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Experimental Investigation of Impact-Echo Method for Concrete Slab Thickness Measurement

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Abstract Accurate estimates of in place thickness of early age (3 to 28 days after casting) concrete pavements are needed, where a thickness accuracy of ±6 mm is desired. The impact-echo method is a standardized non-destructive technique that has been applied for this task. However, the ability of impact-echo to achieve this precision goal is affected by V_P (measured) and β (assumed) values that are applied in the computation. A deeper understanding of the effects of these parameters on the accuracy of impact-echo should allow the technique to be improved to meet the desired accuracy goal. In this paper, the results of experimental tests carried out on a range of concrete slabs are reported. Impact-echo thickness estimation errors caused by material property gradients and sensor type are identified. Correction factors to the standard analysis method are proposed to correct the identified errors and to increase the accuracy of the standard method. Results show that improved accuracy can be obtained in the field by applying these recommendations with the standard impact-echo method.

Keywords: Concrete, Impact-Echo Non-Destructive Evaluation, P-Wave Velocity, Thickness.

1. Introduction

The demand for accurate in-place measurement of concrete slab thickness at early ages (3 to 28 days after casting) stems from the need for performance-predictions, and also as a means to verify performance-related specifications (PRS) during the construction phase. The US Federal Highway Administration supports the development of PRS, and it is a subject of rapidly-growing interest to state transportation agencies (Hoerner et al., 2000). PRS require verification, with an acceptable degree of accuracy, of the in-place properties of concrete pavement relatively soon after casting. The Indiana Department of Transportation prescribes quality-based specifications through contractor pay factors (financial penalties or rewards) based on, among other parameters, the statistics of cast concrete pavement thickness: mean and standard deviation of thickness data. In the case of thickness, the actual pay factors depend on the data variance, but in general an accuracy of ± 6 mm (± ¼ inch) for the thickness measurements on concrete pavements is needed to apply a 1% pay factor adjustments to overall cost (IDOT, 2005). Direct thickness measurement by core extraction does provide this level accuracy. However, coring is a relatively time consuming and expensive procedure that leaves an inconvenient hole in the pavement that must be repaired. As a result core extraction must be applied sparingly and cannot provide the needed spatial precision and large sample of data needed for effective statistical evaluation.

Non-destructive evaluation (NDE) methods provide a potential solution to this problem, as data can be collected at many locations without causing any damage to the concrete. Research

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efforts in this area have been ongoing for many years. The impact-echo echo method has emerged as the most effective and accurate NDE method for concrete pavement thickness estimation over other techniques such as short pulse RADAR (GPR), pulse-echo ultrasound and the spectral analysis of surface waves (SASW) technique (ACI, 1998). The impact-echo procedure for concrete pavement thickness estimation is standardized in the US under ASTM C 1383-98a (ASTM, 1998). This standard describes two separate procedures within the impact-echo method: (*i*) determination of the compressional wave (P-wave) velocity and (*ii*) measurement of the impact-echo resonant frequency. Results from impact-echo case studies carried out on new concrete pavements report pavement thickness accuracy within 3%, where impact-echo usually under-estimates actual thickness (Graveen, 2001; Sansalone and Street, 1997).

2. Impact-Echo Background

The impact echo resonant frequency represents the local dynamic response of a structure that is subjected to a light impact event applied to the surface. The out-of-place surface displacement with respect to time is monitored with a sensor at a location near by the impact event, where the displacement time signal is recorded over a given duration. The time-dependent displacement response by itself cannot be interpreted in most cases. However, the signal can be mapped to the frequency domain by applying a Fourier transform. Typically, FFT algorithms are applied to compute the transform of the discrete time signal. The result of the transformation is complex-valued, so the magnitude of the transform is usually presented at each point, which is now a function of frequency. The amplitude spectra can be interpreted directly wherein the frequency values at signal maxima (peaks) are recorded. These structural resonance frequencies are called "impact-echo" modes. Typical impact-echo signals collected from a solid concrete slab are shown in Fig. 1. In the case of plate-like structures, such as slabs, the fundamental impact-echo frequency (frequency at the lowest-valued significant peak) F is related to the P-wave velocity of the material V_P and the thickness t by

$$F = \frac{\beta V_P}{2t} \tag{1}$$

where β is a dimensionless correction parameter (Sansalone, 1997; Sansalone and Street, 1997). Recent work shows that the exact value of β for free plates (slabs) comprised of ideal homogeneous and elastic materials varies within a fairly narrow range: β = 0.945 to 0.955 as Poisson's ratio of the concrete varies from 0.25 to 0.15 (Gibson and Popovics, 2005). In ASTM C1383, however, β is assigned the constant value 0.96.

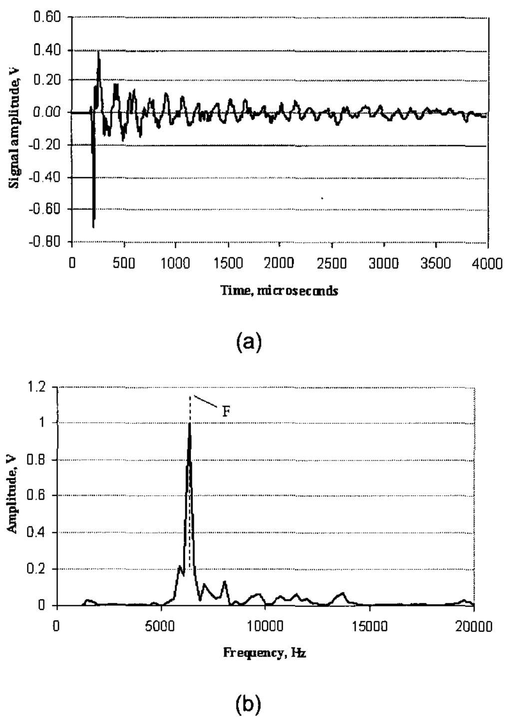
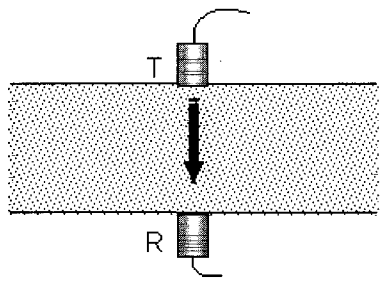


Fig. 1 Impact-echo data collected from a 300 mm thick, defect free concrete pavement slab. V_P = 3800 m/s: (a) time domain signal and (b) associated frequency domain signal.

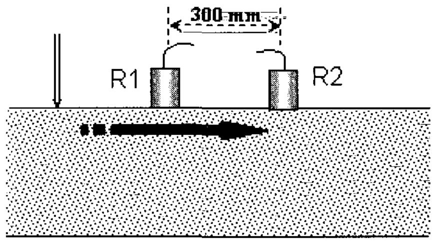
One cannot obtain the thickness directly from the frequency value alone since t, V_P and β are coupled in the formulation, as seen in eqn. (1). Thus good estimates of V_P and β are needed to obtain accurate thickness measurements from the frequency. Previous studies have demonstrated that an estimated, constant value of V_P does not provide accurate measurements because of localized natural variation of V_P within the concrete along the length of the slab (Clemeña, 1995). Thus the ASTM standard procedure specifies a direct measurement of V_P, which is carried out along the top surface of the pavement. The P-wave time of flight between two sensed points is determined by measuring the difference in the time of the first arrival (first departure from signal baseline value) of the surface-propagating P-wave pulse in each signal; the wave pulse is generated by an impact event applied to the surface at another nearby location (Fig. 2b). The standard specifies the sensor to be a broad-band piezoelectric transducer that responds to surface displacements; in this paper, this type of sensor is called a "displacement transducer". In the case of free slabs, where access to the opposing surfaces is available, another measurement of V_P can be obtained: V_P determined along the path through the thickness of the slab (Fig. 2a). The standard process to measure the through-thickness ultrasonic P-wave velocity (UPV) in concrete is given in ASTM C597 (ASTM, 2002). The P-wave time of flight through the slab thickness is determined by measuring the time required for a P-wave pulse to travel from sending to receiving transducers that are axially aligned at testing points on opposing slab surfaces. Through-thickness V_P is then directly determined knowing the thickness of the slab.

3. Research Significance

Accurate estimates of in-place thickness of early age (3 to 28 days after casting) concrete pavements are needed, where a thickness accuracy of ± 6 mm is desired. The impact-echo method is a standardized non-destructive technique that has been applied for this task. However, the accuracy of impact-echo is affected by V_P (measured) and β (assumed) values that are applied in the computation. An understanding of the effects of these parameters on the accuracy of impact-echo, and the fundamental reasons behind this behavior, are therefore of interest and may allow the technique to be improved to meet the desired accuracy goal.



(a)



(b)

Fig. 2 Wave velocity testing configurations for the slabs: (a) through-thickness with ultrasonic transducer set and (b) one-sided with impact point source and receiving transducer set. The black arrow indicates assumed P-wave propagation path

4. Experimental Program

Three plain concrete (without steel reinforcement) test slabs were cast. The slabs have the same nominal thickness (18 cm), with natural variation and error as the only reasons for differences in actual thickness at a given location. This practice simulates actual practice, where a target nominal thickness is sought by the paving contractor. The slabs differ in concrete composition, however, to simulate the range of concrete classes used in pavements. The slabs are tested in the days after casting, again simulating tests on new concrete pavements for quality-based specification compliance. The tests were carried out over several weeks, to determine any effect due to the material property changes owing to hydration in these first few weeks after casting.

Test Specimens

The slabs were cast horizontally into pre-formed wooden forms, including the bottom surface. The cast concrete slab forms measured 152 cm x 152 cm x 18 cm (60 inches x 60 inches x 7 inches). The fresh concrete was spread and compacted by hand, and the top surface struck off. The slabs' top surfaces were kept moist and covered with an impermeable sheet for 24 hours. Approximately one day after casting, the slabs were de-molded and testing locations were identified and marked on each surface of the slab. Each slab has a different concrete mixture, simulating a range of concrete strengths: normal strength (slab 1), moderate strength (slab 2) and high strength (slab 3). Three companion cylinders (150 mm x 300 mm) were also cast for each slab, and the dynamic Young's modulus (ASTM C 215) and through-thickness ultrasonic pulse velocity (ASTM C597) of those cylinders were determined at the age of 28 days after mixing. All concrete was obtained from a local ready-mix supplier, and relevant properties of the concrete mixtures are given in Table 1. The coarse aggregate was crushed limestone with a maximum size of 19 mm. The fresh concrete had slump of 75 mm ± 10 mm. All concrete mixtures contained entrained air, with total air content of 6% ± 1%.

Experimental Testing Procedure

For each slab, two different testing locations were identified. Impact-echo (one-sided velocity and resonance test components) and through-thickness ultrasonic pulse velocity (UPV) tests were carried out at those defined points. The tests were repeated over the course of several weeks at the same testing locations. Then full-thickness cylindrical core samples were taken at those same testing locations, upon which the actual slab thickness was determined directly. Subsequent tests were then carried out on the core samples.

Impact-Echo

The impact-echo tests were carried out using a commercially-purchased impact-echo testing package that satisfies the requirements set out in ASTM C1383. This equipment package consists of a Windows 98 laptop computer containing the testing software, a set of spherical steel impactors, and two sensing transducers (displacement transducers) separated a fixed distance by a spacing bar. The Impact-Echo software, developed by Impact-Echo Instruments, LLC guided the data collection, analysis (FFT) and storage processes.

The impact-echo test involves a two-step process. First, the P-wave velocity of the concrete at each testing location was determined using the direct one-sided surface technique specified by

Table 1 Concrete mixture description

Slab designation	nominal w/cm	Average E_d at 28 days (GPa)	Average UPV at 28 days (m/s)
1	0.49	31.7	4199
2	0.47	37.5	4329
3	0.45	39.0	4436

ASTM C1383. The P-waves were generated by a 4.5 mm diameter steel sphere impactor, and two sensing transducers were aligned and separated by a distance of 300 mm (see Fig. 2b). The P-wave signal data were digitized using 2048 data points with 0.5 μs sample interval. In each signal the P-wave arrival time was determined by the controlling software. The operator then visually verified that these times coincided with the first departure from the baseline value of the signal. The operator then accepted the arrival times or modified as necessary to coincide with the observed signal. Five repeated P-wave velocity values along one line at the testing point were measured, and the average value recorded. Then the same procedure was carried out along another orthogonal line centered about the same point. The average of the velocity values along each line was reported at each point.

The impact-echo resonance frequency was then measured at that same point. The impact-echo resonances were excited using a 12 mm diameter impactor, and a single transducer detected the resulting vibration. As per ASTM C 1383 requirements, the source-transducer spacing did not exceed 40% of the known thickness of the slab. The resonance frequency signal data were digitized using 2048 data points with 1 μs sample interval, which were then converted to the frequency domain using an FFT algorithm provided by the testing package software. Three repeated measurements were performed at each point, and the average value was reported. The systematic error of the testing configuration is that caused by signal digitization and processing limitations (Sansalone and Street, 1997). The total systematic error can be computed assuming nominal values of V_P (e.g. 4000 m/s) and t (e.g. 180 mm). Following Sansalone and Street, velocity error $e_p = \pm 0.0067$, frequency error $e_f = \pm 0.023$, and total error $e_t = \pm 0.024$ (Sansalone and Street, 1997). This gives a theoretical systematic thickness error of ± 4.3 mm in this case, which is within the desired accuracy target.

UPV

The UPV tests were carried out using commercially-purchased UPV testing unit that satisfies the requirements set out in ASTM C597. This equipment package conists of a pair of 54 kHz ultrasonic transducers and an associated timing and display unit. The unit measures the P-wave time of flight and displays the result to the nearest 0.1 μs. Because this test requires access to opposing surfaces of the specimen (see Fig. 2a), it was necessary that the slabs be in a vertical position. Thus, both large surfaces of the slab can be considered to be free boundaries for both impact-echo and UPV testing.

Coring

At the conclusion of the NDE tests, two cylindrical core samples were drawn from each of the slabs at the identified testing locations, labeled as locations “a” and “b”. The slabs were cored using a 3.75 inch diameter wet power coring machine. The actual thickness of the slab at the testing locations were then determined directly from the core sample using a set of calipers. Subsequently, the cores were sawn into 5 disks, each disk having a thickness of approximately 40 mm, the thickness of each disk was determined using a set of calipers. The disks were immersed in water for 24 hours in order to obtain saturated moisture conditions. Then, the disks were subjected to UPV measurements through the 40 mm thickness of the disk (see Fig. 2a).

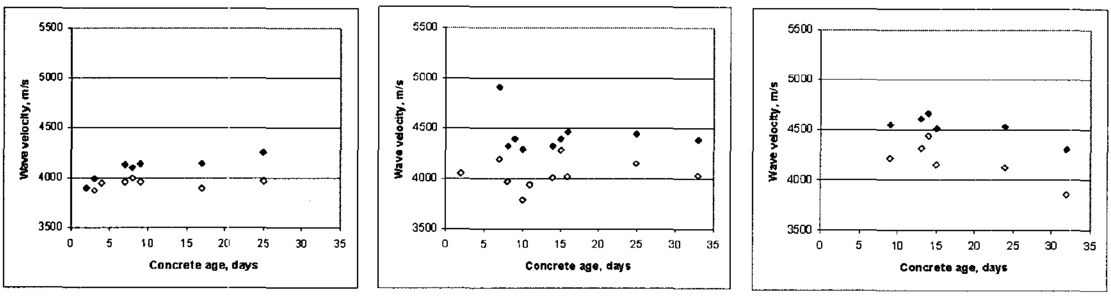
5. Experimental Results

Wave Velocity

Figs. 3a, 3b and 3c show P-wave velocity measured by one-sided and through-thickness methods at a selected core location for all three slabs, respectively, as a function of age after casting. As expected the slabs show some increase in velocity within the first several days after casting because of intensive hydration activity, leveling off to a relatively constant value by day 7. Slabs 2 and 3 exhibit a slight decease in velocity after day 30, likely because of internal drying over time in the dry laboratory air environment. Data collection on slab 3 could not be started until 7 days after casting. At all ages, the through thickness (UPV) velocity is significantly larger than the one-sided velocity. On average, 1-sided velocities are 300 m/s lower than UPV, which represents differences on the order of 6 to 8%. This difference, which has been observed and confirmed by other researchers (Boyd and Ferraro, 2005; Qixian and Bungey; 1996; Jones, 1962), and it is greater than that caused by velocity systematic error (△V = ± 50 m/s), and therefore must have some other cause.

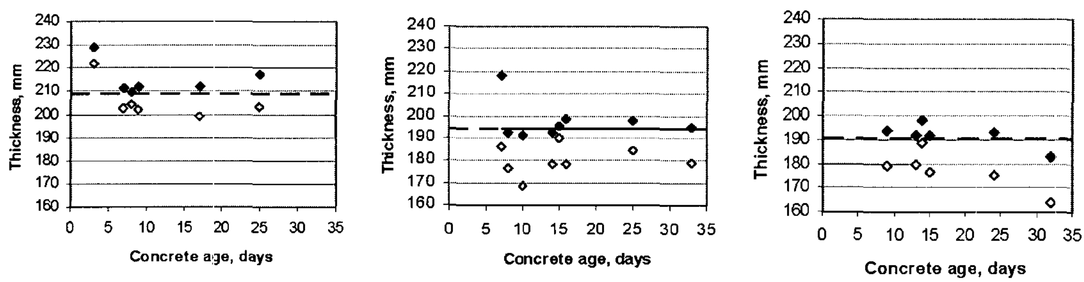
Impact-Echo Thickness Eestimates

Because of the observed velocity differences the thicknesses predicted by impact-echo, using eqn. (1), will vary depending on the velocity value applied. Fig. 4 shows the predicted thicknesses for the three slabs, as a function of age, using both velocity values and assuming a β value of 0.952, which represents a typical expected theoretical value for concrete. Although the data show some scatter the values are fairly constant as a function of concrete age, so there is no clear influence of concrete age on the estimated thickness values. It is clear however that the thickness estimates are closer to the actual thickness (determined by core sample) at all ages when the through-thickness UPV is used with this value of β. The thickness estimates using one-sided velocity are lower than the



(a) (b) (c)

Fig. 3 Through thickness UPV (solid symbols) and one sided P wave velocity (hollow symbols) as a function of concrete age for slabs 1 (a), 2 (b) and 3 (c).



(a) (b) (c)

Fig. 4 Predicted impact echo slab thickness using through thickness UPV (solid symbols) and one sided wave velocity (hollow symbols) as a function of concrete age for slabs 1 (a), 2 (b) and 3 (c). Actual slab thickness (core) indicated by dashed line.

actual thickness in nearly all cases. Again, these differences are greater than that caused by system resolution error. To illustrate, the thickness estimates and errors for the two core locations in all three slabs at the age of 25 days are shown in Table 2. Standard impact-echo using one-sided velocity under-predicts the slab thickness on average by approximately 11.7 mm, while UPV over predicts by about 6.8 mm. Significant variability in the thickness estimates is evident in both cases. The average squared error for thickness of all slabs, core locations and ages is 6.7 mm when using UPV and 11 mm when using one-sided P-wave velocity in eqn. (1) and assuming β=0.952, both of which are beyond the desired accuracy limit of 6 mm.

Beta Values

By manipulating eqn. (1), β values can be back-computed using actual core thickness and measured values of P-wave velocity. β values obtained in this way are shown in Fig. 5 for all core locations and slabs, using the two types of P-wave velocity measurement. The data show a significant degree of scatter, and it is clear that the experimentally back-computed β values differ than the range of 0.945 to 0.955 that is theoretically predicted. In the case of one-sided P-wave velocity, the β values are generally above 1 with an average value of 1.01, while for UPV the values are lower, generally below 1 with an average value of 0.935. These differences are due only to the method of wave velocity measurement, as consistent resonance frequency values were used, so the scatter in the data is a result of variability in wave velocity data rather than that in the resonance frequency data. The resonant frequency values showed excellent consistency upon repeated tests.

6. Discussion

In this section, the reasons for P-wave velocity discrepancy and variability are analyzed. The analysis is divided into two parts: (i) effects possibly caused by material property gradients through the thickness of the concrete

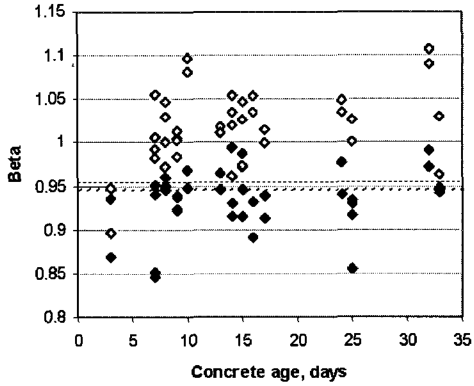


Fig. 5 Back-computed β values using through-thickness UPV (solid symbols) and one-sided P-wave velocity (hollow symbols) obtained from all slabs and core samples. Theoretical limits of β values indicated by dashed lines.

Table 2 Actual and predicted slab thickness estimates, and resulting error, for all cores and slabs at the age of 25 days. β=0.952.

Slab-core designation	Actual thickness (mm)	Predicted thickness: 1-sided (mm)	Error: 1-sided (mm)	Predicted thickness: UPV (mm)	Error: UPV (mm)
1 - a	209	203	-6	217	8
1 - b	200	204	4	207	7
2 - a	198	184	-14	198	0
2 - b	191	176	-15	212	23
3 - a	194	179	-15	193	-1
3 - b	191	175	-16	193	2

slab and (ii) effects possibly caused by systematic errors associated with the velocity measurement itself. Recommendations for testing are then given based on the analysis, and verified through tests carried out on other concrete pavement slabs.

Material Property Gradient

It is reasonable to assume that underestimation of V_P by the one-sided method is caused by material property gradients through the thickness of the slab, since this method interrogates primarily the top section of the concrete (see Fig. 2b). Material property gradient can be caused by aggregate settlement and bleeding in early-age concrete, leaving the upper portion of the slab with lower aggregate content. It has been shown that moisture content variations (Popovics et al., 1998) and surface deterioration mechanisms such as sulfate attack (Boyd and Ferraro, 2005) may also establish wave velocity gradients with respect to slab depth; those effects will not be studied here. The aggregate settlement should cause an increase in material wave velocity from top to bottom, with respect to the casting direction. The one-sided measurements are likely more affected by material property gradients than through-thickness measurements; if this were the case, V_P measured along the surface would likely under-estimate through thickness velocity when a gradient caused by aggregate settlement exists.

Here material property gradients in the drawn cores are established by UPV measured through slab height, from the individual sectioned slices of cores. The tests are carried out on the concrete disks in the saturated moisture condition to eliminate any effects owing to internal moisture gradients. Fig. 6 shows the velocity trend for all sectioned cores as function of depth through the cores, where disk 1 is the top and disk 5 the bottom of the core with respect to the casting direction. The results are normalized with respect to the top-most disk of each core in order to present results from all cores in a single plot. The average at each disk layer for all core samples is shown by the dashed line. Despite some data scatter, a trend of increasing wave velocity with depth is seen; on average the wave velocity of the material increases 8% as we move through the slab from the cast finished surface at the top (disk 1) to bottom (disk 5). The observed established gradient likely contributes to the discrepancy between velocity measured along the surface (mostly disk 1) and through the thickness (average of all disks).

The most accurate slab thickness prediction is obtained in the location where 1-sided P-wave velocity and UPV values are most similar. The thickness prediction error at this location is 4 mm when using one-sided P-wave velocity and 7 mm when using UPV through the slab height (to predict the slab thickness). The disks from the cores taken at this location show the smallest difference between the finished surface at the top (disk 1) and the surface at the bottom of the slab (disk 5), the difference of UPV between both disks was 2.7% (UPV difference between disk 1 and disk 5 on average was 8%, considering all the cores). On the other hand, the most inaccurate slab thickness prediction is obtained when the difference in velocity using both methods was the largest.

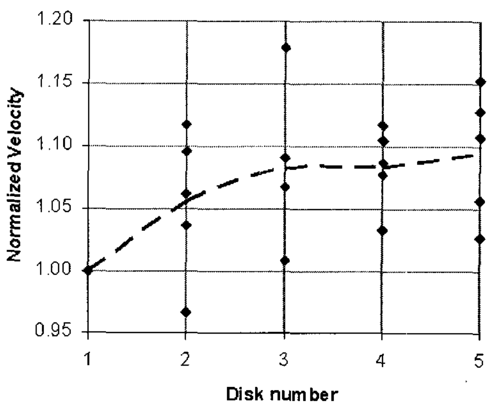


Fig. 6 Trend of UPV in sectioned core samples with increasing depth from top (cast) surface. Velocity values normalized with respect to top-most disk of each core.

Based on the observed behavior in the presented data, a coefficient that accounts for the P-wave velocity difference between the top and bottom regions of the slab is proposed to improve the thickness prediction based on one-sided velocity measurements. This coefficient, β_1, modifies the measured one-sided velocity by an amount equal to one half of the relative UPV difference from the bottom region to the top region where the velocity results are normalized with respect to the top-most region

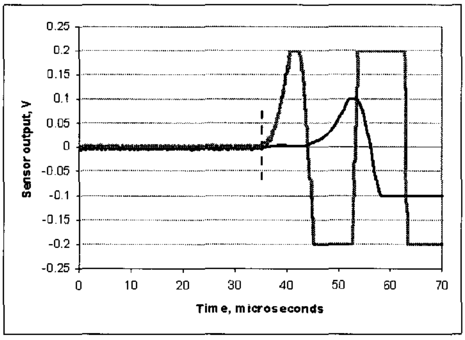
$$\beta_1 = (1 + \frac{UPV_{bottom} - UPV_{top}}{2\,UPV_{top}}) \qquad (2)$$

This approach assumes that the extent of material property gradient is fairly uniform across the slab area. In the analyzed case, β_1 = 1.04 considering that the UPV difference between disk 1 and disk 5 on average was 8% from all core locations in the three slabs.

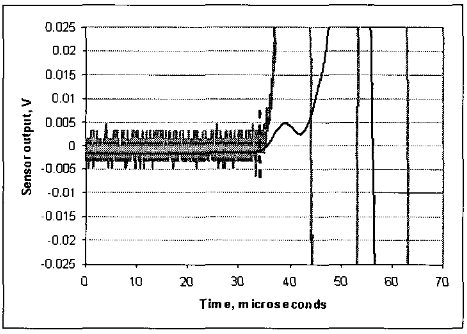
In order to obtain this value, it is recommended that a core from slab be taken. The core must be sliced to obtain one slice from the top part (4 cm from the finished surface) and one slice from the bottom part (4 cm from the bottom surface). UPV values from each disk are used to compute β_1. When a core cannot be taken or the material property gradient coefficient it is not possible to compute, β_1 = 1.04 is recommended.

Systematic Velocity Measurement Error

It is known that the measured apparent wave velocity can be disrupted by inaccuracies on

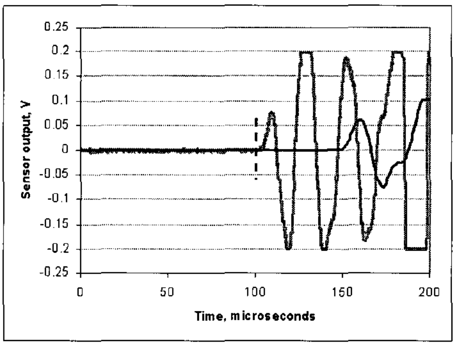


(a)



(b)

Fig. 7 Time domain signals from one sided velocity measurements for near displacement transducer (black line) and accelerometer (grey line) sensors. Expected P-wave arrival indicated by vertical dashed line: (a) full amplitude scale and (b) magnified amplitude scale.



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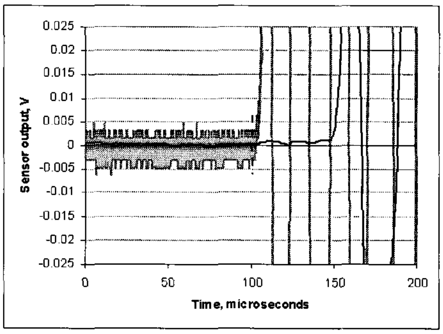

(b)

Fig. 8 Time domain signals from one-sided velocity measurements for far displacement transducer (black line) and accelerometer (grey line) sensors. Expected P-wave arrival indicated by vertical dashed line: (a) full amplitude scale and (b) magnified amplitude scale.

determining the precise moment of wave arrival (Popovics et al., 1998). The level of disruption is controlled by the type of wave source, type of detection sensor and wave arrival determination algorithm applied in the analysis, and manifests itself as changes in the average and variance of multiple velocity data.

To investigate this effect on one-sided measurements, thirty repeated velocity measurements were carried out on the surface of one of the test slabs (slab 3) using two different testing set-ups: (i) conventional impact echo displacement transducers and 4.5 mm steel ball as an impact source; and (ii) two miniature accelerometers (which monitor surface motion acceleration as opposed to displacement) as the sensors and 4.5 mm steel ball as the source. The accelerometers are miniature sensors manufactured by the PCB company, model These sensors exhibit flat frequency response between 3 Hz and 10 kHz and have a nominal sensitivity of 10.89 mV/g at 100 Hz. In all cases, the near and far sensors are mounted on the surface and separated by 300 mm. Fig. 7 and 8 show typical received time domain signals from the tests. The accelerometer signals exhibit a larger and sharper leading edge coincident with the wave arrival time; this enables superior (more precise) wave arrival identification in the signal. The superiority of the accelerometer signal is especially evident in the signals from the far receivers (Fig. 8).The signals are then analyzed using three different procedures: wave arrival determined visually by the test operator (displacement sensor signals only), the arrival determined by applying a 7 mV threshold criterion (accelerometer signals only), and arrival determined with a curve-fitting criterion as proposed by Popovics et al., 1998 (accelerometer signals only). The results are presented in Table 3. Clearly the standard impact-echo method, where arrival time is determined visually by the inspector, provides significantly lower velocity values than those obtained using the accelerometers when threshold and fitting algorithms are applied: the average values from the accelerometers converge to a consistent high value. This difference can only be caused by the type of signal (i.e. displacement vs. acceleration), indicating a systematic error in the measurement. The data from the displacement transducers also show higher variability as indicated by the standard deviation and coefficient of variation values than those obtained from the accelerometers. Thus, the most consistent one-sided values are obtained using accelerometers. One-sided velocity obtained using the threshold method is more consistent than that obtained using the fitting method. When the threshold method is applied to compute 1-sided P-wave velocity, the average wave velocity value is on average 3.8% higher than that obtained using the standard impact-echo testing configuration and analysis.

We observed previously that standard one-sided P-wave velocity is lower (by 6 to 8%), and also provides less accurate impact-echo thickness predictions, than that from through thickness UPV measured at the same location. Thus we propose that one-sided velocity measured by accelerometers will provide more accurate impact-echo thickness predictions than standard measurements because they are considerably higher on average and also more consistent. We

Table 3 Statistical results from thirty repeated measurements of one-sided velocity using different wave arrival time procedures.

Method	Average 1-sided P-wave velocity (m/s)	Standard deviation (m/s)	Coefficient of variation (%)
Impact-echo screen	4358.7	40.6	0.93
Threshold (0.007V)	4524.8	23.7	0.52
Fitting (0.007V)	4554.2	24.9	0.55

propose another coefficient, which accounts for the noted systematic error, to improve further the thickness prediction obtained using standard one-sided velocity measurements with impact-echo. This coefficient, β_2, increases the obtained velocity to account for this error in the standard measurement. Based on the presented data, we propose $\beta_2 = 1.038$ when standard one-sided velocity measurements (displacement transducers and visual identification of the arrival) is employed. $\beta_2 = 1$ when accelerometers are used and arrival is determined with a threshold procedure.

Re-Evaluation of Data

The impact-echo analysis equation takes the form

$$F = \frac{\beta \beta_1 \beta_2 V_P}{2t} \qquad (3)$$

when the proposed modifications are employed. The application of these modifications to impact-echo analysis, considering material property gradients and systemic sensor error, are illustrated using the data presented previously. In this case $\beta_1 = 1.04$, considering the average difference in UPV values from top and bottom disks was 8% considering all cores, $\beta_2 = 1.038$ since standard impact-echo measurements were employed and $\beta = 0.952$ as before. We observe that the product of all three beta coefficients is 1.028, which is similar to the average back-computed value of beta (1.01) shown in Fig. 5. Now we consider the thickness estimates for all three slabs at one particular day of testing at the age of 25 days. On that day the average absolute thickness error using standard impact-echo (eqn. 1) was 11 mm. Applying eqn 3. on the same data gives more accurate thickness estimates, with an average absolute error of 5.7 mm for all core locations and slabs at the age of 25 days. This error is smaller than the desired accuracy limit of ± 6 mm. Therefore, the application of both coefficients is an effective way to achieve the desired goal.

When possible, it is recommended to measure material property gradient coefficient (β_1) for each slab to be tested in order to obtain a more accurate thickness prediction. Otherwise, a β_1 value of 1.04 is recommended.

Verification on Concrete Pavement

As a final verification, the proposed approach is implemented on site to predict the thickness of a concrete pavement having nominal thickness of 250 mm. The concrete pavement was cast atop a dense asphalt concrete base layer. The pavement was cast 90 days before standard impact-echo tests were carried out at three different locations of the slab: locations “A” and “B”, which were cast from a single batch of concrete and location “C” which was cast from a second batch of concrete. Cores were then extracted at the testing locations and actual thickness was measured using a set of calipers.

The actual thickness of the pavement obtained from the cores, the standard impact-echo thickness prediction (displacement transducers and visual estimation of wave arrival time, applying

Table 4 Thickness prediction error obtained using conventional impact-echo and the core-corrected approach

Slab-core designation	Actual thickness (mm)	Predicted thickness: Impact-echo (mm)	`Error: Impact-echo (mm)	Predicted thickness corrected impact-echo (mm)	Error: corrected impact-echo (mm)
A	251	232	-19	250	-1
B	263	247	-16	267	4
C	245	242	-3	261	16

eqn. 1), the "corrected" thickness prediction (eqn. 3) and the error of both methods are presented in Table 4. In the corrected computation, we assumed β_1 = 1.04 and β_2 = 1.038. The thickness prediction obtained using standard impact-echo under-estimate the thickness by 19 mm and 16 mm for locations A and B respectively. The corrected thickness (eqn. 3) gives dramatically improved estimates of thickness for locations A and B, with absolute error less than 6 mm in both cases. At location "C" however, the standard impact-echo estimate is more accurate than the corrected estimate, which shows an error of 16 mm. The cause of this error remains unknown, but we continue research efforts to investigate consistency issues such as this. Nonetheless, the proposed approach shows promise since average absolute thickness error considering all three locations is much lower with the corrected estimate (9.5 mm) than in the standard estimate (14.4 mm).

7. Conclusions

The accuracy of the conventional, standard impact-echo method is affected by the material property gradients in concrete and by sensor systematic errors associated with the measurement of one-sided P-wave velocity. These errors can be reduced significantly by applying two correction coefficients. One coefficient accounts for the material property gradients through the thickness of the slab. The second coefficient accounts for the systematic error that affects one-sided P-wave velocity measurements when standard displacement sensors are used; this coefficient is not needed when accelerometer sensors are used to measure velocity. In general accelerometers are recommended for one-sided velocity measurements since they exhibit superior result consistency. Verification in a concrete pavement with a nominal thickness of 250 mm shows that the combination of coefficients to overcome thickness prediction errors can be effective, providing improved thickness estimates overall.

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