Measurement of Concrete Thickness and Detection of Defects Using Ultrasound Methods

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ABSTRACT

The use of Non-destructive Evaluation (NDE) techniques has proven to be effective in determining the thickness of plate like concrete elements and locating defects such as cracks, delaminations, voids, honeycombing, and debonding. Some of the problems that have plagued the concrete paving industry are testing for quality assurance and verification of thickness of existing concrete slabs without compromising their structural integrity by traditional coring methods. There are several Non-Destructive Evaluation (NDE) techniques that have been proven to be an effective way to combat these problems. This paper outlines one of these techniques, Ultrasound-Echo (UE). Requirements for self calibration of the wave speed and testing procedures for the ultrasound test equipment are discussed. To verify the accuracy of UE to identify defects, a test slab with purpose-built delaminations and air voids at known locations was constructed. A comprehensive measurement of this special test slab was performed using an UE device, and analyzed results are presented. Defective sections of the test slab are clearly identified by the UE method with recommendation given for detection of the defects.

INTRODUCTION

The Ultrasound Echo method (UE) is based on the use of a transmitter probe to administer broadband waves into the concrete surface. The probe is made of piezoelectric crystal (PZT) elements. A short duration high voltage pulse is applied to the PZT elements. The applied voltage pulse induces crystal expansion. The expansion produces a pressure pulse which emits a broadband wave field into the concrete. The wave field generated by the crystals, unlike mechanical impact, is independent of the surface condition (hardness and texture).

RESONANCE METHOD

Waves generated by UE can be used to estimate the concrete thickness of slab like structures (lateral dimensions at least 6 times greater than the thickness) using the Resonance Method. The wave field generated by the ultrasound input propagates through the concrete. The input sets up a repetitive reflection of many cycles in the concrete specimen corresponding to the shortest travel path. A waveform with period T (corresponding to twice the object thickness, TH) develops (Equation 1). Using a high sampling frequency and real time FFT (Fast Fourier Transform) allows determination of the dominant frequency which corresponds to the background echo reflections (discontinuity due to concrete-to-air or concrete-to-sub-grade interface). In the case of additional discontinuities in the specimen like spalls, delaminations, or horizontal flaws, the frequency spectrum will identify a shift in the dominant resonant frequency or may contain additional frequencies.

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Thickness Measurement

Thickness measurements are obtained from the resonant frequency which corresponds to twice the specimen thickness. The specimen thickness is given by the equation:

$$TH = Ws/(2F) \quad (1)$$

Where "Ws" is the P-wave speed and "F" is the dominant resonant frequency of the waveform.

Thickness measurement is best obtained by placing the receiver and transmitter probes in close proximity on a clean concrete surface and applying the broadband input. The tested concrete surface may be painted or covered with bonded floor tile. Figure 1 is the normalized frequency spectrum with dominant peak corresponding to the resultant thickness "TH."

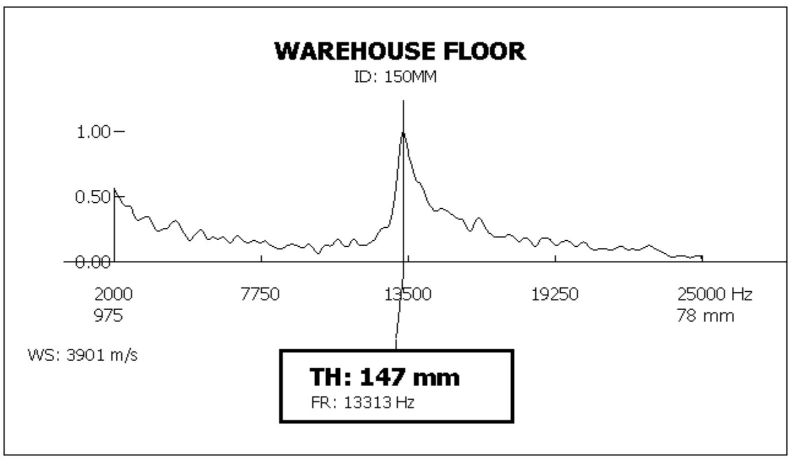

Figure 1: Thickness measurement (normalized)

Wave Speed Measurement

As noted in equation 1, the wave speed (measured or assumed) is used to convert the measured resonant frequency to a concrete thickness. According to ASTM C 1383, the concrete P-wave speed of an unknown thickness can be determined by measuring the direct surface P-wave in the concrete. P-wave speed is then calculated by dividing the distance between two probes (Δd) by the arriving time delay (Δt). The measured P-wave speed gives a more accurate thickness than an assumed wave speed.

If a specimen with a known thickness is available, the wave speed can be "calibrated". If the thickness is unknown, a destructive core could be obtained to determine thickness but usually an assumed wave speed is used (with resulting uncertainty). However, the standard UE test equipment is equipped to measure the P-wave speed of an unknown thickness. The transmitter and receiver probes are spaced from 450 mm (18 in) to 610 mm (24 in) apart on clean concrete surface. The Δt is measured as the P-wave initiation time (T0) subtracted from the direct surface P-wave initial arrival time at the receiver sensor (T1). Figure 2 shows the resultant P-wave speed measurement. Improved wave speed accuracy may be achieved by averaging several measurements at varied probe spacing.

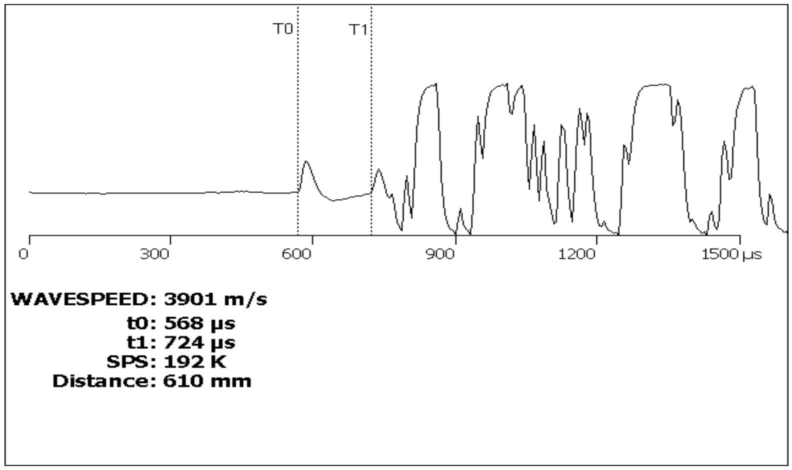

Figure 2: Wave speed measurement

THICKNESS TESTING

To verify the accuracy of the UE method, surface P-wave speed and thickness measurements were performed on several vertical cast-in-place walls. The walls were of known thickness. Specimens tested had thicknesses of 197 mm, 305 mm, 315 mm, 405 mm, 415 mm, and 510 mm. For the specimens tested, there was a variance in the thickness over the length of the wall. The tolerance for the actual thicknesses was conservatively determined to be ± 2 mm.

For each structure a thickness and percent error was determined from the dominant peak frequency using the measured wave speed and assumed wave speed. The measured wave speed was determined by measurement of the surface P-wave (method used for unknown thicknesses). For the assumed wave speed, 4000 m/s was used. (Nominal values of good concrete wave speed are 3505 m/s to 4520 m/s).

Test Procedure

For each structure, a 300 mm X 300 mm grid area was tested. The measurement grid spacing was $\Delta X = \Delta Y = 50$ mm. Thus, a total of 49 measurements were obtained for each structure. The measurements consisted of the peak resonant frequency. The peak resonant frequency was automatically converted to a thickness using a calibrated wave speed and assumed wave speed. The calibrated wave speed was the average of 9 measurements using probe spacing of 450 mm, 500 mm, and 550 mm along the coordinate line of Y = 0 mm, 150 mm, and 300 mm. A thickness measurement percent error was determined for each structure using the measured wave speed and assumed wave speed. The percent error using the measured wave speed was identified as εm and the percent error using the assumed wave speed was identified as εa. Results of the measurements are detailed in Table 1.

Table 1: Thickness measurements and percent error

Actual TH	Measured THm	Measured THa*	Measured Ws	Error εm	Error εa*
mm (in)	mm (in)	mm (in)	m/s (ft/sec)	%	%
197 (7.8)	196 (7.7)	214 (8.4)	3672 (12,047)	-0.5	8.6
305 (12.0)	305 (12.0)	290 (11.4)	4200 (13,779)	0	-4.9
315 (12.4)	314 (12.4)	324 (12.8)	3879 (12,726)	-0.3	3.1
405 (15.9)	402 (15.8)	424 (16.7)	3791 (12,437)	-0.7	4.7
415 (16.3)	418 (16.4)	439 (17.3)	3806 (12,487)	0.7	4.6
510 (20.1)	516 (20.3)	531 (20.9)	3890 (12,762)	1.2	4.0

* thickness and % error using assumed wave speed of 4000 m/sec (13123 ft/sec)

Results

Measured thicknesses using the measured resonant frequency and measured wave speed were within 2% of the actual thickness. Measured thicknesses using the measured resonant frequency and the assumed wave speed were within 8.6% of the actual thickness. The results clearly show that thickness measurements using a measured wave speed versus an assumed wave speed were significantly better. Using the same test method, it is reasonable to achieve similar thickness measurement accuracy on slabs with unknown thicknesses.

DELAMINATION TESTING

To demonstrate the defect detection capability of the UE method, a concrete slab was constructed where delaminations and air voids were incorporated (Figure 3). The slab has a length of 1520 mm (60 in) and width of 3040 mm (120 in) with depths of 200 mm and 100 mm (8 in and 4 in). The slab was constructed upon excavated compacted clay with a level crushed limestone base using steel reinforcement. A 305 mm X 610 mm (12 in X 24 in) section had a 20 mm (3/4 in) thick foam sheet over the limestone and a 610 mm X 610 mm (24 in X 24 in) section had a 25 mm (1 in) thick layer of river rock over the limestone.

Figure 3: Test slab with purpose built defects

Defects were incorporated in the 200 mm (8 in) depth only. Delaminations were artificially created with .8mm (1/32 in) thick adhesive backed ethylene propylene diene monomer (EPDM) rubber Sheets. Three (3) delaminations were 305 mm X 305 mm (12 in X 12 in) and located at depths of 50 mm, 25 mm, and 38 mm (2 in, ½ in and 1-1/2 in). Two (2) delaminations were 150 mm X 150 mm (6 in X 6 in) and located at depths of 25 mm and 100 mm (1 in and 4 in). An air void was artificially created with a 80 mm X 80 mm X 580 mm (3-1/8 in X 3-1/8 in X 23 in) sealed plastic conduit with the top surface at a depth of 110 mm (4-1/2 in). A steel plate, 305 mm X 305 mm X 6mm (12 in X 12 in X ¼ in), was located over the river rock sub grade at a depth of 130 mm (5 in). The test specimen also included a 610 mm X 610 mm (24 in X 24 in) honeycomb defect (grout and hermiculite mix). Figure 4 details the design of the test slab.

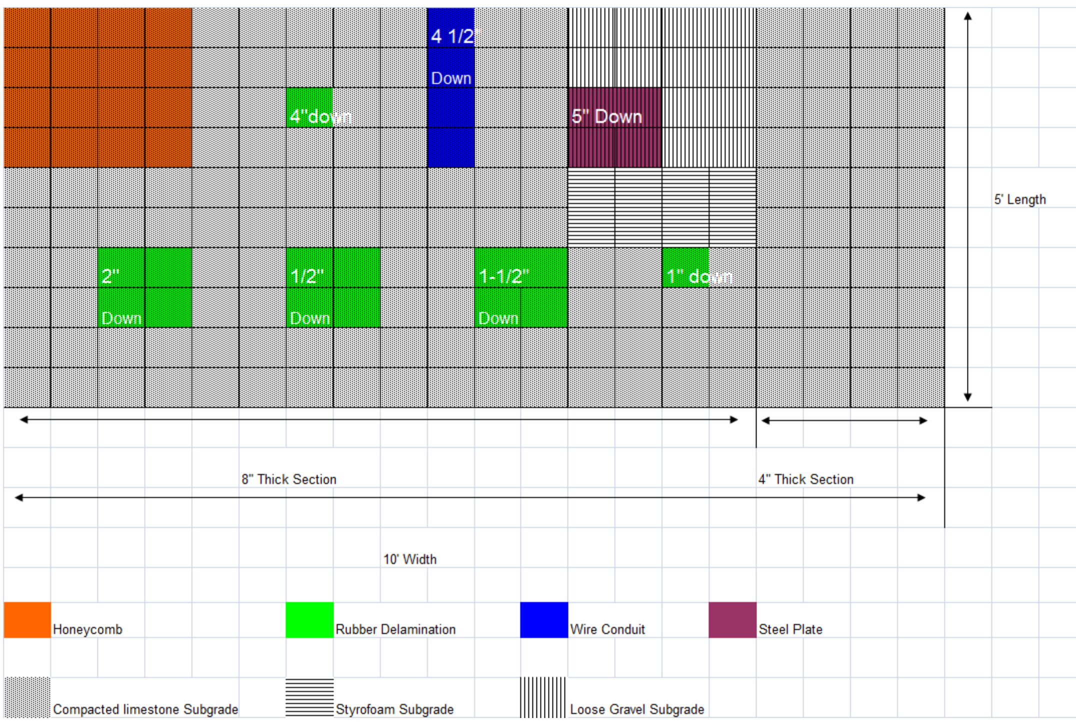

Figure 4: Design layout of test slab

Test Procedure

A UE scan of the slab was performed. The scan comprised of 1121 data points using a 50 mm (2 in) grid pattern on an X-Y coordinate system ($\Delta X = \Delta Y = 50$ mm). No data points were collected along the edges. Use of a telescoping pole allowed efficient and accurate probe placement during data collection. For each data point a peak resonant frequency within a range of 2K – 30K Hz was obtained. Importing the collected peak frequency data into a spread sheet allowed enhanced display of results for analysis. A contour plot of the results is depicted in Figure 5. A 2-D gray scale was used with white being the lowest frequency and dark gray the highest.

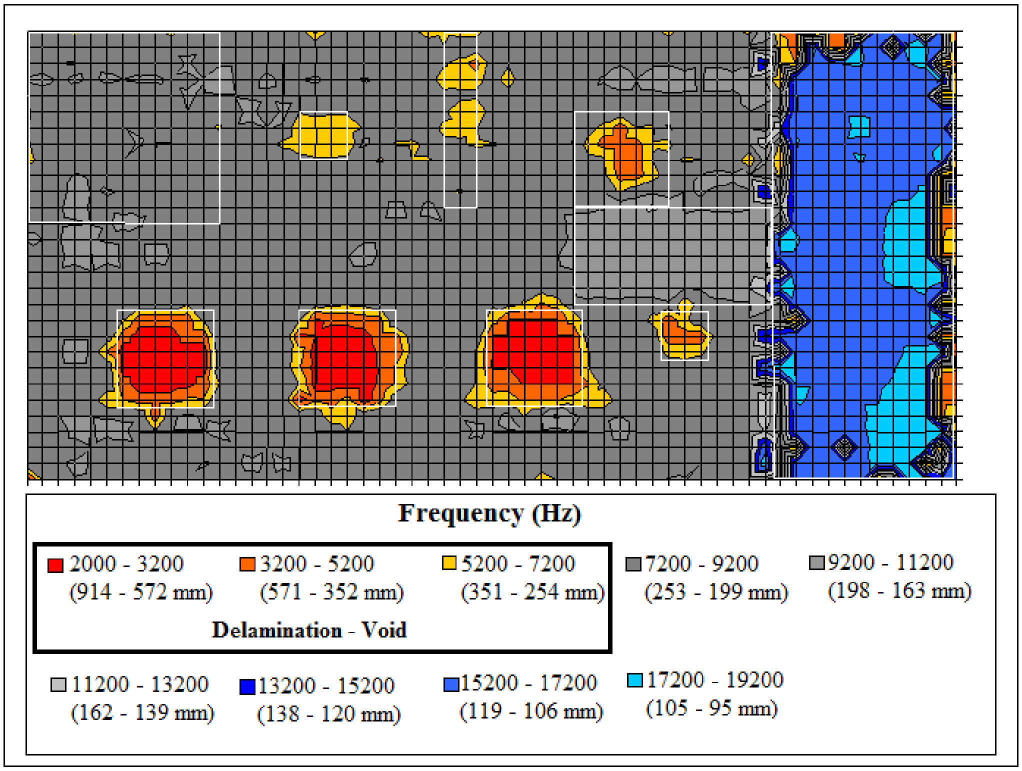

Figure 5: Frequency scan of purpose built test slab

Results

In areas where defects were not present, the peak resonant frequency (thickness resonance) corresponded to the slab thickness of 200 mm and 100 mm (8 in and 4 in). In areas of delaminations or air void, the peak resonant frequency shifted from the thickness resonance to a low frequency resonance (flexural). The lower frequency gave thickness measurements that were greater than the actual thicknesses. The low frequency resonance (flexural response) was very dominant compared to the thickness resonance.

For the 305 mm square delaminations the low frequency shift increased as the depth to delamination decreased. For the 150 mm square delaminations the low frequency shift also increased as the depth to delamination decreased. The 305 mm square 50 mm deep delamination had a greater frequency shift than the 150 mm square 25 mm deep delamination. Results indicate that for a given depth, a larger delamination (surface area) had a greater resonant frequency shift from the thickness resonance. And for a given delamination size a shallower delamination had a greater resonant frequency shift from the thickness resonance.

For the sealed plastic conduit, the low frequency shift was similar to that of the 100 mm deep delamination. However, a shift in the peak frequency did not occur over the entire conduit. It is likely that grout filled the conduit at the standoff locations resulting in only a partial void or a higher resolution grid.

In the area of the foam base, a higher peak resonant frequency resulted corresponding to the decrease in concrete thickness. In the areas of the river rock base and honeycombing, the peak resonant frequency closely matched the thickness resonant frequency. Due to a wet concrete mix and honeycomb simulation material, the honeycomb simulation was not effective and the concrete easily seeped around the river rock incorporating the rock into the slab thickness. Defect location and scan results were superimposed clearly showing the accuracy in identifying the delaminations and voids (Figure 5).

CONCLUSION

The Ultrasound-Echo method proved to be effective in the measurement of concrete slab thicknesses and in the detection of delamination and void areas. Using the measured P-wave speed gave accurate thicknesses in cases of known actual thicknesses. Testing on the purpose built defect test slab clearly identified areas of delamination and air void. At the location of a delamination or air void the peak resonant frequency shifted from the thickness resonance to a low frequency resonance. In general, the low frequency shift increased as the delamination size increased and as the depth decreased. A surface area plot of the collected data clearly showed the accuracy in identifying the delaminated and air void locations.

REFERENCES

1. ASTM C 1383-04, "Standard Test Method for Measuring the P-Wave speed and the Thickness of concrete Plates Using the Impact Echo Method"
2. ACT Manual, December 2007, Inspection Instruments Inc.
3. Carino, N. J., "The impact-echo method: an overview." *Proc., Structures Congress and Exposition,* ASCE, Reston, Va., 2001.
4. Christian U. Grosse, Hans W. Reinhardt,). "The Resonance Method – Application of a new nondestructive technique which enables thickness measurements at remote concrete parts.", *NDTnet October 1996, Vol.1 No.10,* http://www..ndt.net/article/grosse2/grosse2.htm, Oct. 13, 2005.
5. Pristov, E., Dalton, W., Piscsalko, G., and Likins, G. "Comparison of Impact-Echo with Broadband Input to Determine Concrete Thickness." *Proc., NDE Conference on Civil Engineering August 14-18, 2006 St. Louis, Missouri,* 2006