Slab-on-Ground Thickness Measurement

A comparison of data collected using laser scanning, ground-penetrating radar, impact-echo, and coring methods

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In a previous article,[1] we questioned the practice of specifying F-number criteria for slabs designed with textured finishes. In addition to industry experience, our arguments were supported by flatness measurements obtained for a 6 in. thick, 20 x 80 ft slab-on-ground test panel constructed by The Conco Companies, a member of ACI and the American Society of Concrete Contractors (ASCC). We also used the test panel to collect thickness data based on laser scanning, ground-penetrating radar (GPR), impact-echo (IE), and coring methods. The results are presented in this article.

Ground Truthing

Prior to the placement of reinforcing steel, the contractor used a laser scanner to survey the surface elevation of the compacted aggregate base in the test panel area. After concrete placement and finishing, the contractor used the same laser scanner to survey the finished surface of the test panel. Point cloud database software was used to find the difference between the two surveyed surface elevations and thus concrete slab thicknesses at specific locations within the test panel footprint.

Thickness values were then found by taking the differences in the elevations over a 1 ft horizontal grid. While this resulted in about 1700 thickness values, the point cloud data could have easily been "mined" to obtain 17,000 thickness values.

But how good was this data? We couldn't find anything in the literature that compared laser scan thickness data to measurements taken using other methods. Further, we realized that this test panel provided a great opportunity to make such comparisons, particularly because the contractor owned a GPR device and the ASCC Education Foundation had recently purchased an IE device for ASCC members to use on their research projects.

We used both devices to collect thickness data, and we obtained funding from the ASCC Education Foundation to evaluate 30 cores to compare with the three nondestructive test (NDT) methods. Cores were taken in accordance with ASTM C42/C42M, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete," and they were evaluated in accordance with ASTM C174/C174M, "Standard Test Method for Measuring Thickness of Concrete Elements Using Drilled Concrete Cores," and ASTM C1542/C1542M, "Standard Test Method for Measuring Length of Concrete Cores."

Joint ACI-ASCC Committee 117, Tolerances, is updating its tolerance specification and has created a new subcommittee on measurement protocols. While ACI 117-10(15), Section 4.5.4.3,[2] provides tolerances for core test and IE thickness measurements, other NDT methods are used to determine slab thickness. With the goal of assisting in the determination of appropriate tolerances for additional NDT methods, the slab thickness data reported herein was presented to the main Joint ACI-ASCC Committee 117 at the ACI Concrete Convention in Orlando, FL, USA, in March 2022.

Cores Going, Going, Almost Gone

For this study, the costs for extracting a core and transporting it to the testing agency were about \$100 and \$10, respectively; the costs for measuring a core in accordance with ASTM C174/C174M and ASTM C1542/C1542M were about \$100 and \$75, respectively; and the material and labor costs of filling a core hole totaled about \$50. Thus, the cost of a thickness evaluation ranged from \$235 to \$260 per core sample. ACI 117-10(15), Section 4.5.4.1, requires slab thickness evaluation using four cores per 5000 ft^2, so the cost of a thickness evaluation would total about \$1000 per 5000 ft^2 of slab area.

As of 2018,[3] approximately half of the departments of transportation in the United States have tested magnetic pulse induction (T2) devices for nondestructive pavement thickness measurements. We understand that the cost of a T2 measurement—including the metal target that must be placed

Table 1:
Slab-on-ground thickness values meeting ACI tolerances

Specified slab thickness, in.	Average of all samples		Individual sample	
	Allowed value, in.	Reduction in specified thickness, %	Allowed value, in.	Reduction in specified thickness, %
4	3-5/8	9.4	3-1/4	18.8
5	4-5/8	7.5	4-1/4	15.0
6	5-5/8	6.3	5-1/4	12.5
7	6-5/8	5.4	6-1/4	10.7
8	7-5/8	4.7	7-1/4	9.4
9	8-5/8	4.2	8-1/4	8.3
10	9-5/8	3.8	9-1/4	7.5
11	10-5/8	3.4	10-1/4	6.8
12	11-5/8	3.1	11-1/4	6.3

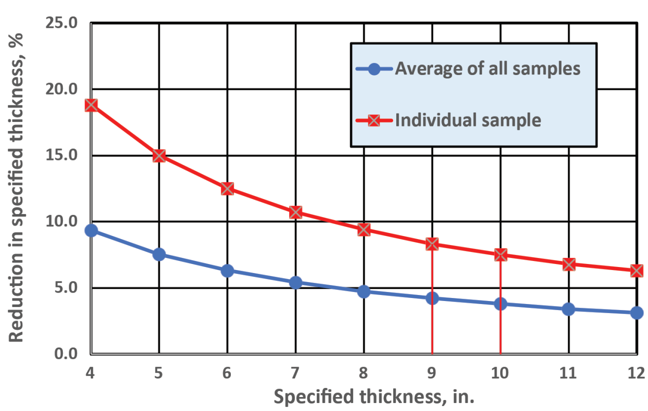

Fig. 1: Percent reduction in specified thickness for ACI 117-10(15)[2] tolerances. Because average and individual thickness tolerances are constant—that is, independent of slab thickness—they have a greater effect on thinner slabs than thicker slabs

on the pavement base—is less than $20. While ACI-ASCC Committee 117 has yet to consider this NDT approach (and we did not include it in this study), the low unit cost of the T2 test and its utility for rapid, damage-free inspection indicate that this NDT method may eventually replace coring for thickness evaluations of road pavements. Because the NDT methods considered in this study have similar advantages, they can also be expected to gain acceptance for thickness evaluation of slab-on-ground construction.

Thickness Tolerances

The 2021 IBC,[4] Section 1907, Minimum Slab Provisions, requires the thickness of concrete floor slabs supported directly on the ground to be no less than 3-1/2 in. This provision generally results in a minimum specified thickness of 4 in. for a slab-on-ground.

ACI 117-10(15), Section 4.5.4.3, allows for cores and core measurements in accordance with ASTM C174/C174M, as well as IE measurements, provided the device is calibrated "using a minimum of three random locations within the test area where the concrete thickness is known." While not in the specification, ACI 117-10(15), Commentary Section R4.5.4.3, addresses the use of GPR for measuring slab thickness. The commentary recommends a larger number of thickness data to be taken due to the precision of the method, providing the same degree of reliability as other methods allowed by the standard. It also recommends the use, calibration, and data collection to be in accordance with ASTM D4748, "Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar." ACI 117-10(15) does not provide recommendations on the use of laser scanning technology to evaluate slab thickness.

ACI 117-10(15), Section 4.5.4, provides slab-on-ground thickness tolerances of 3/8 in. below the specified thickness (for the average thickness of all samples) and 3/4 in. below the specified thickness (for individual samples). These tolerances are independent of slab thickness. While this follows the reasonable expectation that the construction processes for the base and the concrete surface are independent of slab thickness, it must be noted that the relative effects are not independent of slab thickness (refer to Table 1 and Fig. 1).

Fortunately, the precision of ASTM C174/C174M and C1542/C1542M are independent of slab thickness. ASTM C174/C174M and C1542/C1542M report measurement precision based on slab thickness varying from 4 to 12 in. and from 2.5 to 4.6 in., respectively, for both the jaw caliper and ruler procedures.

An interesting conundrum arises when the accuracy of NDT slab thickness measurements is not independent, but rather dependent on slab thickness. The accuracy of laser scan thickness data is likely independent of slab thickness, while the accuracy of IE and GPR are dependent on slab thickness. This is discussed later in the article.

Slab Thickness Measurement Techniques

The four methods used in this study to measure slab thickness include: laser scanning (Fig. 2), GPR (Fig. 3), IE (Fig. 4), and coring (Fig. 5). Brief descriptions of the four methods and equipment follows.

Laser scanning

A laser scanner emits a beam of infrared laser light onto a rotating mirror that paints the surrounding environment with light. The scanner head rotates, sweeping the laser across the object. Objects in the path of the laser reflect the beam back to

Fig. 2: A laser is used to scan the top concrete surface elevations. Previously, a laser was used to scan elevations of the compacted aggregate base substrate. Slab thickness was calculated as the difference between the two scans

Fig. 3: GPR was used to obtain slab thickness at different locations on the concrete surface

the scanner, providing the geometry that is interpreted as three-dimensional (3-D) data points. These millions of 3-D data points are known as point clouds. Point clouds are typically processed to provide a colored, interval-scaled elevation contour map, commonly called a "heat map."

Equipment used: Leica P40 3D laser scanner, Leica GZT21 4.5 in. black/white targets.

GPR

The procedure to determine the thickness of concrete slabs is described in ASTM D4748. The GPR system transmits and receives electromagnetic signals by means of an antenna. As the electromagnetic wave propagates through the slab layers, it is refracted and reflected at layer interfaces and received by the antenna. The received signal is recorded by the GPR system in terms of amplitude and two-way travel time. Layer thickness can be determined if the velocity and the two-way travel time for the radar wave to travel through a given layer are known. The relative dielectric constant or the radar wave velocity of a layer can be obtained by metal plate calibration, ground truth cores at locations where the GPR data were collected, or the common midpoint (CMP) method.

Equipment used: Geophysical Survey Systems, Inc. (GSSI) StructureScan Mini XT.

Fig. 4: IE was used to obtain slab thickness at various locations on the concrete surface. As needed, the surface was ground smooth to ensure solid contact with the transducer

IE

The procedures to determine the thickness of concrete slabs are described in ASTM C1383, "Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method." The standard requires Procedure A—measurement of the P-wave speed, and Procedure B—IE test at each point where thickness is determined. Procedure A measures the time for the P-wave generated by a short-duration, point impact to travel between

Fig. 5: Two core drilling machines were used to extract the nominal 4 in. diameter cores that were then measured for thickness

two transducers positioned a known distance apart along the slab surface. The P-wave speed is calculated by dividing the distance between the two transducers by the travel time. Procedure B measures the frequency of the P-wave generated by a short-duration, point impact reflected between the parallel (opposite) slab surfaces. The thickness is calculated from this measured frequency and the P-wave speed obtained from Procedure A.

Equipment used: Olson Instruments Concrete Thickness Gauge (CTG).

Coring

The procedures for obtaining cores to determine slab thickness are described in ASTM C42/C42M. The cores must have a minimum diameter of at least 3.70 in. when measured in accordance with ASTM C174/C174M. ACI 117-10(15), Section 4.5.4.3.1, requires cores used for slab thickness to be measured in accordance with this standard.

Equipment used: two core drilling rigs with water and vacuum attachments and a nominal 4 in. diamond core barrel.

Calibration to Concrete Properties

GPR

The GPR device measures the elapsed time between the antenna sending out the radar pulse and then receiving the reflection from the bottom of the concrete slab. The slab thickness is calculated using this travel time along with the dielectric constant. The dielectric constant decreases with the moisture content of the concrete. It might be as high as 14 during the concrete's initial month, reducing to about 8 after 4 to 5 months and approaching 6 after a year of drying.

Unlike ASTM C1383, which does not require the wave speed to be calibrated with the concrete, ASTM D4748 requires the dielectric constant to be calibrated with the concrete in one of three ways: metal plate calibration; ground truth cores at locations where GPR data was collected; or common midpoint (CMP) method. The ground truth core method is considered the most accurate.

IE

The IE measures the time required for an echo to bounce off the bottom of the concrete slab. The slab thickness is calculated by using this travel time along with the speed of sound in the concrete. The speed of sound in concrete varies from about 10,000 to 16,000 ft/s depending on the mixture design, aggregate types, and age of the concrete. As the concrete ages and gets stronger, the velocity increases. Thus, the velocity in the concrete is time-dependent, especially for the first month. Lower-strength mixtures typically have lower velocities and high-strength mixtures have higher velocities. The device's default velocity is 12,000 ft/s.

Although ASTM C1383 does not require the wave speed to be calibrated, ACI 117-10(15), Section 4.5.4.3.2, requires the wave speed to be calibrated "using a minimum of three random locations with the test area where the actual concrete thickness is known." The manufacturer of the instrument used in our study indicates that using the default velocity should provide a thickness within 10% or less of the actual value. They also state that calibration of the concrete velocity at any location where the user knows the actual concrete thickness improves the accuracy to approximately 2%. The user's manual indicates that calibration can occur with cores or at slab edges.

Calibration with Cores

Originally, we did not intend to include the measurement of cores in our study. Thus, slab edge calibration was the only option for calibration of the GPR and IE devices. The dielectric constant and wave speed were calibrated at three slab edges where the thickness was measured using a tape measure. The manufacturer of the IE device recommended holding the device back 6 to 12 in. from a slab edge to avoid edge reflection frequencies during calibration. We chose to hold the IE device 6 in. from the slab edge during calibration.

The manufacturer of the GPR provided no cautions regarding calibration near a slab edge, so we held the GPR at the slab edge during calibration.

Cores were taken at measured IE and GPR locations; thus, calibration was determined with cores once they were measured. Tables 2(a) and (b) provide the calibration of wave speed and dielectric constant for three sets of three cores (chosen randomly) and at three slab edges, respectively:

- Cores—The average wave speed of the three sets of cores was 13,995, 14,018, and 13,744 ft/s, with a range between

Table 2(a):
Calibration of IE wave speed and GPR dielectric constant with cores

Core	No.	30	12	20	23	6	16	18	22	2
	Length, in.	5.67	6.69	5.51	5.71	5.97	5.78	5.78	5.95	6.10
IE wave speed, ft/s		13,882	14,360	13,742	14,276	14,034	13,743	13,743	13,810	13,679
Average		13,995			14,018			13,744		
GPR dielectric constant		8.20	8.57	8.27	8.67	8.53	8.50	8.40	8.70	8.45
Average		8.35			8.57			8.52		

Table 2(b):
Calibration of IE wave speed and GPR dielectric constant with slab edges

Slab edge	No.	1	2	3
	Length, in.	5.875	5.438	5.875
IE wave speed, ft/s		14,082	14,122	13,909
Average		14,038		
GPR dielectric constant		8.30	9.67	8.14
Average		8.70		

the three sets of 274 ft/s. The average dielectric constant of the three sets of cores was 8.35, 8.57, and 8.52, with a range between the three sets of 0.22. The choice of any three cores does not appear to make a significant difference in the wave speed or dielectric constant calibration (Table 2(a)); and

- Slab edges—The average wave speed and dielectric constant at three slab edges were 14,038 ft/s and 8.70, respectively (Table 2(b)).

Based on this study, calibration with either cores or slab edges is an acceptable procedure. As Fig. 6 shows,[3] from GPR data, the calibration locations—cores or slab edges—might not be as important as the quantity of reference measurements. Fortunately, ACI 117-10(15), Section 4.5.4.3.2, requires calibration at three locations, which would indicate the accuracy of the average NDT measurements to be within 5% of the core measurements.

Measurement Methodology and Data

Measurement locations were laid out using chalk lines and spray-painted onto the concrete slab surface at 7 or 8 ft spacing along the long axis, and at 8 ft spacing along the short axis, with a minimum 2 ft clearance from slab edges. Figure 7 shows the 30 test locations where cores were taken, while Table 3 provides individual slab thickness measurements. Table 4 provides a summary of slab thickness measurements at an additional 45 locations. Cores were not taken at these locations; however, GPR measurements were repeated twice and IE measurements were repeated three times, all on different days.

GPR

The dielectric constant determined during calibration was input into the equipment before obtaining a GPR scan at each core location. For each measurement, first, the center of the GPR scanner was located on the layout chalk line 1 ft away from the measurement location, and the scanner survey wheel was rolled, passing the measurement location by 1 ft. Then, it was rolled back so that the backup cursor aligned with the measurement location to obtain the signal. The onboard software then displayed depth scale, position, hyperbola, and black band. Next, the crosshair line to the top of the black band on the touch screen was located, and the depth reading

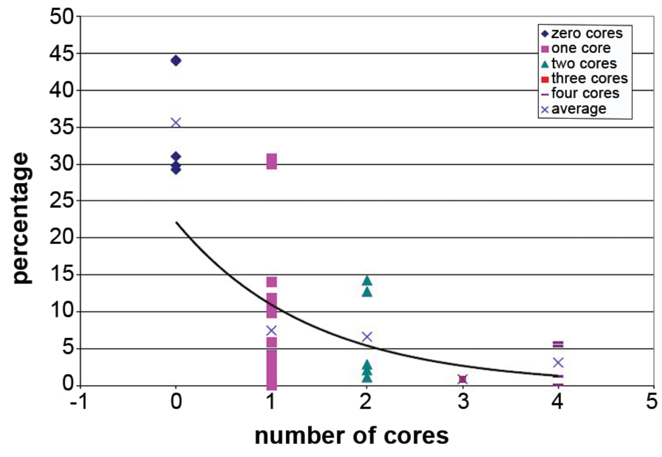

Fig. 6: The accuracy of GPR to the core measurements improves as the number of cores used for calibration increases.[3] ACI 117-10(15), Section 4.5.4.3.2, indicates that three locations must be used to calibrate for IE but is silent on GPR calibration. Based on our data, the calibration with three cores keeps the accuracy of the GPR to core data within 5%

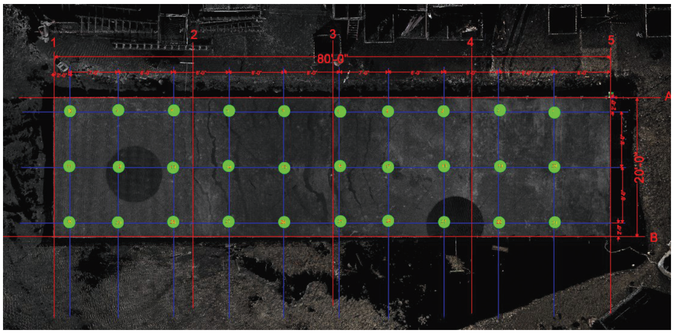

Fig. 7: Slab thickness was evaluated by laser scanning, IE, GPR, and cores at 30 measurement locations in the 1600 ft² slab

was saved. Two tests were taken at each core location to verify repeatability.

IE

Once the instrument was calibrated, for each measurement, the IE head was positioned over a measurement location and the trigger button was pressed to create an impact. The displacement transducer sensor recorded the echo and the software displayed thickness, frequency spectrum, and time domain signal. The waveform signal in the time domain plot (between 0.1 and 0.8 V) was evaluated as well as the presence of a prominent peak in the frequency spectrum. The acceptable data with the measured thickness was saved. Two tests were taken at each core location to verify repeatability.

Because of the rough textured swirl surface, a handheld cordless grinder was used on some of the 30 test locations to achieve good contact.

Laser scanning

An initial laser scan was performed after the aggregate base had been compacted and prior to reinforcement

Table 3:
Thickness measurements at 30 core locations

Sample No.	Measurement method			
	Laser scanning, in.	GPR, in.	IE, in.	Core, in.
1	5.45	5.81	5.73	5.55
2	6.05	6.19	6.08	5.90
3	5.33	6.04	5.45	5.60
4	5.47	6.12	5.66	6.00
5	5.91	6.13	5.89	5.75
6	5.73	5.64	5.82	6.00
7	5.56	5.60	5.68	5.95
8	6.16	6.50	6.29	6.55
9	6.03	6.21	6.08	6.30
10	6.17	6.56	6.10	6.40
11	6.09	6.23	6.06	6.40
12	6.52	6.30	6.22	6.65
13	6.19	6.48	6.01	6.40
14	5.52	6.12	5.56	5.80
15	5.68	6.17	5.65	6.00
16	5.74	6.27	5.65	5.75
17	5.99	6.13	5.93	6.25
18	5.65	6.13	5.65	5.85
19	6.04	6.25	6.01	6.25
20	5.49	6.10	5.53	5.55
21	6.42	6.23	6.53	6.70
22	5.81	6.35	5.97	5.90
23	5.58	6.12	5.56	5.70
24	6.32	6.08	6.33	6.55
25	6.29	6.15	6.31	6.55
26	5.56	6.06	5.56	5.75
27	6.20	6.31	6.14	6.40
28	6.23	6.04	6.01	6.55
29	6.10	6.27	6.12	6.30
30	5.52	6.10	5.58	5.85
Mean	5.89	6.16	5.91	6.11
Standard deviation	0.33	0.21	0.29	0.36
Coefficient of variation	5.60%	3.41%	4.91%	5.84%
Maximum	6.52	6.56	6.53	6.70
Minimum	5.33	5.60	5.45	5.55
Range	1.19	0.96	1.08	1.15

placement to obtain base elevations. A second laser scan was performed the day after slab-on-ground concrete placement to obtain the concrete surface elevations. Four targets were used on both scans to locate the bottom and top scans in space (registration). Slab thickness was calculated by subtracting base elevation from the top slab surface elevation.

Coring

Waterproof layout marks for each core location were provided on the top of the concrete slab for the drilling crew. Cores were drilled, dried, numbered, tagged, photographed, bagged, and boxed for pickup and transportation to the testing agencies for measurement.

Figure 8 illustrates the thickness data for each of the 30 locations provided in Table 3. While the average thicknesses for each NDT method are reasonably close, thicknesses determined from the cores are generally greater than the thicknesses by laser scanning or IE. Figure 9 shows the difference between the NDT thickness measurements and the core thickness for each core location. The most important part of this graph shows the variations between the individual NDT measurements and the core measurements (in accordance with ASTM C174/C174M) range to about ±1/2 in.

Accuracy of Average Thickness Measurements

Drilled cores obtained in accordance with ASTM C42/C42M and measured in accordance with ASTM C174/C174M are considered the reference standard for this slab-on-ground thickness study. The NDT thickness measurements are compared to cores to determine their accuracy. There is no literature on the accuracy of laser scanning for thickness, but ASTM D4748 and ASTM C1383 provide information on the accuracy of GPR and IE, respectively. Based on five studies,[5-9] ASTM D4748 states the accuracy to be 15% or less. Based on one study by Sansalone and Streett,[10] ASTM C1383 states the accuracy between cores and IE as ±3% for slab thicknesses varying from about 7.5 to 11.5 in.

The user's manual provided by the GPR manufacturer recommends calibration by ground truth but does not provide information on accuracy for slab thickness. The user's manual provided by the IE manufacturer indicates the accuracy between their instrument readings and core measurements to be ±10% if the device was not calibrated with each concrete placement and ±2% if the device was calibrated. The manual recommends IE calibration from cores or at slab edges or openings of known thickness.

Table 5 summarizes the accuracy information from the manufacturer, ASTM standards, and this study. An important qualification about the accuracy of this study: it represents the accuracy of the average of 30 measurements compared to the average of 30 core measurements in accordance with ASTM C174/C174M. The comparison of the measured thickness to each individual core length is a separate issue.

The data in Table 5 show the accuracy of the three NDT measurement techniques as +0.8% for GPR, −3.3% for IE, and −3.6% for laser scanning. A t-test at the 95% confidence level indicates that the three average values are considered the same.

Accuracy of Individual Thickness Measurements

While the accuracy of the average measured values is important, so is the accuracy of the individual measurements, as ACI 117-10(15) provides a tolerance on each. Using the ASTM C174/C174M core measurements as the reference, Table 6 and Fig. 9 show the differences in NDT measurements from the reference core length. One problem that stands out is that the maximum differences between the individual NDT and core measurements are about 1/2 in. shorter. This −1/2 in. could be an especially important factor in deciding if, or what, remediation needs to occur. For a 6 in. thick slab, the maximum difference represents about 9% of the slab thickness.

Table 4:
Summary of thickness measurements at 45 locations

Measurements	Laser scanning	GPR		IE		
		1	2	1	2	3
Total	45	45	45	45	45	45
Mean, in.	5.93	6.14	6.18	5.93	6.06	5.90
Standard deviation, in.	0.44	0.20	0.14	0.48	0.46	0.45
Coefficient of variation, %	7.39	3.23	2.29	8.02	7.65	7.64
Maximum, in.	7.11	7.36	6.44	6.96	7.22	6.96
Minimum, in.	5.20	6.01	5.90	4.81	4.95	4.81
Range, in.	1.91	1.35	0.54	2.15	2.27	2.15

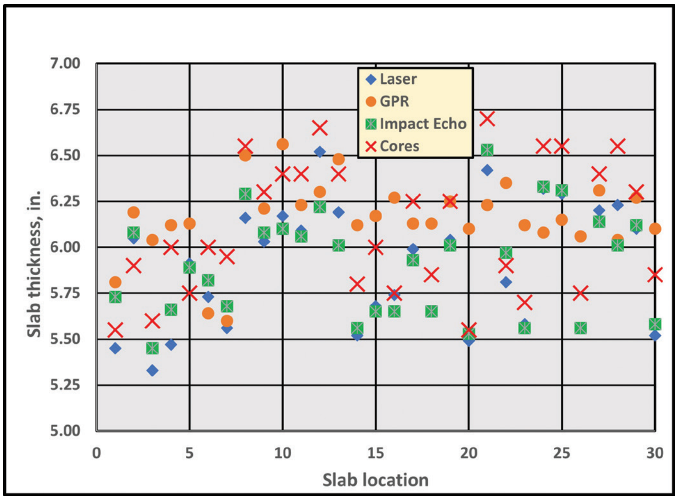

Fig. 8: Individual thickness measurements provided by laser scanning, GPR, IE, and drilled cores measured in accordance with ASTM C174/C174M. The averages of the 30 measurements were 5.89 in. for laser scanning, 6.16 in. for GPR, 5.91 in. for IE, and 6.11 in. for drilled cores

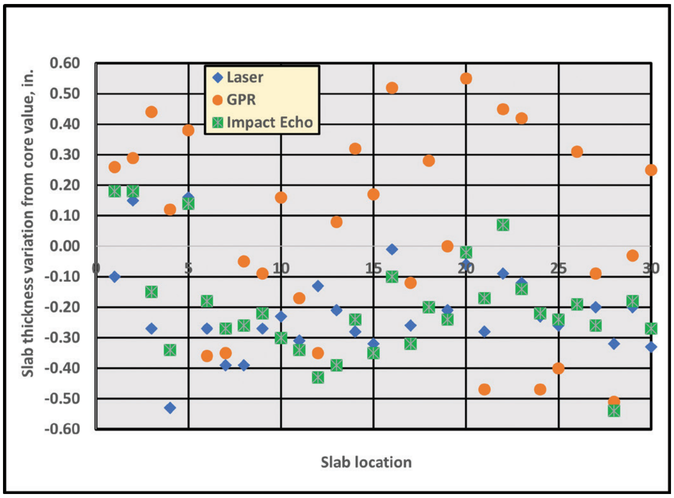

Fig. 9: Slab-on-ground thickness variation. Note that the differences range up to ±1/2 in. The average difference between laser and core measurements was –0.21 in., between GPR and core measurements was 0.05 in., and between IE and core measurements was –0.20 in.

Table 5:
Accuracy of thickness measurement method for 6 in. thick slab

Measurement method	Manufacturer 6 in. nominal	ASTM D4748 and C1383	ASTM C174/C174M based on 6.11 in.
GPR	—	±0.90 in. or less	+0.05 in. (+0.8%)
IE	±0.60 in. (no calibration) ±0.12 in. (calibrated)	±0.18 in.	−0.20 in. (−3.3%)
Laser scanning	NA	NA	−0.21 in. (−3.6%)

This could mean that for a 12 in. thick slab, the individual NDT measured value is about 1 in. below the core value.

For one standard deviation, the differences between the NDT and core measured values are 0.15 in. for laser scanning, 0.33 in. for GPR, and 0.17 in. for IE (Table 6). This difference raises three questions:

- Should individual NDT measurements be used as a tolerance?
- If they are used, should the tolerance be adjusted to account for the difference in measurement?
- What reduction in slab thickness is necessary for a tolerance based on a single NDT measurement?

Table 6:
Measurement variations for each core

Sample No.	Laser scanning – core, in.	GPR – core, in.	IE – core, in.
1	−0.10	0.26	0.18
2	0.15	0.29	0.18
3	−0.27	0.44	−0.15
4	−0.53	0.12	−0.34
5	0.16	0.38	0.14
6	−0.27	−0.36	−0.18
7	−0.39	−0.35	−0.27
8	−0.39	−0.05	−0.26
9	−0.27	−0.09	−0.22
10	−0.23	0.16	−0.30
11	−0.31	−0.17	−0.34
12	−0.13	−0.35	−0.43
13	−0.21	0.08	−0.39
14	−0.28	0.32	−0.24
15	−0.32	0.17	−0.35
16	−0.01	0.52	−0.10
17	−0.26	−0.12	−0.32
18	−0.20	0.28	−0.20
19	−0.21	0.00	−0.24
20	−0.06	0.55	−0.02
21	−0.28	−0.47	−0.17
22	−0.09	0.45	0.07
23	−0.12	0.42	−0.14
24	−0.23	−0.47	−0.22
25	−0.26	−0.40	−0.24
26	−0.19	0.31	−0.19
27	−0.20	−0.09	−0.26
28	−0.32	−0.51	−0.54
29	−0.20	−0.03	−0.18
30	−0.33	0.25	−0.27
Mean	-0.212	0.051	−0.200
Standard deviation	0.15	0.33	0.17
Maximum	0.16	0.55	0.18
Minimum	−0.53	−0.51	−0.54
Range	0.69	1.06	0.72

NDT Thickness Measurement Repeatability

Table 4 provides the measurement data for two GPR scans by two different operators and three IE trials by two different operators. This data was taken on different days, with the concrete calibration occurring each day. The averages of the two GPR scans are close (6.14 and 6.18 in.), as are the standard deviations (0.20 and 0.14 in.). The individual GPR measurements, however, are not. GPR 1 found the maximum thickness of 7.36 in., almost 1 in. higher than the maximum of 6.44 in. in the second scan. The average difference between individual measurements of GPR 1 and 2 was 0.16 in., just over 1/8 in., with the maximum difference of 1.36 in. and the minimum difference of 0.02 in. The equipment manufacturer reports the precision of the GPR as 0.02 in. That statement is difficult to reconcile with the data for this study.

The average of the three IE tests was 5.93, 6.06, and 5.90 in., which is reasonably close. The average difference of individual IE measurements was 0.20 in., about 1/4 in., with the maximum difference of 0.48 in. and the minimum difference of 0.07 in.

It is interesting that the GPR scans provided greater thickness than the IE trials, and the GPR scans measured the thickness range as 1.35 and 0.54 in., while the IE trials measured the thickness range as 2.15, 2.27, and 2.15 in. It is unclear whether this is the result of a systematic bias. What is clear is that while the average of the 45 measurements for GPR and IE are reasonably close, the individual measurements between repeated GPR or IE, or between GPR and IE, can be an issue when applying individual thickness tolerances.

Core Measurement Methods

ACI 117-10(15) allows for core measurements in accordance with ASTM C174/C174M only, but cores can also be measured per ASTM C1542/C1542M. ASTM C1542/C1542M provides two core measurement procedures: jaw caliper and ruler.

ASTM C174/C174M states that it's a method to determine the slab thickness using drilled cores for compliance of concrete construction with design specifications. ASTM C1542/C1542M states this test method to determine length should be used in conjunction with condition surveys, density, and void analysis, as well as other applications. These two standards create confusion, and in addition, some test agencies can only measure cores one way but not the other, though some do both. The measurement precision is different for both standards. A brief description of each measurement procedure is provided:

- ASTM C174/C174M requires that at least one end of the core be a finished or formed surface. A core is placed in the measuring apparatus (finished or formed surface down) where nine measurements, equally spaced at intervals around the core, are taken from the bottom of the top plate to the top of the core. The nine measurements are averaged and reported as the core length to the nearest 0.05 in.;
- ASTM C1542/C1542M jaw caliper measurements are made by placing the open jaws of the caliper midpoint between the center and edge of the core, and measurements are taken at four locations (0, 90, 180, and 270 degrees) to the nearest 0.01 in. In addition, one measurement is obtained along the axis of the specimen, averaged with the other four measurements, and then reported as the core length to the nearest 0.05 in.; and
- ASTM C1542/C1542M ruler measurements are made by placing the core with the finished or formed surface down against a flat and level surface, then placing the ruler against the side of the core and measuring at four locations (0, 90, 180, and 270 degrees) to the nearest 0.05 in. The average of the four measurements are reported as the core length to the nearest 0.05 in.

Single-operator precision comparison

ASTM C174/C174M—Single-operator and multilaboratory precision indexes are based on the results of an interlaboratory study conducted by the NCHRP (2010).[11] Cores, representative of different concrete pavement test sections, either 4 or 6 in. in nominal diameter, with lengths ranging from 4 to 12 in., were used for the study. The single-operator standard deviation was found to be 0.02 and 0.03 in. for 4 and 6 in. core diameters, respectively.

ASTM C1542/C1542M—Single-operator and between-laboratory precision of the jaw caliper and ruler procedures was estimated from the results of an interlaboratory study that included 12 laboratories, each measuring a core three times from each of three concretes. The length of the cores ranged from 2.5 to 4.6 in. The single-operator coefficient of variation for the jaw caliper procedure was found to be 1.02%. The single-operator coefficient of variation for the ruler procedure was found to be 1.94%. These coefficients of variation are based on the mean length of the core.

Comparison—This study used nominal 4 in. diameter cores of a nominal 6 in. thick slab. Based on the precision statements in both ASTM standards, the measurement precision for C174/C174M was 0.02 in., for C1542/C1542M jaw caliper was 0.06 in., and for C1542/C1542M ruler was 0.12 in. (Table 7). The coefficients of variation for C1542/C1542M were converted to standard deviations based on a mean core length of 6 in.

Table 7:
Comparison of core measurement precision from ASTM standards

ASTM standard	Precision, in.		Difference, in.	
	1 standard deviation (68%)	2 standard deviations (95%)	1 standard deviation	2 standard deviations
C174/C174M	0.02	0.04	NA	NA
C1542/C1542M jaw caliper	0.06	0.12	2 × C174	3 × C174
C1542/C1542M ruler	0.12	0.23	3 × C174	6 × C174

Fig. 10: A view of the irregular bottom surfaces of Cores 2 and 8. The range of nine measurements on these two cores were the highest, with Core 2 at 0.25 in. and Core 8 at 0.375 in. This range indicates the measuring issue for concrete cores removed from an open-graded aggregate base

Cores with Base Material

This thickness study was for a concrete slab-on-ground placed over a compacted aggregate base course. Thus, there is the potential for base course particles to adhere to the bottom of the core. The intent of both ASTM C174/C174M and C1542/C1542M is not to include any adhered base particles in the length measurement. ASTM C174/C174M requires the adhered particles to be removed to expose the concrete. A core, however, shall not be used for length measurement if the concrete is broken during the removal of the particle such that the measurements are not representative of the original core length. ASTM C174/C174M also allows the measuring points to be adjusted slightly because of a small projection or depression.

ASTM C1542/C1542M states that material bonded to the concrete core shall not be included in the measurements. The ruler procedure requires the measurement from the end of the core to the interface of the concrete with any adhering material. While the intent of C1542/C1542M is not to include adhered particles in the length measurement, the jaw caliper procedure is silent on the issue.

Figure 10 shows the bottom of two cores for this study. The test agency provided length measurements for all three cores; however, as the photos indicate, some measurements may be subjective.

Core Measurement Data

Table 8 provides the 30 core thickness measurements reported by the testing agencies for ASTM C174/C174M and ASTM C1542/C1542M jaw caliper and ruler procedures. The table also provides the differences between C174/C174M (the measurement procedure currently required by ACI 117-10(15)) and C1542/C1542M procedures.

Accuracy of average measurements

The average length of the 30 cores measured in accordance with ASTM C174/C174M was 6.11 in., while the average length of the 30 cores was 6.03 in. for both the ASTM C1542/C1542M jaw caliper and ruler procedures. Considering C174/C174M as a reference, the jaw caliper and ruler procedures were within −1.31% of the reference. A t-test at the 95% confidence level indicates that the average C1542/C1542M measurements are considered the same as the average C174/C174M measurements.

Accuracy of individual measurements

The maximum negative difference between individual ASTM C1542/C1542M and ASTM C174/C174M measurements was −0.26 in. for the jaw caliper and −0.24 in. for the ruler procedures, respectively. The standard deviation of the difference was 0.13 in. for C1542/C1542M procedures.

Adjustments to ACI 117 Tolerances for NDT Measurements

Joint ACI-ASCC Subcommittee 117-0P, Measurements, has been tasked with determining what NDT measurements might be appropriate for specified tolerances and what, if any, adjustments to the tolerances are necessary when using NDT equipment.

Table 8:
Core thickness measurements for 30 cores per ASTM C174/C174M and ASTM C1542/C1542M

Sample No.	ASTM C174/C174M, in.	ASTM C1542/C1542M, in.		ASTM C174/C174M, in.	
		Caliper	Ruler	− Caliper	− Ruler
1	5.55	5.49	5.52	−0.06	−0.03
2	5.90	6.13	6.07	+0.23	+0.17
3	5.60	5.43	5.42	−0.17	−0.18
4	6.00	5.74	5.75	−0.26	−0.25
5	5.75	6.13	6.13	+0.38	+0.38
6	6.00	5.95	5.99	-0.05	−0.01
7	5.95	5.76	5.73	−0.19	−0.22
8	6.55	6.48	6.50	−0.07	−0.05
9	6.30	6.19	6.20	−0.11	−0.10
10	6.40	6.26	6.31	−0.14	−0.09
11	6.40	6.19	6.19	−0.21	−0.21
12	6.65	6.69	6.67	+0.04	+0.02
13	6.40	6.34	6.30	−0.06	−0.10
14	5.80	5.62	5.62	−0.18	−0.18
15	6.00	5.85	5.85	−0.15	−0.15
16	5.75	5.77	5.78	+0.02	+0.03
17	6.25	6.11	6.12	−0.14	−0.13
18	5.85	5.77	5.79	−0.08	−0.06
19	6.25	6.19	6.19	−0.06	−0.06
20	5.55	5.50	5.50	−0.05	−0.05
21	6.70	6.58	6.54	−0.12	−0.16
22	5.90	5.94	5.94	+0.04	+0.04
23	5.70	5.70	5.69	0.00	−0.01
24	6.55	6.45	6.41	−0.10	−0.14
25	6.55	6.55	6.55	0.00	0.00
26	5.75	5.62	5.62	−0.13	−0.13
27	6.40	6.34	6.33	-0.06	−0.07
28	6.55	6.35	6.34	−0.20	−0.21
29	6.30	6.24	6.24	−0.06	−0.06
30	5.85	5.67	5.68	−0.18	−0.17
Mean	6.11	6.03	6.03	−0.07	−0.07
Standard deviation	0.36	0.36	0.35	0.13	0.13
Coefficient of variation, %	5.84	5.94	5.84	NA	NA
Maximum	6.70	6.69	6.67	0.38	0.38
Minimum	5.55	5.43	5.42	−0.26	−0.24
Range	1.15	1.25	1.25	0.64	0.63

Table 9:
Comparison of slab-on-ground thickness tolerances based on cores and NDT methods

Specified slab thickness, in.	Tolerance on average				Tolerance on individual			
	ACI 117-10(15)		NDT (5%)		ACI 117-10(15)		NDT (0.25 in.)	
	in.	%	in.	%	in.	%	in.	%
4	3-5/8	10.3	3-1/2	13.9	3-1/4	23.1	2-7/8	34.4
5	4-5/8	8.1	4-3/8	12.1	4-1/4	17.6	3-3/4	27.5
6	5-5/8	6.7	5-3/8	10.9	5-1/4	14.3	4-3/4	22.9
7	6-5/8	5.7	6-1/4	10.1	6-1/4	12.0	5-5/8	19.6
8	7-5/8	4.9	7-1/4	9.5	7-1/4	10.3	6-5/8	17.2
9	8-5/8	4.3	8-1/4	9.0	8-1/4	9.1	7-5/8	15.3
10	9-5/8	3.9	9-1/8	8.6	9-1/4	8.1	8-1/2	13.8
11	10-5/8	3.5	10-1/8	8.2	10-1/4	7.3	9-1/2	12.5
12	11-5/8	3.2	11.0	8.0	11-1/4	6.7	10-3/8	11.5

This will not be an easy task. With the recognition that further studies are needed, we present our recommendations for these tolerances in the following discussion.

Average NDT measurements

The accuracy of the average NDT to the ASTM C174/C174M core measurements for this study was +0.8% for GPR, −3.3% for IE, and −3.6% for laser scanning. If NDT equipment and procedures are used to measure tolerance compliance, we believe they should have a proven accuracy to within ±5% of average C174/C174M core measurements. If the NDT measurement falsely overestimates the slab thickness, as opposed to core measurements, no action is taken. If, however, the NDT measurement underestimates the slab thickness, then remediation or removal and replacement may unnecessarily be considered. To alleviate this liability imposed by the NDT measurement method, we propose that a 5% reduction in the average tolerance be considered. However, this 5% should not be based on the 3/8 in. ACI 117-10(15) average tolerance but based on the slab thickness. If it is 5% of 3/8 in., that is only 0.02 in. and would not need to be considered as an adjustment. However, if it is 5% of a 6 in. thick slab, which is 0.3 in., it should be added to the 3/8 tolerance to provide an NDT average tolerance at 6 in. of 0.675 in. (0.30 in. + 3/8 in.). The result of that approach is shown in Table 9 and graphically in Fig. 11.

The reduction in slab thickness for a 4 in. thick slab due to the proposed average NDT tolerance is 13.9%, an increase from the 10.3% for the ACI 117-10(15) tolerance. The resulting change in the average tolerance is small, 1/8 in., from 3-5/8 to 3-1/2 in. The reduction in slab thickness for a 12 in. thick slab due to the proposed average NDT tolerance is 8%, an increase from the 3.2% for the ACI 117-10(15) tolerance. The resulting change in the average tolerance for the 12 in. slab changes from 11-5/8 to 11 in. While the proposed 11 in. average tolerance for the 12 in. slab may appear large, the construction hasn't changed. What changed, and needs to be accounted for, is the accuracy of the NDT measuring device.

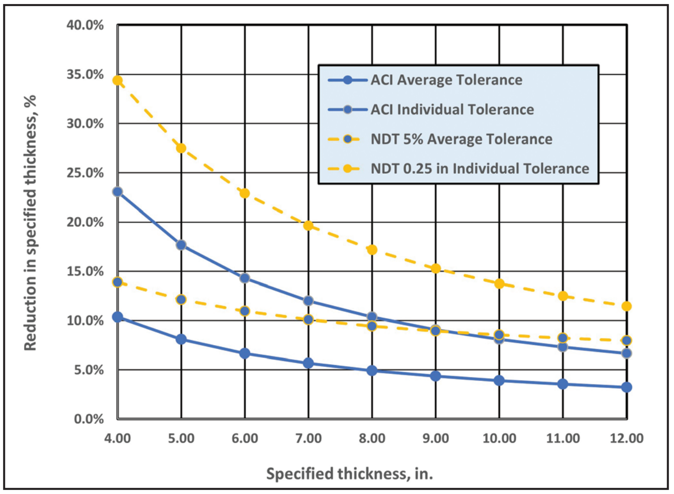

Fig. 11: Percent reduction in specified thickness for tolerances. Accounting for average NDT measurements that are within −5% of the average core measurements and individual NDT measurements that are within −0.25 in. of core measurements reduces the specified thickness

Individual NDT measurement

ACI 117-10(15) requires an individual thickness value to be no more than −3/4 in. of the specified thickness; or, looking at it another way, because the average value is constant, at no more than −3/8 in. below the average tolerance value. If the proposed average thickness value for NDT testing of a 12 in. thick slab is 11 in., it doesn't make sense to have the individual thickness value at −3/4 in. below the specified 12 in. thickness, at 11-1/4 in., which is greater than the proposed NDT average thickness.

Thus, we used the −3/8 in. below the average tolerance value and added an adjustment of 1/4 in. (a total of 5/8 in.) to account for underestimating the thickness using an individual NDT measured slab thickness. As stated previously, the maximum negative difference between the individual NDT and core measurements was about 1/2 in. Therefore, the 0.25 in. adjustment only accounts for part of the difference. Table 9 shows that for a 4 in. thick slab, the minimum measured value of 3-1/4 in. using ASTM C174/C174M measured core thickness to be 2-7/8 in. using NDT measured slab thickness. The minimum thickness for a 12 in. slab would change from 11-1/4 in. using C174/C174M measured core thickness to 10-3/8 in. using NDT measured slab thickness.

The percent reduction in slab thickness with the proposed individual NDT tolerance changes from 23.1 to 34.4% for a 4 in. thick slab and from 6.7 to 11.5% for a 12 in. thick slab.

Average ASTM C1542/C1542M core measurements

As previously stated, considering ASTM C174/C174M as a reference, the jaw caliper and ruler procedures were within −1.31% of the reference. Based on this study, we see no need to adjust the average tolerances if core thickness is measured using ASTM C1542/C1542M instead of C174/C174M.

Individual ASTM C1542/C1542M core measurement

As previously stated, the maximum negative difference between individual ASTM C1542/C1542M and C174/C174M measurements was −0.26 in. for the jaw caliper and −0.24 in. for the ruler procedures, respectively. Based on this study, we propose that if C1542/C1542M measurements procedures are used, then the tolerance for an individual sample changes from 3/4 to 1 in. to account for the differences in individual measurements.

Number of NDT sample measurements

ACI 117-10(15) currently requires four thickness samples per 5000 ft^2. The average NDT measurements are likely to change if only four measurements, instead of 30, as in this study, were used. Certainly, one of the benefits of NDT measurements is the speed at which data can be collected. ACI 117-10(15) does not require more samples when an IE device is used but does state in Commentary Section R4.5.4.3 that GPR “may require that a larger number of samples be taken to provide the same degree of reliability as the (other)

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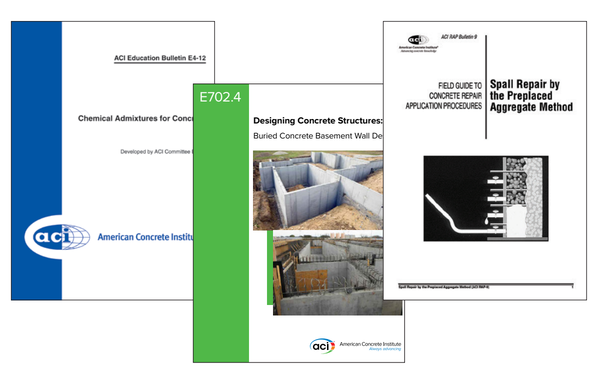

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Engineering Judgment—Balancing Decisions

Some projects are currently using NDT measurements for slab-on-ground thickness and the ACI 117-10(15) slab-on-ground tolerances established by core measurements. ACI 117 incorporated the use of IE for measuring slab thickness in 2006.

While approving the use of IE, the document did not address or change any tolerances or sampling for this NDT method. Commentary Section R4.5.4.3 did, however, recommend taking more samples when using GPR.

Because the concrete construction industry is currently using NDT methods to determine specification compliance of thickness tolerances, we need to balance the NDT accuracy and precision, appropriate average and individual thickness tolerances, and number of samples with the needs of the owner and workmanship of the contractor. Our recommendations presented in this study are a first attempt at reaching these objectives. Collaboration between experts in NDT, statistics, tolerances, construction, and pavement design is likely necessary to formulate applicable requirements.

Project credits

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