USE OF NONDESTRUCTIVE TESTING FOR CONCRETE PAVEMENTS

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ABSTRACT

The Federal Highway Administration (FHWA) has promoted the use of nondestructive testing techniques for over 20 years in an effort to reduce the cost and time of construction quality control. Many of the available nondestructive techniques, however, are still under-utilized by state highway agencies. This paper presents FHWA's experience with two nondestructive test methods that show great promise for application in concrete pavement construction; maturity and impact-echo. This paper includes a brief discussion of background and theory, as well as a detailed discussion of each of the case studies in terms of both results and conclusions.

INTRODUCTION

The FHWA has actively promoted the use of nondestructive testing techniques over the past 20 years. The majority of the emphasis has been on techniques that can be used to predict the strength of concrete during early ages and locating distresses/flaws in the concrete at later ages. There has been an increasing demand by state highway agencies to determine the strength of the concrete at early ages to make early opening to traffic decisions, to improve quality assurance/quality control and to establish pay factors for use with performance related specifications.

Numerous methods have been used in the past to predict concrete strengths with varying degrees of success; such as rebound number, penetration resistance, pullout, break-off, ultrasonic pulse velocity, maturity and cast-in-place cylinders[1]. The FHWA has been involved with many projects using these different techniques for estimating concrete strength. One method in particular has proven to be quite promising in terms of strength prediction, namely maturity. This paper will concentrate on results and experiences from three paving projects where maturity was utilized to forecast and estimate pavement strengths for opening to traffic decisions.

In terms of crack and flaw detection, FHWA has had significant success with the impact echo method. Although developed primarily as a flaw detection device, recent efforts have been made to apply it to pavement thickness measurements as well. The latter portion of this paper will discuss three projects where the impact-echo method was used for measuring pavement thickness nondestructively.

MATURITY CONCEPT

Maturity Background

It is well recognized that the strength of a given concrete mixture that has been properly placed, consolidated and cured is a function of its temperature history and its age. This interrelationship can be accounted for by the maturity concept.

The maturity concept was first proposed in the late 1940's and early 1950's as a technique to account for the combined effects of time and temperature on the strength development of a concrete mixture (Nurse 1949; McIntosh 1949; Saul 1951)[2]. Interest in the maturity concept significantly increased in the mid 1980's as the concrete industry began looking for ways to accelerate the construction of rigid pavements. The accelerated construction schedule required the sampling and testing phase of the project to be accelerated as well. This accelerated schedule resulted in a significant increase in the volume of required testing, and testing them at these early ages became very labor intensive. The issue of in-place strength versus laboratory test specimen strength also became an issue with concrete for these accelerated projects, due to the different thermal histories the pavement and laboratory specimens experience. An improved method was necessary that would allow these strengths to be determined much sooner and more easily, and preferably in-place.

The maturity concept has been successfully used on numerous "fast-track" projects as well as conventional paving projects since 1986. In addition to providing continuous in-place strength predictions, maturity testing provides information to field engineers to help them adjust curing measures to optimize the rate of strength development. This in turn can affect the joint sawing and opening to traffic operations[3,4].

Several state highway agencies have recently adopted the use of maturity on paving projects to estimate concrete strength for early opening to traffic. Data from recent work in North Dakota, Indiana and Nebraska shows how maturity testing can be used effectively to make early opening to traffic decisions and reduce the number of samples required for testing.

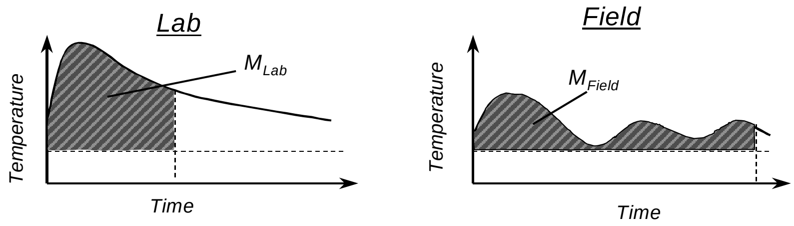
Maturity Theory

The maturity method is a technique for estimating the strength gain of concrete based upon the temperature-time history recorded by a maturity meter. It is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index (Figure 1). Using the temperature-time data collected by the maturity meter, a maturity function (mathematical expression) converts the actual temperature-time history of the concrete to a maturity index that is indicative of strength development. The applicable standards are AASHTO TP 52 and ASTM C 1074, Standard Practice for Estimating Concrete Strength by the Maturity Method.

Two maturity functions are commonly used for computing the maturity index. One maturity function, the *Nurse-Saul* equation, is used to calculate the temperature-time maturity index.

$$M = \Sigma \sum_{0}^{t} (T - To)\,\Delta t \qquad \text{where,}$$

M = maturity at age, t
T = average temperature of the concrete during time interval, t
To = datum temperature



When Mlab=Mfield, strengths are equal

Figure 1. Maturity method is based on the assumption that the same concrete mixture will attain the same strength if they have the same maturity values.

The other maturity function, the *Arrhenius* equation, is used to calculate the equivalent age maturity index. Equivalent age represents the duration of the curing period at the reference temperature that would result in the same value of maturity as the curing period at other temperatures.

$$t_e = \Sigma\, e^{-Q(1/Ta-1/Ts)}\,\Delta t \qquad \text{where,}$$

t_e = equivalent age at specified temperature Ts
Q = activation energy divided by gas constant
Ta = average concrete temperature during time interval Δt
Ts = specified temperature
Δt = time interval

The Nurse-Saul equation appears to be the most commonly used method by the state highway agencies due to its simplicity.

<u>Procedure to Develop Strength-Maturity Relationship</u>

Prepare at least 15 cylinders using the mixture design and materials to be used later on a project where the in-place strength is to be estimated. Embed temperature sensors in at least two cylinders, connecting the sensors to a maturity meter. Moist cure the specimens under standard laboratory conditions. Test at least two cylinders in compression at 1, 3, 7, 14, and 28 days. At each test age, record the average maturity index for the instrumented cylinders. Plot the average compressive strength as a function of the average value of the maturity index. Draw a best-fit curve through the data. The resulting curve is the strength-maturity relationship to be used for estimating the strength of the in-place concrete. The maturity curve is mixture specific. If mixture design changes a new calibration must be performed. Also it is important to note that the method does not account for relative humidity, which has a major effect on paste porosity, shrinkage, and strength of fresh concrete. The maturity method could also be used to establish a correlation with flexural strength as well.

Procedure to Estimate In-Place Strength

Install temperature sensors at locations in the structure that are critical in terms of exposure conditions and structural requirements (Figure 2). Connect the sensors to maturity instruments as soon as practical. When the strength is to be estimated at a sensor location, record the value of the maturity index from the maturity instrument or calculate the maturity from the temperature record. Using the strength-maturity graph previously developed for the concrete mixture, read off the value of compressive strength corresponding to the measured maturity index.

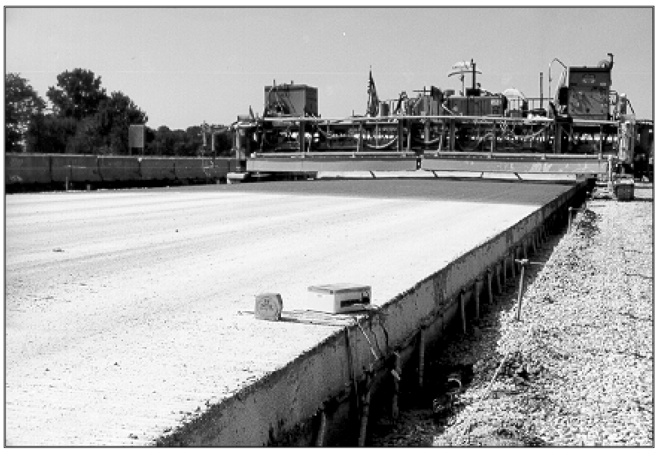


Figure 2. Typical application of maturity method in the field. Note maturity meter in the foreground with three thermocouple wires inserted into the pavement at different depths.

MATURITY FIELD APPLICATIONS

North Dakota Case Study

During the summer of 1999 FHWA's Mobile Concrete Laboratory (MCL) was involved with the reconstruction of I-94 near Richardton, North Dakota. The reconstruction involved replacing 12.9 km of a 36-year old 230 mm thick dowel-jointed concrete pavement with North Dakota's standard highway concrete mixture. One of the technologies of interest to North Dakota was maturity. The state was interested in evaluating the use of maturity for concrete strength predictions, and possibly for making decisions about when to open recently placed pavements to construction-traffic.

The new concrete pavement is 230 mm thick, with doweled joints spaced at 4.6 m. The subbase was a cement stabilized recycled (crushed) concrete. The concrete mixture contained a siliceous gravel, type II cement, and 20% class C fly ash by replacement of cement. Placement occurred during June and July, with temperatures, humidities and wind speeds varying significantly. A single coat of liquid curing compound was utilized, and paving times generally fell between 7:00 am and 3:00 pm.

The maturity calibration curve was developed using specimens cast from concrete placed during paving on June 14. A total of 15 150x300 mm cylinders were cast, three for each of the ages of 1day, 3 days, 7 days, 14 days and 28 days. Two of the 28 day cylinders were instrumented with maturity probes. The maturity indexes were recorded at each test age, and plotted versus the strength to generate the calibration curve.

Similarly, on June17, cylinders were cast from concrete placed during paving operations. For this placement, one set of cylinders was cast for each of three different curing regimes; ASTM standard cure, field box-cure and open-air cure. Two cylinders from each set were instrumented with maturity probes, and the maturity recorded during each strength test. In addition, the pavement section was instrumented with maturity probes as well, to see how the in-place concrete gained maturity. The strength versus maturity curves generated for this concrete (verification curves) were then compared to the calibration curve. If in fact the mixtures placed on 6-14 and 6-17 are the same, the curves generated should be identical, regardless of the curing history.

This test program was repeated for concrete placement operations on June 30, but only the pavement was instrumented with maturity probes. Core strengths were used to gauge the strength of the in-place concrete. A verification curve was generated and compared to the calibration curve (Figure 3).

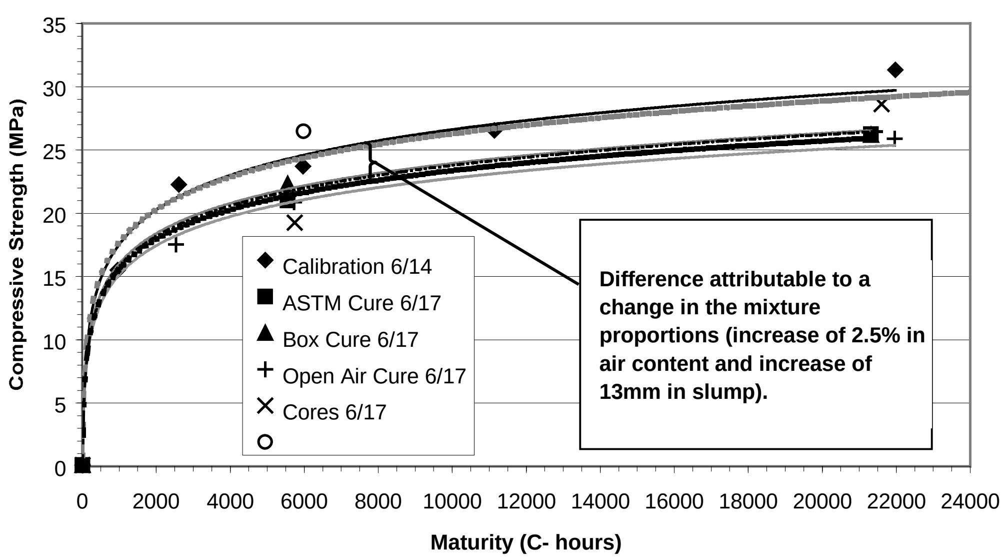


Figure 3. Comparison of maturity-strength data from both pours.

Figure 3 shows the calibration / verification curves and strength values for these placements. As is evident from the figure, there are two distinct families of curves; the curves that include the calibration curve and the verification curve generated on June 30, and the verification curves from June 17. Initially, this may seem troubling, since all the curves should in theory be the same. However, after examining the concrete properties from the three placements more carefully, it becomes clear why the concrete placed on June 17 has a different maturity curve – the mixture is in effect different from the other two. The concrete placed on June 17 had a measured air content 2.5% higher than the concrete placed on the other two dates, and its slump was between 13 and 19 mm higher, effectively changing the mixture properties and lowering the strength. This reduction in strength was confirmed by the ASTM standard cured specimens as well.

From this data we can conclude that maturity can be used to reliably estimate concrete strengths, as long as the mixture proportions do not change. This case history clearly illustrates the importance of ensuring that the concrete production and placement process is under control. If mixture proportions are allowed to vary significantly during a days placement or from day to day, the applicability of the maturity calibration curve comes into question. The data indicates that for this particular mixture, during summer conditions in North Dakota, the pavement generally reaches a compressive strength of 24 MPa in less than six days.

Indiana Case Study

During the summer of 2000, the MCL participated in a test program surrounding the reconstruction of a 1.6 km portion of I-465 southeast of Indianapolis, Indiana. The project included both mainline paving as well as several overpasses, bridges and exit/entrance ramps. The mainline reconstruction project involved replacing a 356 mm thick, 30 year old plain jointed concrete pavement with a similar 356 mm thick pavement. One of the aspects of the MCL involvement was to see how well maturity predicts and forecasts pavement strengths. The concrete mixture consisted of a crushed limestone coarse aggregate, type I cement, type C fly ash and a w/c of .42. The subbase was a crushed stone open-graded drainage base. Concrete placement took place through July and August with the wind, temperature and humidity varying significantly. A single coat of liquid curing compound was used, and paving times generally fell between 7:30 am and 1:30 pm.

The initial maturity calibration curve was generated prior to start of mainline paving by researchers at Purdue University. The curve was generated in substantial conformance with ASTM C 1074, except flexural beams were used instead of compressive cylinders. The contractor supplied the university with concrete that had been batched in the field using the approved mixture proportions.

Maturity verification curves were generated in the field using maturity probes placed in flexural beams on a total of eight different sublots, as well as maturity probes placed in the pavement section itself on two of the sublots. Concrete was placed during six days over a two-week period from July 24 through August 4. A total of four 150x150x530 mm beams were cast from each sublot. Two beams were to be broken at 7 days, and the remaining two at 28 days. One of the 28 day beams from each of the eight sublots was instrumented with two maturity probes, and the maturity values were averaged and recorded with the flexural strength at each test age. Figure 4 shows the strength versus maturity curves for these eight sublots.

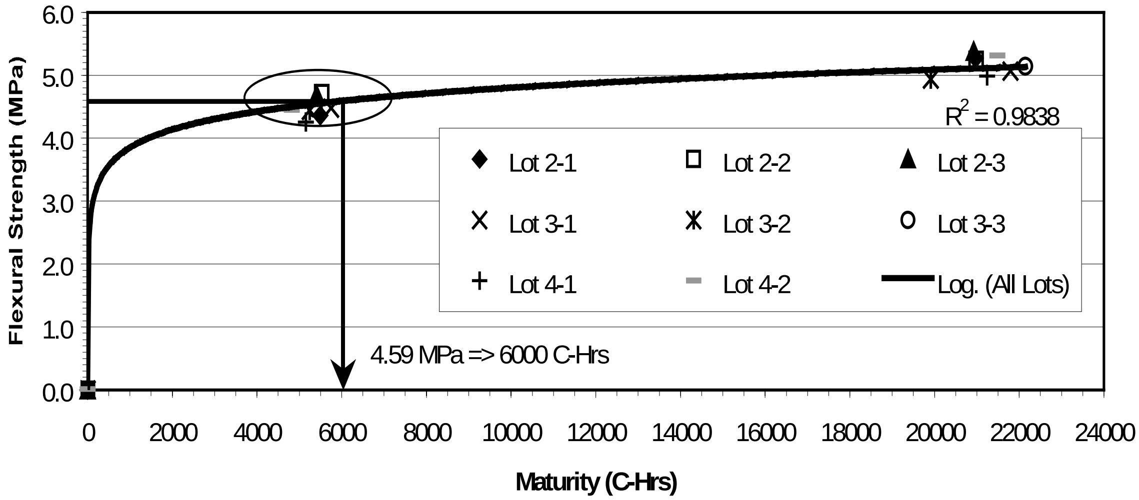


Figure 4. Maturity-strength curve for all lots.

From this figure, we see that all the maturity strength data fall along the same general curve. The differences that exists between the various lot's strength and maturity, is partly due to mixture variability over the two week period. Slumps averaged 63 mm with a standard variation of less than 13 mm and air contents averaged 5.7% with a standard deviation of about 0.5%. The differences are also partly due to variability with the flexural test itself. Past studies have shown that the maturity curves are much more reproducible using compressive strengths as compared to using flexural strengths[5]. Nevertheless, this level of variability is acceptable, since maturity is not proposed for acceptance of the material, but only for early opening to traffic decisions. The data also shows that the maturity of the in-place concrete (verified with thermocouples at three depths in the pavement) increased more rapidly than in the companion flexural beams. This is consistent with our intuitive knowledge of how "mass" concrete gains strength compared to smaller volumes of concrete, such as 150x300 mm specimens.

Nebraska Case Study

During the early fall of 2000, the MCL was involved in a concrete paving project along US 275, in Valley, Nebraska. Among other things, the State was interested in using maturity for early opening to traffic decisions. The project included construction of 13 km of a 230 mm thick jointed plain concrete pavement, on new alignment. The mixture consisted of a coarse siliceous sand, a crushed limestone coarse aggregate, type II cement and 9% class C fly ash by replacement of cement. The w/c was limited to .45 or less. The subbase material consisted of a compacted coarse sand. Concrete sampling took place from October 11 through 19, with the temperature and humidity varying significantly, and wind speeds approaching 48 km/h. A single coat of liquid curing compound was utilized, and paving times generally fell between 8:00 am and 2:30 pm.

Maturity calibration curves were developed using both compression and flexural specimens cast on October 11. A total of two beams and two cylinders were cast for each of four test ages (2 days, 5 days, 7 days and 28 days), where one of the 28 day beams and two additional spare cylinders were instrumented with maturity probes. The maturities were recorded at each test age and plotted versus the strength to generate the calibration curves.

Similarly, beams and cylinders were again cast on both October 17 and 19 during paving operations, and instrumented in an identical fashion. The pavement section was instrumented with maturity probes at three different depths as well, to compare test specimen maturity gain-rate versus pavement maturity gain-rate. Figure 5 shows the compressive strength versus maturity data for the three placements.

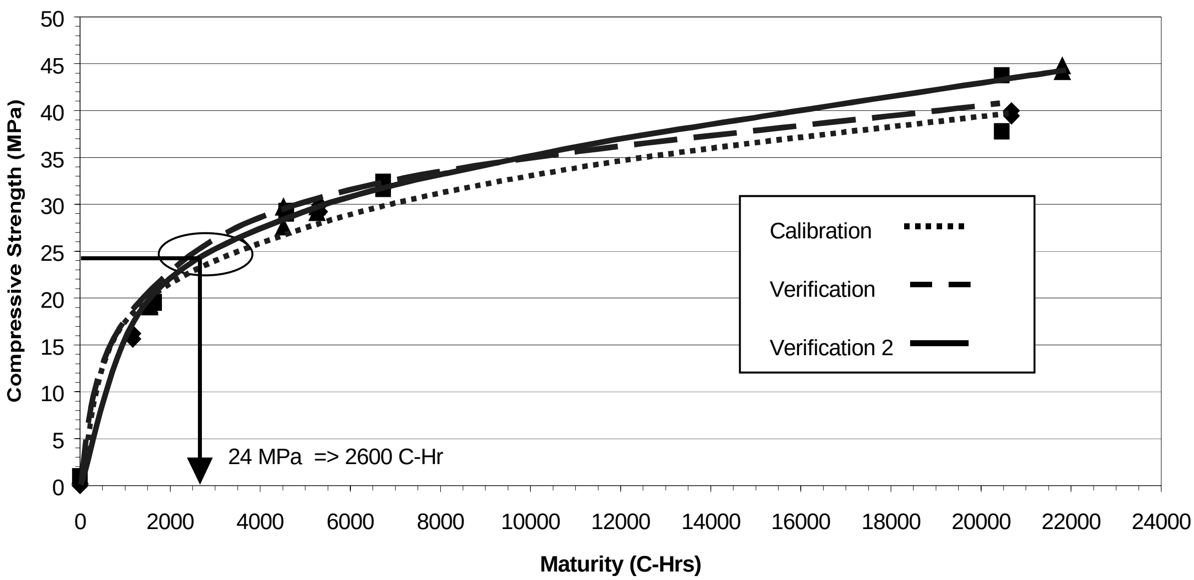


Figure 5. Compressive strength maturity data for three placements.

This figure clearly illustrates the repeatability of the maturity method. All three placements show maturity curves that are virtually identical. For these concrete placements, the opening to traffic value of 24 MPa was equivalent to a maturity of about 2600^0 C-hr. It took about 80 hours for the in-place pavement to reach this value. Test data from this project also show that the maturity curves are much more reproducible when using compressive strengths as opposed to using flexural strengths.

IMPACT-ECHO METHOD

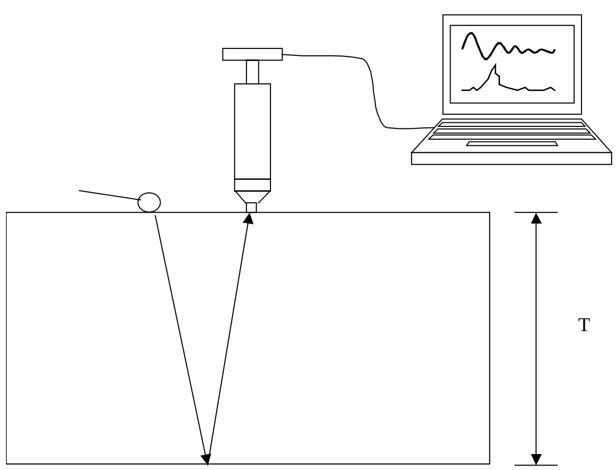
Impact-Echo Background

Impact-echo testing is a nondestructive technique based on stress wave analysis and is used to locate and determine the depth to internal voids, cracks, honeycombing, and delaminations in a concrete structure, as well as measure concrete thickness. The research that led to the development of the impact-echo method began in 1983 at the National Institute of Standards and Technology (formerly the National Bureau of Standards) and has continued since 1987 at Cornell University[6].

Verification of suspected internal voids, cracks, honeycombing, and delaminations in a concrete structure is often difficult with conventional techniques. Random coring is time consuming, expensive, and often does not provide adequate data. The effective and efficient use of the pulse-velocity technique is limited by needing to have access on opposite sides of the structure. Also, the pulse velocity technique is affected by the presence of reinforcing steel (structures) or dowels (pavements) and does not indicate the depth of the flaw. The impact-echo technique however, requires access only from one side of the structure and the method is capable of locating both the extent and depth to a flaw.

Impact-Echo Theory

A stress wave is generated when an impact is applied to a solid. Stress waves are generally categorized into three types: compression waves (P-waves), shear waves (S-waves), and surface waves (R-waves). In the impact-echo technique, a stress pulse is introduced into a structure by mechanical impact (steel spherical impactor) at a point on the surface. P- and S-waves propagate into the structure along spherical fronts while R-waves propagate along the surface. P- and S-waves are reflected by internal interfaces (e.g., cracks, voids, and delaminations) and by external boundaries of the structure. Reflected waves then arrive at the surface where the impact has occurred and produce displacements, which are measured by a receiving transducer (Figure 6). Multiple reflections from each interface become dominant peaks in the frequency spectrum at values corresponding to the frequency of arrival of reflected waves from each interface. An interface can be the boundary between two materials with different acoustic properties such as the concrete/air interface at a crack, or the bottom of a bridge deck. The dominant frequency and P-wave speed are used to determine the depth to the interface where the reflection has occurred. The P-wave speed is determined by spacing two transducers a known distance apart on the surface of the concrete, creating an impact adjacent to the transducers, and measuring the time it takes for the P-wave front to move from one transducer to the second transducer.



$$T = \frac{Cp}{2f}$$

T = thickness, m

Cp = wave speed, m/s

f = frequency, Hz

Figure 6. Illustration of the impact-echo principle

Several pieces of commercially available equipment are currently available. Typically an impact-echo system includes a portable computer used to collect and analyze data in the field, surface displacement transducers and hand-held impactors that are both small and lightweight (Figure 7). The equipment is relatively easy to use. However, appropriate interpretation of test results requires significant experience, and knowledge of impact echo theory.

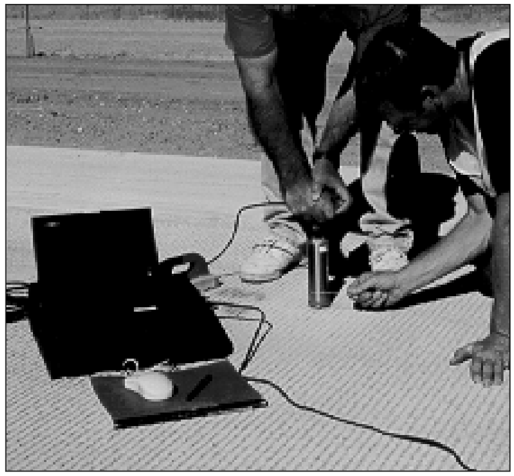


Figure 7. Typical impact-echo set-up for field applications.

Pavement Thickness Case Studies

The service life of a concrete pavement is influenced not only by the quality of the concrete mixture but also by the thickness of the concrete. Many states currently core newly constructed pavements about every 300 linear meters of pavement in each traffic lane to verify thickness. If the average thickness of a concrete pavement is deficient in thickness by more than 5 mm, an adjustment in payment is made. This coring process is undesirable because coring is time consuming, expensive and most importantly destructive. Coring leaves discontinuities that can weaken the pavement. The concerns with cost and potential effect of the process on the pavement being inspected often leads to a tendency to compromise the thoroughness of the inspection. Therefore, there is a need for an alternative inspection technique which is nondestructive, rapid, inexpensive and of sufficient accuracy[7]. The use of nondestructive testing allows for more testing to be performed on the pavement without affecting its integrity. See ASTM Standard Test Method C 1383-98 “Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method” for a description of the test method.

Arizona Case Study

In May 1995, researchers from Cornell University in conjunction with the Federal Highway Administration and the Arizona Department of Transportation conducted some testing to determine the feasibility of using the impact-echo method to measure the thickness of newly placed concrete pavements. The testing was performed at a previously constructed Strategic Highway Research Program (SHRP) SPS-2 test site. The SHRP section contained two different nominal thicknesses (200 mm and 300 mm) and three different types of subgrades (lean concrete base LCB, asphalt stabilized permeable base ASPB, and dense graded aggregate base DGAB). For each location the P-wave speed was determined by measuring the time required for the P-wave to travel between two transducers positioned 300 mm apart on the surface of the pavement. This wave speed was then used to conduct an impact echo test as described previously. Tables 1 and 2 summarize the data.

Subbase Type	Average P-wave speed (m/s)	Impact-Echo Thickness (mm)	Core Thickness ASTM C 174 (mm)	Difference IE-Core Thickness (mm)	%
LCB	4255	203	205	-2	-1.0
ASPB	4080	212	209	3	1.4
DGAB	3920	195	197	-2	-1.0
DGAB	4080	209	212	-3	-1.4

Table 1. Results based on 200 mm thick concrete pavement

Subbase Type	Average P-wave speed (m/s)	Impact-Echo Thickness (mm)	Core Thickness ASTM C 174 (mm)	Difference IE-Core Thickness (mm)	%
LCB	4255	291	294	-3	-1.0
ASPB	4255	300	294	6	2.0
DGAB	4080	279	288	-9	-3.1
DGAB	4080	279	287	-8	-2.8

Table 2. Results based on 300 mm thick concrete pavement

Results

The results in Table 1 show a maximum difference of only ± 3 mm between the impact-echo results and the average core lengths. These results are within the range of accuracy that the states are currently specifying – 5 mm. There was no noticeable difference in thickness results between the different subbases.

The results in Table 2 show a range of -9 to +6 mm between the impact-echo results and the average core lengths. This range is slightly larger than the range for the 200 mm thick pavement. Recent research suggests that the radius of the effective measurement zone below the transducer is proportional to the root of the pavement depth[8]. This suggests the effective area the impact-echo measurement covers is larger for thicker pavements, whereas for cores the effective measurement area stays constant (50 mm radius). The results for the lean concrete base are still within 3 mm of the core results, which is probably in part due to the relatively smooth surface of the base material, which created a clean boundary for the pressure waves to reflect from. Core measurements indicate that length variations around the perimeter of the 100 mm diameter core were less than 2 mm. The variation around the core perimeter for the dense graded aggregate base however, was between 7 and 10 mm. This may explain why the impact echo results are only within 8 or 9 mm of the average core lengths. These differences are greater than most states allow before making a price adjustment for pavements with deficient thickness.

Indiana Case Study

A summary of the project and construction details for this project is provided in the previous section (Maturity Field Applications). One of the key factors required for performance related specifications is the thickness of the pavement. Therefore, a limited amount of verification cores are taken. A study was performed during this project to determine the practicality of using the impact-echo method to measure the pavement thickness nondestructively. The specified pavement thickness for this project was 350 mm. Prior to the state's normal coring operations, members of the MCL staff in conjunction with INDOT personnel randomly selected locations where acceptance cores would be taken. The impact echo method was used to first determine the wave speed at each location and, using that wave speed, an impact-echo thickness test was performed. Table 3 provides a summary of the data collected.

	Average P-wave speed (m/s)	Impact-Echo Thickness (mm)	Core Thickness ASTM C 174 (mm)	Difference IE-Core Thickness (mm)	%
Lot 2, sublot 1a	3883	353	356	-3	-0.8
Lot 2, sublot 1b	3991	363	357	6	1.7
Lot 2, sublot 2a	4065	376	364	12	3.3
Lot 2, sublot 2b	4048	373	359	14	3.9
Lot 2, sublot 3a	3868	358	360	-2	-0.6
Lot 2, sublot 3b	4034	359	357	2	0.6
Lot 2 average	**3413**	**364**	**359**	**5**	**1.4**
Lot 3, sublot 1a	3841	352	351	1	0.3
Lot 3, sublot 1b	3791	365	357	8	2.2
Lot 3, sublot 2a	4117	412	389	23	5.9
Lot 3, sublot 2b	3815	348	365	-17	-4.7
Lot 3, sublot 3a	3904	365	363	2	0.6
Lot 3, sublot 3b	3959	347	354	-7	-2.0
Lot 3 average	**3965**	**365**	**363**	**2**	**0.6**
Lot 4, sublot 1a	3920	363	369	-6	-1.6
Lot 4, sublot 1b	4135	383	356	27	7.6
Lot 4, sublot 2a	3843	351	360	-9	-2.5
Lot 4, sublot 2b	3947	365	358	7	2.0
Lot 4 average	**3961**	**366**	**361**	**5**	**1.4**

Table 3. Results based on concrete pavement over open graded drainage layer.

Results

Table 3 shows the results obtained from three different lots tested on this project. All of the impact-echo tests were conducted within 6-9 days of concrete being placed. For each sublot location, 4-5 direct P-wave speed measurements were made within 1 m of the core location and the results were averaged. All of the sublot results were also averaged for each Lot. There were significant variations in the measured wave speed both at each core location and between locations. This variation is most likely due to a combination of several factors: 1) pavement surface irregularities (aggressive tining) make it difficult to get good surface contact with the transducer, 2) some measurements were performed on concrete that was only 6 days old while others were performed on 7, 8 and 9 day old concrete - this difference in concrete age translated to a difference in strength, density and consequently wave speed, and 3) surface pressure wave speeds may vary depending on the quality of the surface concrete – this means that variations in finishing may influence the wave speed near the surface. Although there was no evidence of finishing problems in any of these areas, it is still an issue that warrants consideration. The predicted pavement thickness using these wave speeds over-predicted the core thickness by as much as 27 mm and under predicted the core thickness by as much as 17 mm. This difference partly caused by the variation in wave speed measurements, is also related to the irregularity of the base material. In some cases the 100 mm diameter cores varied in length around the perimeter by as much as 16 mm. However, when averaging the impact echo thickness predictions for each lot, the predicted thickness was within ± 5 mm of the average core thickness for the same lot. This points to the possible need to increase the number of thickness measurements made with impact echo to increase the overall accuracy. Additional work needs to be done in this area.

Nebraska Case Study

A summary of the project and construction details for this case study is provided in the previous section (Maturity Field Applications). The FHWA's mobile concrete laboratory collected impact-echo data for pavement thickness as part of this project. The contract specified a concrete pavement thickness of 254 mm. The jointed plain concrete pavement was placed directly on top of a compacted coarse sand base material. Prior to the state's normal coring operations, members of the MCL staff in conjunction with Nebraska Department of Roads personnel randomly selected locations where acceptance cores would be taken. The impact echo method was used to first determine the wave speed at each location and, using that wave speed, impact-echo thickness tests were performed.

Location	Average P-wave speed (m/s)	Impact-Echo Thickness (mm)	Core Thickness ASTM C 174 (mm)	Difference IE-Core Thickness	
				(mm)	%
26	3798	251	256	-5	-2.0
21	3976	259	262	-3	-1.1
22	3974	254	257	-3	-1.2
23	3945	251	254	-3	-1.2

Table 4. Results based on concrete pavement placed on a coarse sand base material.

Results

Table 4 shows the results obtained from four different locations on this project. For each location, 4-5 direct P-wave speed measurements were made within 1 m of the core location and the results were averaged. The wave speeds measured for this project were reasonably consistent (ranged from 3798 m/s to 3976 m/s). It is possible that since the concrete in all these locations was more than 21 days old, and since the pavement surface was ground smooth with a carbide stone prior to testing, the variability in wave speed measurements was reduced. The impact-echo thickness tests under-predicted the core thickness by only 3 to 5 mm. This relatively small difference is probably related to; 1) a more consistent and representative wave speed, and 2) a more uniform and smooth subbase allowing for sharp reflections at the interface of the pavement and the coarse sand base material. Overall, these results are within the range of accuracy that most states are currently specifying – 5 mm.

CONCLUSIONS

This paper has presented two nondestructive testing techniques that show great potential for improving the amount and quality of data that can be collected in the field. These improvements can provide both time and cost savings to the users.

Based on the maturity case studies, it is clear that maturity can effectively predict concrete strengths. For all three projects discussed, maturity curves generated from specimens cast on different dates and with different curing histories showed significant reproducibility. In other words, a maturity curve developed on one day also applies to the same concrete mixture placed on another day under different environmental conditions. However, some cautions were also identified. If the mixture proportions change significantly during concrete placement, the maturity curve developed initially may not be valid – significant errors in strength prediction may result. It should also be noted that the maturity method should be supplemented with some limited conformation testing (such as compressive strengths) especially where fresh concrete testing indicates that the production or construction process is not under control (i.e. changes in slump, unit weight or air content). Also, it appears that due to the greater variability of flexural strengths, compressive strengths may be better suited to developing reproducible strength maturity relationships. Ideally, a curve fitting generator (equation fitter) should be utilized to describe the relationship between strength and maturity.

The utilization of maturity for strength predictions can have significant benefits for the concrete construction industry. First, a reduced number of test specimens are necessary to describe the strength gain of a mixture. Second, maturity is inherently an in-place test. Using maturity eliminates the question about whether the test specimens are in fact representative of the in-place concrete, and consequently whether the measured strengths are valid. These benefits are becoming increasingly important as we move forward with fast track construction, where less time is available for testing, and accurate in-place strength measures are more critical.

Due to its simple application with currently available maturity meters, the maturity concept should continue to grow in every area where knowledge of the in-place concrete strength can be advantageously used to reduce construction and time schedules. In a time when public agencies and contractors are concerned with escalating costs and shrinking budgets, this method provides a viable means of reducing costs through testing and scheduling. Increased use of this technique will provide additional information for researchers to improve upon the currently used maturity equations and provide greater accuracy for estimating the strength of the concrete.

The impact-echo (IE) equipment shows good potential for being able to measure the thickness of concrete pavements nondestructively. Based on the three impact echo case histories, we can conclude that IE thickness measurements can determine pavement thicknesses within the accuracy specified by most state highway agencies (SHA's). In most cases, the IE thickness compares very well with the average length of the thickness cores. However, in some cases, the difference in measured thickness is greater than the 5 mm most SHA's require. This difference is most likely caused by one or a combination of the following: 1) significant irregularities of the base material (no clearly defined boundary or interface), 2) inaccurate wave speed measurements due to either poor transducer-surface contact, different concrete ages (maturities), or variations in concrete surface finish, and 3) an IE area of influence greater than the 100 mm diameter of a conventional core.

Additional work needs to be completed to increase the certainty associated with the measured P-wave speed. More study is also warranted to clarify whether the wave speed along the surface is representative of the full depth wave speed. Finally, additional data also needs to be collected for expected responses and accuracies corresponding to different base materials.

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