5	9.20	241	4434	4255	231	10
6	9.40	229	4305	4255	226	3
7	9.40	225	4230	4255	226	1
8	8.40	248	4166	4255	253	5
9	8.00	235	3760	4255	266	31
10	8.40	238	3998	4255	253	15
11	9.30	248	4613	4255	229	19
12	8.10	260	4212	4255	263	3
13	8.20	235	3854	4255	259	24
14	8.30	254	4216	4255	256	2
15	8.80	235	4136	4255	242	7
16	9.60	233	4474	4255	222	11
17	9.20	236	4342	4255	231	5
18	9.20	249	4582	4255	231	18
19	9.50	237	4503	4255	224	13
20	9.00	250	4500	4255	236	14
21	8.80	245	4312	4255	242	3
22	9.10	238	4332	4255	234	4
	Mean	242	4305		240	11
	SD	9	223		13	8
	Minimum	225	3760		222	1
	Maximum	260	4613		266	31

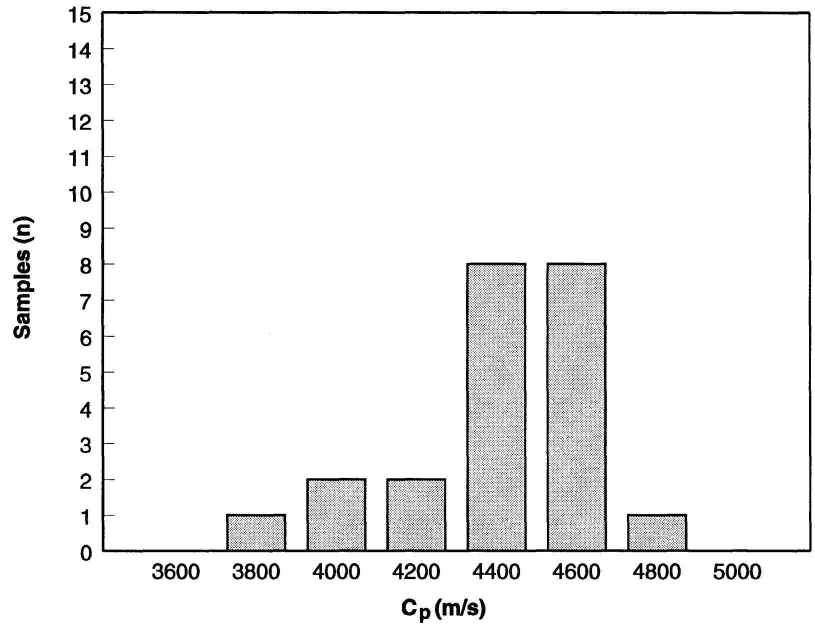

FIGURE 12. Compressional Wave Velocity in Concrete Pavement on Route 460

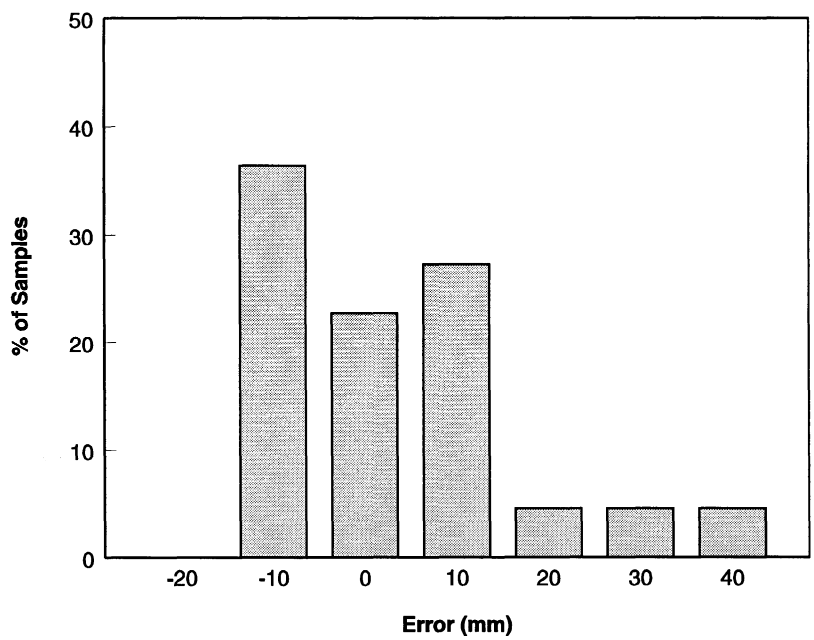

FIGURE 13. Errors in Thickness Measurements Made by Impact-Echo Method on Route 460

TABLE 6. OBSERVED WAVE SPEED AND ERRORS IN THICKNESS MEASUREMENTS

	Route 664		Route 64		Route 460	
	Coring	IE	Coring	IE	Coring	IE
C_p (m/s)						
True	4870		3840		4300	
Mean	210		130		220	
SD	(4.3%)		(3.3%)		(5.2%)	
Assumed for pavement (estimated with limited random coring)	4810		3870		4250	
Slab Thickness (mm)						
Mean	240	236	208	209	242	240
SD	9	5	6	9	9	13
Absolute Error (mm) (compared with coring)						
Mean		8		6		11
SD		6		5		8
Minimum		1		0		1
Maximum		25		19		31

The second source of error, ΔC_p, is directly dependent on the extent to which the compressional wave velocity used in the calculation, $[C_p]_a$, deviates from the true value, $[C_p]_t$, at any test location, i.e.,

$$\Delta C_p = [C_p]_a - [C_p]_t \quad [12]$$

and if a single wave velocity approximating the true mean wave velocity of the pavement is assumed for an entire pavement, as in the approach tested here, then this error would vary between test locations and the resulting errors would assume a distribution similar to that of the C_p in the pavement, as shown earlier. As analysis of the data from Route 664 shows in Figure 14, the combined error was as high as 25 mm in some test locations, indicating that the contribution from error in C_p was considerably larger than the expected contribution from error in f_b measurement.

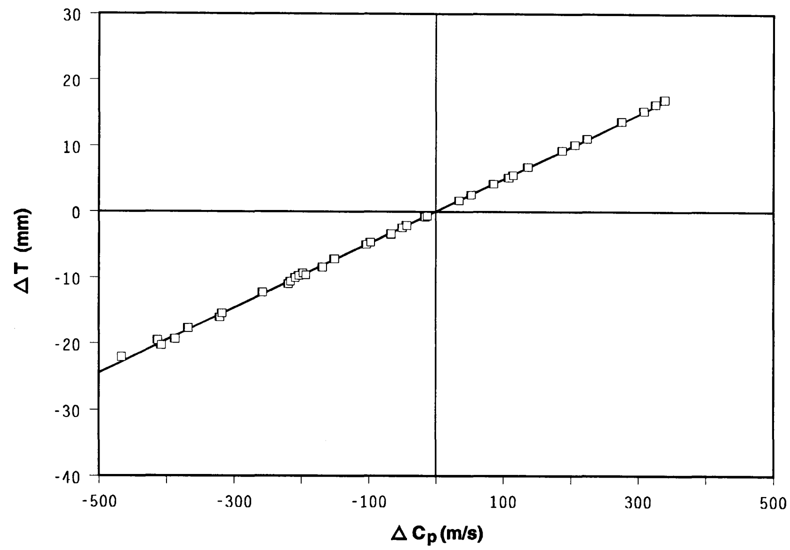

FIGURE 14. Influence of Error in Resonance Frequency *(C_p)* on Error in Thickness Measurements on Route 664

Clearly, if better accuracy—one that is independent of the pavement being tested—is desired, it is necessary to find an appropriate independent nondestructive procedure that would allow the C_p at each test or inspection location to be measured with sufficient accuracy.

Measuring the Stress Wave Velocity at Each Test Location in a Pavement

Figure 14 also provides an indication of the degree of accuracy with which C_p must be measured at any individual test location in order to obtain a given degree of desired accuracy in the thickness measurement. If the desired accuracy is to be within ±5 mm, a procedure must be able to measure C_p to within approximately ±100 m/s, or ±2%, since the slope of the relationship in Figure 14 is 0.050 mm-s/m.

As an initial attempt to search for such a procedure, the indirect transmission, or surface, method of ultrasonic measurements of C_p was considered. As illustrated in Figure 15a, this method is relatively simple and, similar to the IE method, satisfies the constraint that any interrogating probes or transducers used by a method have access to only one side, which is the surface, of any pavement. Equally important, the equipment necessary to conduct the method, a V meter and the transducers, is conveniently available.

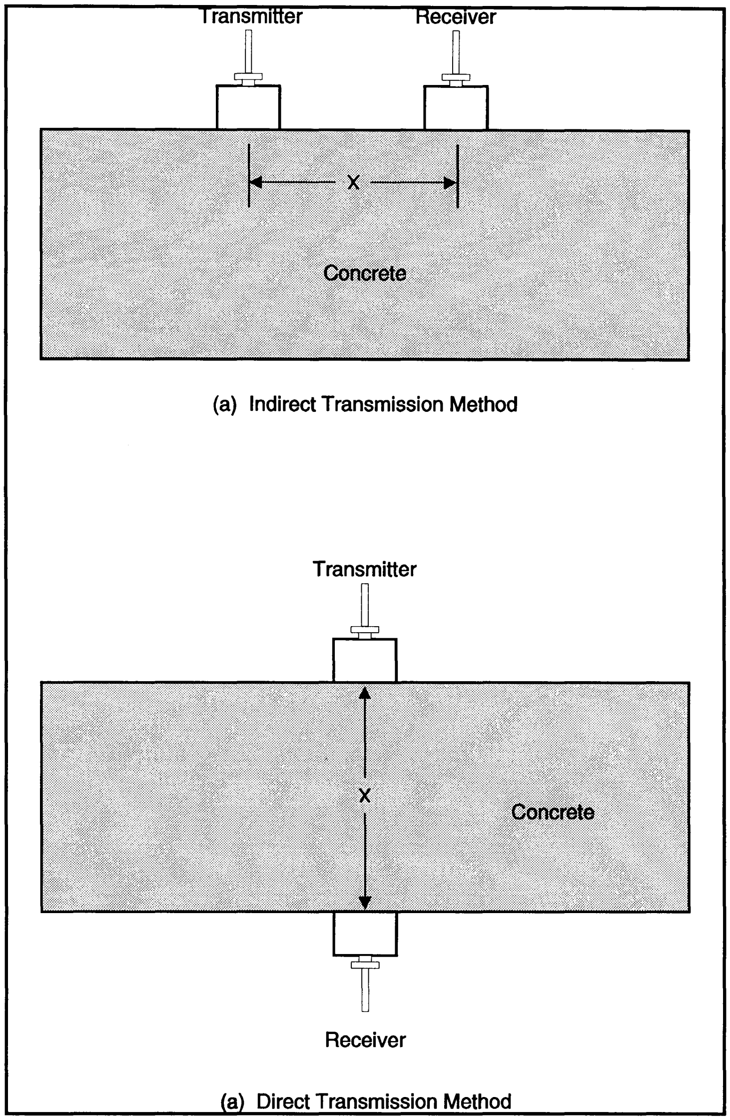

FIGURE 15. Measurement of Ultrasonic Pulse Velocity

Before this method was tested on any of the test pavements, measurements were conducted on test concrete blocks to ascertain that the method was effective and to identify the appropriate spacing between the transducers so that reasonably accurate measurements of the C_p of a concrete slab could be obtained. In these measurements, the transit time of 54-KHz ultrasonic waves between the transmitting and receiving transducers, which were coupled to the (top) surface of a concrete block at a spacing at 10.2 cm, was measured (Figure 15a). The measurement was repeated every time after the receiver was moved away in 2.54-cm increments. For each transducer spacing used, a wave velocity was calculated by using the simple relationship:

$$V=10^4\frac{x}{t} \qquad [13]$$

where V = wave velocity in meters per second; x = spacing between the transducers in centimeters; and t = transit time between the transducers in microseconds.

The actual ultrasonic pulse velocity or C_p of each test concrete block was determined by employing the direct-transmission method, wherein the transducers were coupled to opposite sides of the block (Figure 15b) in all three directions. (Whenever two opposite sides of a test object are accessible, as in the case with these test blocks, this mode of transmission is actually the most preferable since it provides maximum transmission of stress waves and, thereby, the most reliable measure of its velocities.)

Table 7 shows the transit times in two of the concrete blocks tested, which had different W/C's: 0.43 and 0.53. Through direct transmission, the C_p was determined to be 4,244 and 3,834 m/s for the 0.43 and 0.53 W/C concretes, respectively. As Table 7 also shows, when the indirect-transmission mode was employed, it was determined that the transducers must be between 22.9 and 27.9 cm apart in order for the measured stress wave velocities (4,257 to 4,292 m/s) for the 0.43-W/C concrete to approach, to within 1%, the C_p of 4,244 m/s that was measured by the direct-transmission mode (Figure 16). Similarly, for the 0.53-W/C concrete block, the transducers must be between 20.3 and 27.9 cm apart before the resulting velocities (3,755 to 3,815 m/s) would approach, to within 2%, the C_p of 3,834 m/s measured by the direct-transmission mode. The results for a third concrete block indicated that a transducer spacing of 20.3 to 30.5 cm was required.

The reason the indirect method yielded a velocity that appeared to be practically equivalent to the compressional wave velocity measured by the direct-transmission method lies in the probably very small difference between the propagation velocities of elastic waves in two- and three-dimensional concrete objects.[4] The propagation velocity (V_{p2}) of compressional elastic waves in a two-dimensional (plate-like) solid is given by the relationship[5]

$$V_{p2}=\sqrt{\frac{E}{\rho(1-\nu^2)}}=C_o[1-\nu^2]^{-\frac{1}{2}} \qquad [14]$$

where E is the dynamic modulus of elasticity, ρ is the density, and ν is the Poisson ratio, whereas in a three-dimensional solid, the propagation velocity (V_{p3}) is given by the relationship

TABLE 7. ULTRASONIC MEASUREMENTS ON TWO CONCRETE BLOCKS WITH DIFFERENT WATER-CEMENT RATIOS

	0.43 W/C		0.53 W/C	
	t (μs)	*S* (m/s)	*t* (μ/s)	*S*(m/s)
Direct Transmission Method—Transmission Direction				
Y (20.3 cm)	48.1	4225	52.4	3878
X (38.1 cm)	90.4	4215	99.4	3833
Z (30.5 cm)	71.0	4293	80.4	3791
Average		4244		3834
Indirect Transmission Method—Dist. Bt. Transducers (cm)				
10.2	21.3	4770	22.7	4476
12.7	27.2	4669	30.6	4150
15.2	33.7	4522	38.6	3948
17.8	40.2	4423	46.6	3815
20.3	46.6	4361	54.0	3763
22.9	53.7	4257	60.4	3785
25.4	58.6	4334	67.2	3780
27.9	65.3	4279	74.4	3755
30.5	73.3	4158	83.2	3663

$$V_{p3}=\sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}=C_o\left[\frac{(1-\nu)}{(1+\nu)(1-2\nu)}\right]^{\frac{1}{2}} \qquad [15]$$

For a Poisson ratio of 0.2, which is a typical value in concrete, V_{p3} would be only 3% higher than V_{p2}. This difference was probably too small to be discerned by the V meter used and, therefore, would account for the small differences between the velocities obtained with the two methods (Table 7).

In accordance with these findings, this surface, or indirect-transmission, method was employed to measure C_p at the test locations on Routes 64 and 460, supplementing the IE method. In conducting the velocity measurements at each test location, the two transducers were first spaced 22.9 cm apart, then the receiver was moved (along a line) away from the transmitter by 5.0 cm. The average of the resulting two measured velocities was then used as the C_p for that test location, in conjunction with the f_b measured by the IE method to calculate the thickness of the concrete.

Table 8 shows a comparison of the thickness measurements, at each test location on Route 64, made with this combined IE/ultrasonic procedure and coring. Compared to using IE alone

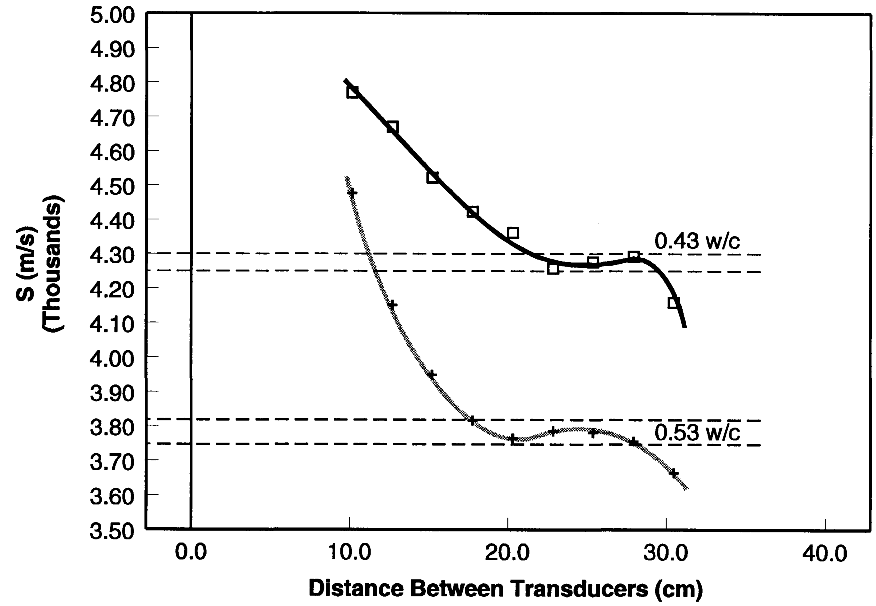

FIGURE 16. Wave Velocity in Concrete Blocks with Different Water-Cement Ratios as a Function of Distance Between Transducers

(Table 4), the use of this combined procedure provided a noticeable improvement in the accuracy of the thickness measurements by reducing the mean absolute error from 6 to 3 mm, with 90% between 0 and 5 mm. This improvement resulted, of course, from the reasonably reliable measurement of C_p made possible by the indirect-transmission ultrasonic procedure. As the data show, the errors associated with the measured C_p were estimated to range from 5 to 117 m/s, with 90% less than 100 m/s.

When the ultrasonic procedure was used on the test locations on Route 460, the C_p's measured were slightly less accurate, as indicated by errors that ranged from 5 to 180 m/s, with 86% of the measurements showing errors of less than 100 m/s (Table 9). The slightly larger errors in C_p observed at several test locations in this pavement were attributed to the presence of surface grooves and the relatively large contact face (50-mm diameter) of the ultrasonic transducers, which combined to cause difficulty in establishing good contact between the transducers and the pavement.

These slightly larger errors in C_p similarly affected the overall accuracy of the calculated slab thicknesses, with a mean absolute error of 3 mm and 90% of the samples ranging from 0 to 7 mm. Interestingly enough, there was no discernible adverse effect on the mean absolute error when compared with the results for Route 64.

TABLE 8. ERRORS IN MEASUREMENT OF SLAB THICKNESS ON ROUTE 64 BY COMBINED IMPACT-ECHO AND ULTRASONIC PROCEDURE

Test Location	UT Measured C_p (m/s)	IE Measured f_b (KHz)	Calculated Thickness (T_i) (mm)	Core Length (T_c) (mm)	Absolute Error T (mm)	Absolute Error C_p (m/s)
64-01	3969	9.60	207	207	0	6
64-02	3775	8.60	219	217	2	43
64-03	4145	9.40	220	218	2	46
64-04	3899	9.50	205	206	1	15
64-05	3775	9.20	205	207	2	34
64-06	3899	9.00	217	215	2	29
64-07	3840	8.90	216	211	5	84
64-08	3934	9.40	209	203	6	117
64-09	3514	8.40	209	211	2	31
64-10	3759	9.40	200	203	3	57
64-11	3681	9.50	194	194	0	5
64-12	3681	8.70	212	210	2	27
64-13	3951	9.20	215	211	4	69
64-14	3987	10.10	197	198	1	13
64-15	3751	9.30	202	206	4	81
64-16	4005	9.40	213	209	4	75
64-17	3759	9.40	200	204	4	76
64-18	3916	9.60	204	200	4	76
64-19	3767	9.10	207	204	3	54
64-20	3996	9.10	220	217	3	46
64-21	4005	9.60	209	207	2	30
		Mean	209	208	3	48
		SD	7	6	2	29
		Minimum	194	194	0	5
		Maximum	220	218	6	117

Overall, the accuracy obtained when using the combined IE/ultrasonic procedure in measuring the thickness of the concrete slab in the two pavements tested represents a considerable improvement over using IE alone and assuming a common C_p for the entirety of each pavement. It can be argued that the accuracy is adequate enough for the procedure to replace coring, when proper consideration is given to the extent with which the length of any core extracted from a pavement can fluctuate at different points around its circumference and that the average of nine separate measurements around a core is reported to the nearest 2.5 mm.

To prove this point, Table 10 presents the results of measurements of core length made on three cores extracted from a pavement with an asphalt-treated base. These data illustrate that the length of a core actually varies along different points around its circumference. The difference between the highest and lowest readings was 4 mm in two of the cores and 13 mm in the third core. With cores extracted from pavements with cement-treated bases, the difficulty in clearly separating the slab from the base adds the additional uncertainty in the core length measurement

TABLE 9. ERRORS IN MEASUREMENT OF SLAB THICKNESS ON ROUTE 460 BY COMBINED IMPACT-ECHO AND ULTRASONIC PROCEDURE

Test Location	UT Measured C_p (m/s)	IE Measured f_b (KHz)	Calculated Thickness (T_i) (mm)	Core Length (T_c) (mm)	Absolute Error T (mm)	Absolute Error C_p (m/s)
1	323	8.50	249	248	1	17
2	435	8.80	252	254	2	35
3	522	.10	248	248	0	8
4	436	9.40	241	241	0	5
5	456	9.20	242	241	1	22
6	281	9.40	228	229	1	24
7	4305	.40	229	225	4	75
8	4198	8.40	250	248	2	32
9	3735	8.00	233	235	2	25
10	3979	8.40	237	238	1	19
11	4704	9.30	253	248	5	91
12	4153	8.10	256	260	4	59
13	3868	8.20	236	235	1	14
14	4158	8.30	250	254	4	58
15	4172	8.80	237	235	2	36
16	4294	9.60	224	233	9	180
17	4424	9.20	240	236	4	82
18	4594	9.20	250	249	1	12
19	4606	9.50	242	237	5	103
20	4379	9.00	243	250	7	121
21	4358	8.80	248	245	3	46
22	4390	9.10	241	238	3	58
		Mean	242	242	3	51
		SD	9	9	2	42
		Minimum	224	225	0	5
		Maximum	256	260	9	180

by the present procedure. When this natural fluctuation in the length of any core is considered, the use of the combined IE/ultrasonic method must be viewed favorably.

Even though the combined use of an independent nondestructive testing method with the IE method to achieve improved accuracy in thickness measurements was tested with only two pavements, the tests nevertheless illustrated that the approach is effective, albeit slightly missing the target accuracy of 3 mm.

TABLE 10. FLUCTUATION OF CORE LENGTH (MM) AT DIFFERENT POINTS AROUND THE CIRCUMFERENCE OF A CORE

	Core		
Point	**1**	**2**	**3**
1	207	208	200
2	211	210	198
3	210	209	205
4	208	208	207
5	211	208	211
6	211	211	207
7	208	207	204
8	209	208	198
Minimum	207	207	198
Maximum	211	211	211
Range	4	4	13
SD	1.5	1.2	4.4
Mean	209	209	204

SUMMARY AND CONCLUSIONS

The IE method offers a simple means for introducing compressional stress waves into a concrete element or slab and measuring the resonance frequencies associated with the reflections of these waves from any internal voids and the bottom of the slab. It is relatively effective for detecting internal voids or delaminations in concrete, which is its original intended application. Even though the method does not measure the propagation velocity of the stress waves in the concrete being tested, this limitation is not serious when it comes to estimating the depth of a detected internal defect, since the assumption of a reasonable velocity would suffice.

However, if its application in nondestructive measurements of the thickness of concrete slabs in new pavements with an accuracy sufficient to replace the present coring procedure is sought, the limitation becomes an obstacle. As revealed by testing of three concrete pavements, the propagation velocity varies between pavements, and even between different test locations within the same pavement, so considerably that it is not possible to assume a velocity for an entire pavement and obtain an acceptable accuracy in the thickness measurements. It is not even possible to supplement the IE method with limited coring at randomly selected locations to determine the mean wave velocity of the pavement being tested and apply this velocity throughout the entire pavement to calculate the slab thickness at all intended inspection locations.

The IE method alone cannot measure thickness with acceptable accuracy. It is necessary to supplement it with an independent method or procedure that can measure wave velocity at each inspection location with sufficient accuracy. In search of such a method, a simple indirect-transmission ultrasonic method was employed and tested, and it appeared close to fulfilling this need. In combination, the IE/UT procedure was able to measure thickness with an absolute error of 5 mm in one pavement and 7 mm in another at a 90% probability, which is slightly larger than the goal of 3 mm.

RECOMMENDATIONS

Since the combined IE/UT procedure missed the desired accuracy of 3 mm only slightly, and it is believed that elimination of the coupling problem between the UT transducers used and the grooved pavement surface that was experienced in some of the test locations can aid significantly in achieving this goal, it is recommended that a preliminary implementation of this combined procedure be pursued on selected new pavements. In such pursuit, a new transducer that has a contact face smaller than the 54-KHz transducers used in this investigation should be sought and used to eliminate the transducer coupling problem. Such a transducer was made available commercially just recently by the manufacturer of the IE field system in response to revelations made by the early data from this investigation.

FUTURE RESEARCH

This author believes that the issue of quality-assurance testing of new pavements needs to be viewed from a broader perspective. As mentioned earlier and reflected in the design equation that is frequently used for predicting the number of equivalent single axle load (ESAL) applications for a rigid pavement, both the quality and thickness of the concrete slab over an entire pavement have a strong influence on the long-term performance of a pavement. It is clear that a section of pavement with a thicker concrete slab would not necessarily last longer than a thinner section if the latter was made of better quality concrete. As the testing of some pavements here showed, the quality of the hardened concrete, as measured by C_p, varies considerably from location to location in a pavement. It is, therefore, just as important to test the quality of the in-place hardened concrete throughout a new pavement if it can be done inexpensively and nondestructively as it is to measure its thickness.

At present, there is really no good method, especially a nondestructive one, for measuring the quality of an in-place concrete, not to mention a method for measuring quality and thickness at the same time. It is not difficult to predict that the IE method can be just such a method when one rearranges Equation 4 as follows:

$$f_b = \frac{C_p}{2T} = \frac{\Omega}{2} \qquad [16]$$

This shows that f_b, which is easily measured by the IE method, can be used as a measure of the combined effect, Ω, of concrete quality and thickness on the future performance of a new pavement. There is an inseparableness of C_p and T, which need not be viewed as a limitation in the application of the IE method for specifically measuring T, or vice versa, but should be viewed as an advantage that allows measurement of a factor (Ω) that relates to both.

To apply this to any specific new pavement project, it would be necessary first to establish the ranges of acceptable C_p that can be expected from the concrete materials that will be used in the project and the design moduli of elasticity and rupture and then to combine this with a range of acceptable thicknesses, which can be determined in accordance with the design moduli of elasticity and rupture, to derive a range of acceptable f_b that the contractor must meet in the construction.

Since the benefit of being able to test nondestructively and inexpensively for both quality and thickness of hardened concrete in newly built pavements is immeasurable, it is recommended that this potential broader application of the IE method be considered for future research.

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