between the thickness obtained nondestructively and the measured core length. The errors ranged between $\pm$ 3 mm. And the last column shows the reported thickness, based on the impact-echo measurement. The reported thickness is the measured thickness (by impact-echo) plus the total system error. Notice that in all cases the actual error is less than the total systematic error of $\pm$ 8 or 9 mm.

Table 4 shows a similar set of results obtained from the 0.3-m thick pavement sections. The actual and systematic errors are larger than those reported in Table 3 for the 0.2-m thick pavements. As pavement thickness increases, the thickness frequency decreases, and the error in measuring thickness increases (given that all other parameters remain the same). Again, the actual errors obtained are less than the total systematic error of $\pm$14 mm in each case.

CONCLUSIONS

This paper presents a procedure for determining pavement thickness using a direct P-wave speed measurement and the impact-echo method. Systematic errors associated with the data-acquisition and testing procedure are summarized. Results of a laboratory test and preliminary field trials are given to demonstrate the use of and the accuracy of the method. These results show that the observed errors in thickness are less than the computed total systematic error, as expected.

Additional field studies on highway pavements are planned. These field studies will be carried out using new PC-based data-acquisition hardware and software that will allow for faster sampling rates and thus improve the accuracy by reducing the maximum systematic error in the wave speed measurement. The results of these studies will establish the basis for a draft ASTM Standard for pavement thickness measurement.

ACKNOWLEDGMENTS

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TABLE 1 — SYSTEMATIC ERROR DUE TO DIGITAL SAMPLING IN P-WAVE SPEED MEASUREMENTS

	Deviation δt (μs)	P-wave speed $C_{p,plate}$ (m/s)	Time difference Δt (μs)	Maximum Error (%)
a	1	3400	88	1.1
b	1	3600	83	1.2
c	1	3800	79	1.3
d	1	4000	75	1.4
e	1	4200	71	1.4
f	2*	3400	88	2.3
g	2*	3600	83	2.5
h	2*	3800	79	2.6
i	2*	4000	75	2.7
j	2*	4200	71	2.9

Note: Receiver spacing 0.3 m in all cases.

TABLE 2 — ERROR IN THICKNESS MEASUREMENTS DUE TO SPECTRAL RESOLUTION AND TOTAL SYSTEMATIC ERROR

	Error in Wave Speed (%) +	Thickness Frequency (kHz) *	Frequency Error (%) ++	Total Error (%)**
a	1.1	6	2.1	2.4
a	1.1	10	1.2	1.6
b	1.2	6	2.1	2.4
b	1.2	10	1.2	1.7
c	1.3	6	2.1	2.5
c	1.3	10	1.2	1.8
d	1.4	6	2.1	2.5
d	1.4	10	1.2	1.8
e	1.4	6	2.1	2.5
e	1.4	10	1.2	1.8
f	2.3	6	2.1	3.1
f	2.3	10	1.2	2.6
g	2.5	6	2.1	3.3
g	2.5	10	1.2	2.8
h	2.6	6	2.1	3.3
h	2.6	10	1.2	2.9
i	2.7	6	2.1	3.4
i	2.7	10	1.2	3.0
j	2.9	6	2.1	3.6
j	2.9	10	1.2	3.1

+From Table 1.
*Values listed represent range of typical pavement thickness frequencies.
++Error due to spectral resolution; spectral resolution = 0.244 kHz.
**Square root of sum of square of two errors.

TABLE 3 — RESULTS OBTAINED FROM 0.2-M-THICK PAVEMENT SECTIONS

Sub-base	C_p (m/s)	IE Thickness (mm)	Core Length (mm)	Actual Error (mm)	Reported Thickness (mm)
LCB[a]	4255	203	205	-2	203 ± 9
PBTB[b]	4080	212	209	+3	212 ± 9
DGAB[c]	4080	209	212	-3	209 ± 9
DGAB	3920	195	197	-2	195 ± 8

[a]Lean concrete base.
[b]Permeable bituminous treated base.
[c]Dense graded aggregate base.

TABLE 4 — RESULTS OBTAINED FROM 0.3-M-THICK PAVEMENT SECTIONS

Sub-base	C_p (m/s)	IE Thickness (mm)	Core Length (mm)	Actual Error (mm)	Reported Thickness (mm)
LCB	4255	291	294	-3	291 ± 14
PBTB	4255	300	294	+6	300 ± 14
DGAB	4080	279	288	-9	279 ± 14
DGAB	4080	279	287	-8	279 ± 14

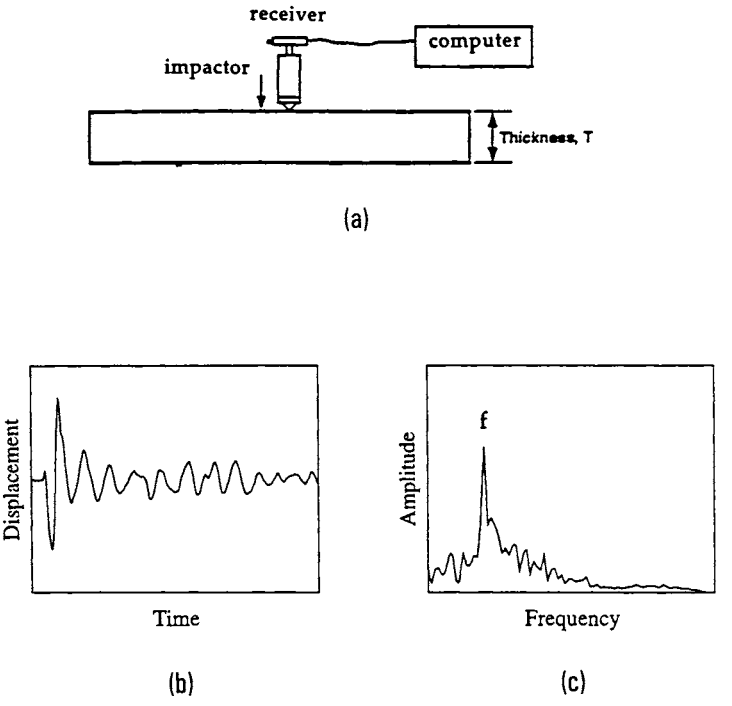

Fig. 1—Impact-echo test on solid plate: a) test configuration; b) displacement waveform; c) amplitude spectrum

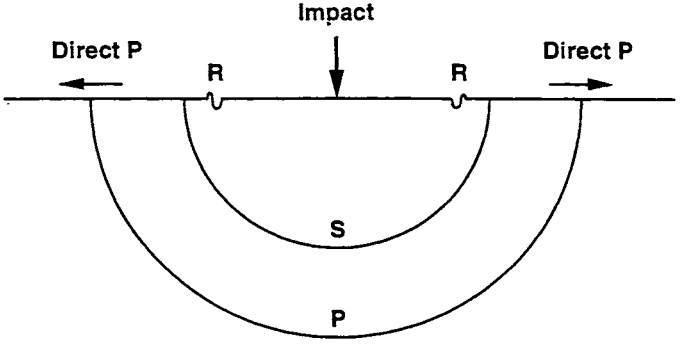

Fig. 2—Schematic representation of P, S, and R-wavefronts generated by point impact

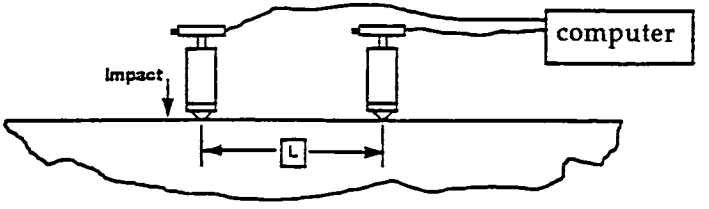

Fig. 3—Schematic representation of test setup in wave speed measurements

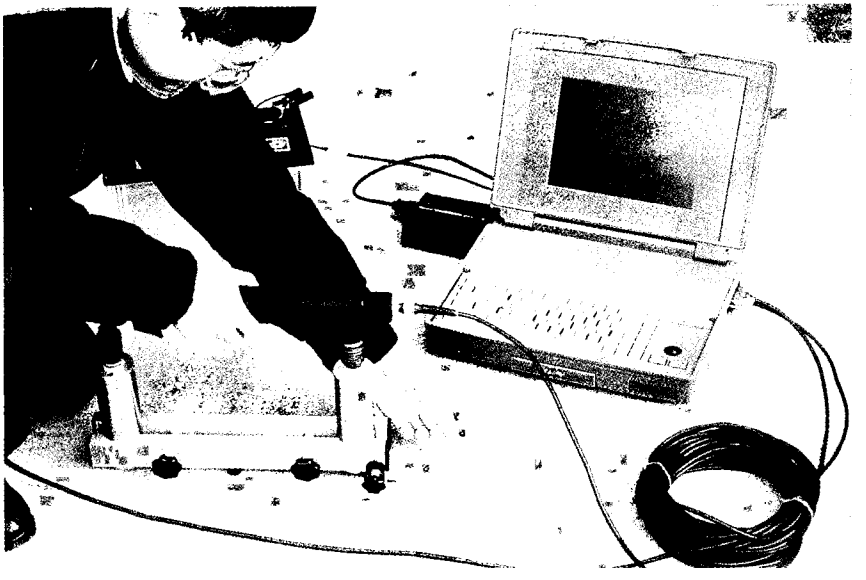

Fig. 4—Photograph of instrumentation used in wave speed measurements

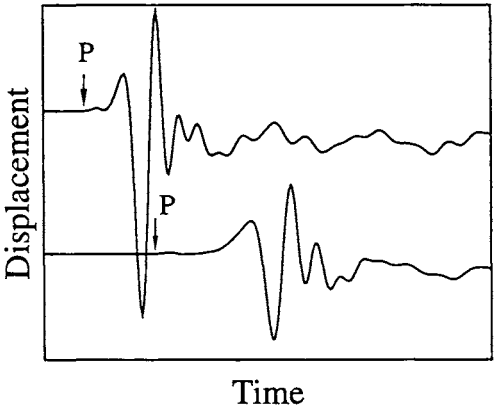

Fig. 5—Typical waveforms in direct P-wave speed measurements

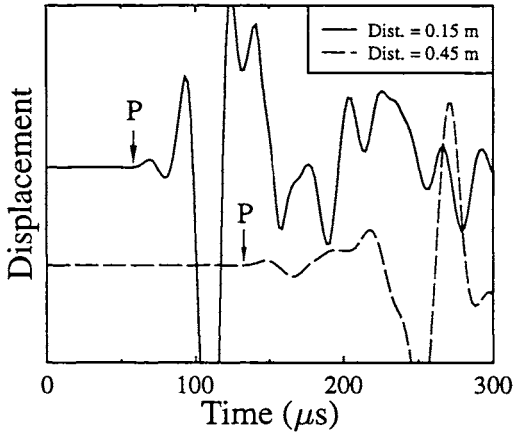

Fig. 6—Result of direct P-wave speed measurement

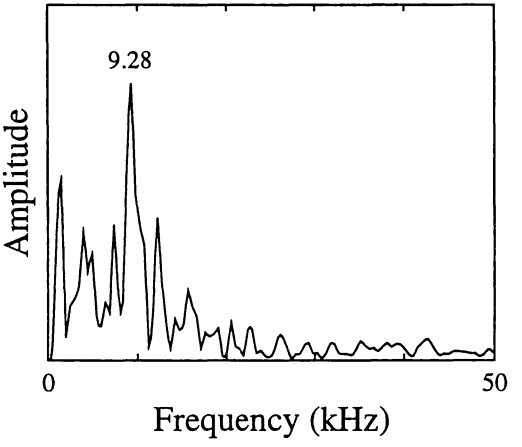

Fig. 7—Result of impact-echo measurement

Locating Delaminations and Other Defects in Concrete Silo Walls Using the Impact-Echo Procedure

by N. A. Cumming and O. S. Ooi

Synopsis: A major structural repair and strengthening program was undertaken at a large grain shipping terminal on Canada's northwest coast. The work was required to correct problems of excessive cracking and internal delamination in the silo walls. During the repair work, it was necessary to survey 42 silos to locate zones of delaminated or deteriorated concrete. This was done successfully using the impact-echo procedure.

This paper describes the impact-echo survey and its findings. It further discusses correlation of test results to actual conditions encountered in the field.

Keywords: concretes; impact tests; nondestructive tests; repairs