

Bridge Deck Health Monitoring

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ABSTRACT

An NDE technique is developed for early age assessment of concrete bridge deck durability. The technique has potential implementation in the quality control and quality assurance (QC/QA) specifications level II field tests for measurement of performance parameters. The technique is also recommended for intelligent health monitoring for example, in timing the positive maintenance interventions. The NDE technique is based on ultrasonic pulse velocity (UPV) measured on field concrete and compared to measurements made on standard specimens. The basis of the technique is the theoretical relationship derived between UPV and concrete permeability, which justifies the use of ultrasonic pulse velocity (UPV) as the concrete soundness indicator. The intelligent monitoring procedure is called the paste quality loss (PQL), where standard concrete specimens made from field concrete mixture are utilized as reference sensors. The lab tests conducted on six 1000 mm x 1500 mm x 230 mm bridge deck specimens, some with curing defects, showed that the PQL parameter computed from the UPV measurements as early as the 28th day is a good predictor of soundness. The UPV measurements are also performed on the 7th, 14th and 90th days. The measurements made at increasing age of concrete more clearly document the rapid loss of soundness of improperly cured concrete decks.

INTRODUCTION

There is a trend towards using performance-related concrete specifications (PRS) for the construction of transportation infrastructure in the United States. Literature indicates that one performance parameter that is being emphasized with the use of PRS is concrete durability. Current implementations of PRS are reportedly used for high performance concrete (HPC) in Federal Highway Administration (FHWA) "showcase" projects. Common performance parameters (durability, strength), characteristics, and its measures that are used in these specifications are listed in Table 1.

In Table 1, concrete durability is characterized by its ability to resist water penetration. Poston et al. presented the forms of concrete distress and deterioration and the typical causes of these distresses [Poston, *et. al.* 1995]. Among the seven distress types again cracking, scaling, and spalling were listed and the typical causes point out the importance of permeability. Mehta listed the principle causes of deterioration of concrete structures in decreasing order of importance as: corrosion of reinforcing steel, exposure to freezing and thawing, alkali-silica reaction and sulfate attack [Mehta, 1997]. The ingress moisture to the interior of concrete also initiates these

deterioration mechanisms. The expectation in using PRS with durability, as a performance parameter is that the life of structures can be increased by reducing the permeability of concrete used in infrastructure.

Table 1. Common Performance Measures

Performance Parameter	Performance Measure	Standard Test Method
Durability	Freeze-thaw durability	AASHTO T 161 ASTM C 666
	Scaling resistance	ASTM C 672
	Abrasion resistance	ASTM C 944
	Chloride penetration	AASHTO T 277 ASTM C 1202
Strength	Compressive strength	AASHTO T 2 ASTM C 39
	Elasticity	ASTM C 469
	Shrinkage	ASTM C 157
	Creep	ASTM C 512

Permeability of concrete depends on its pore structure and its soundness. The pore structure is a representation of the size, shape, distribution and tortuosity of the pores. Soundness of the concrete is defined in terms of the amount of observed cracking. In properly cured concrete, permeability is primarily influenced by the capillary pores (the largest pores in the material's structure). The size of these pores increase with increasing water cement ratio (w/c) and decrease with increasing degree of hydration (curing). The higher the w/c, the larger the size of the initial pores to be filled during the cement hydration process. As hydration progresses, the capillary pores are replaced by the hydration products in which the pores on the average are considerably smaller and more segmented. This condition results in a less permeable medium.

Some of the most commonly used laboratory test methods for determining concrete permeability include hydraulic permeability, air or gas permeability, capillary suction, chloride ion penetration and rapid test for permeability to chloride ions [Kropp, Hilsdorf 1995]. Common on site test methods includes capillary suction, initial surface absorption test, Figg test, etc. A careful review of test procedures, specimens, and variability of results indicate that most are not sui for use in PRS. In the current implementation of PRS two tests, rapid chloride permeability testing (RCPT) and chloride ion penetration (CIP), are used for establishing concrete permeability. It is important to note that these tests and the current implementations of performance-related specifications are strictly for material acceptance purposes. It is assumed that the field performance of concrete is controlled by placement and curing specifications. In moving towards full implementation of performance-related specifications FHWA proposes a two level approach. Level I consist of the utilization of current acceptance tests by the State Highway Agencies [FHWA 1998]. Level II consists of developing and implementing in-situ acceptance testing.

The potential use of the procedures developed in this research is in-situ acceptance testing of permeability. The properties that control concrete permeability and those that control ultrasonic pulse velocity (UPV) of concrete have both been the subjects of extensive research. Review of those articles shows a link between permeability and UPV, as both parameters are largely dependent on the pore structure of the concrete material [Udegbumam *et. al.* 1999]. The approach used here in developing the relationship between permeability and UPV is by establishing the theoretical relationship between the two and by conducting a parametric experimental study to verify and calibrate the theoretical relationship. In implementing the in-situ permeability measurement procedure on field concrete British Standards, BS 4408, Part 5 "The condition assessment of field concrete using UPV" [Tomsett 1980] is adopted. The BS 4408 standard

describes six uses of UPV in obtaining concrete properties or defects, one of which is the estimation of concrete quality in relation to a standard quality. The field concrete quality is estimated by measuring the reduction in UPV of field concrete from specimens prepared from the ingredients of the field concrete and cured in a standard manner. In the permeability measurement procedure the reduction in UPV measured in the field will represent increase in permeability. The procedure is described as the “principle of paste efficiency”. Using the concept of “paste efficiency” the hypothesis of this investigation is that the change in permeability is proportional to the decrease in UPV. The decrease in UPV in ratio to the UPV measured from standard specimens is described as “paste quality loss” (PQL).

BACKGROUND

In a medium, ultrasonic waves propagate primarily with longitudinal and shear distortion. The propagation of longitudinal UPV in an infinite elastic medium is described by the equation given below:

$$V_l = \sqrt{\frac{E(1-m)}{r(1+m)(1-2m)}} \quad (1)$$

where,

- V_l : Longitudinal UPV,
- ρ : Mass density,
- E : Elasticity modulus,
- m : Poisson's ratio.

In this equation UPV is dependent on elasticity modulus, mass density, and Poisson's ratio. The elasticity modulus and Poisson's ratio are both also dependent on porosity. However, the variation of modulus of elasticity with porosity is of a higher order than the variation of UPV with density. Hence, UPV becomes largely dependent on material porosity.

The relationship between elasticity modulus and porosity has been widely investigated. The Mori-Tanaka theory, one of the most popular models, treats the voids as inclusions with a vanishing elasticity modulus [Martin *et. Al.* 1996]. Assuming spherical void shapes, and neglecting the effect of changing Poisson's ratio, it gives an expression for elasticity modulus as a function of porosity, as shown below:

$$E \approx E_0(1 - mp) \quad (2)$$

where,

- m : Parameter of Poisson's ratio
- E : Elasticity modulus of porous material,
- E_0 : Elasticity modulus of material with zero porosity,
- p : Porosity of material (volume fraction of voids).

From eq. (1), the elasticity modulus and longitudinal UPV, in elastic materials with different porosities, are approximately related as in eq. (3a) and eq. (3b):

$$E \approx rV_l^2 \quad (3a)$$

$$E_0 \approx r_0V_{l_0}^2 \quad (3b)$$

where, ρ : Mass density of porous material, ρ_0 : Mass density of material at zero porosity,
 V_{l_0} : Longitudinal UPV in material at zero porosity.

Substituting eq. (3a) and eq. (3b) into eq. (2), a linear equation relating longitudinal UPV to porosity is obtained, as given in eq. (4):

$$V_l \approx V_{l_0}(1 - mp) \quad (4)$$

Eq. (4) illustrates that longitudinal UPV is a linear function of porosity for the range of porosity for which eq. (2) is valid. In this equation V_{l_0} "Y-intercept" is the longitudinal UPV at zero porosity and can be shown to be a constant for a given concrete mix made from the same ingredients and of the same quality of construction.

Rewriting eq. (4), the material porosity is expressed as:

$$p = \frac{\Delta V}{mV_{l_0}} \quad (5)$$

where, ΔV is the drop in UPV from the zero porosity concrete ($\Delta V = V_{l_0} - V_l$).

Considering a unit volume of hardened concrete with N number of cylindrical pores, let the orientation of these pores be such that they intersect a unit cross-section normal to the direction of the pores with a diameter 'd'. The quantity " $Npd^2/4$ " is the total volume of voids, and represents the porosity (p) of this volume of concrete. Assuming laminar flow and accounting for viscosity, then intrinsic permeability (k) can be expressed in terms of porosity as given below:

$$k = \frac{pd^2}{32} \quad (6)$$

Substituting eq. (5) into eq. (6), an expression for permeability in terms of UPV is obtained:

$$k = 0.0313d^2 \frac{\Delta V}{mV_{l_0}} \quad (7)$$

Equation above describes permeability as a function of reduction in UPV (ΔV), square of average pore diameter (d^2), and Poisson's ratio parameter (m). Since, pore size is largely a function of w/c, for specimens made from different batches, but of the same mix proportion, ingredients, casting and curing conditions, m , V_{l_0} , and d , will remain approximately constant. Therefore, the changes to permeability can be predicted by comparing the UPV measured on field concrete to the baseline value determined for standard concrete. This comparison is the basis of the principle of paste efficiency.

Concrete used in the infrastructure in colder climates is often air entrained. It is shown that the porosity term that appears in eq. (6) can be replaced by the total void volume in air entrained concrete. Whereas the porosity term appearing in eq. (7) will remain as the volume of permeable voids [Yaman, *et al.* 2000].

From a parametric experimental study conducted by the authors using typical air entrained bridge deck concrete, the following empirical relationship was obtained:

$$V_l = 5104 - 24.0 (\text{Air Content}) - 24.5 (\text{Permeable Porosity}) \quad (8)$$

In this relationship '5104' represents the intrinsic longitudinal UPV at zero entrained air and porosity. In implementing the procedure we will measure the UPV of field concrete (V_{I_f}) and UPV of standard concrete (V_{I_s}). If for a hypothetical implementation we assume a standard concrete with zero porosity and a fixed percentage of entrained air, then the relationship between the UPV of field concrete and standard concrete can be obtained from eq. (8) as shown below:

$$V_{I_f} = V_{I_s} - 24.5 p \quad (9)$$

This equation shows UPV as a function of change of porosity between field and standard concrete of a specific air content. Field concrete UPV's practical upper limit is UPV of standard concrete. The decrease in UPV between standard and field concrete can be written from eq. (9) in terms of increase in porosity of field concrete as shown below:

$$p = \frac{DV}{24.5} \quad (10)$$

where, $DV = V_{I_s} - V_{I_f}$.

EXPERIMENTAL STUDY

Experiments are designed to assess the usability of the paste efficiency procedure in evaluating the field quality problems related to compaction and curing of bridge decks. The field quality problems are simulated on lab-deck specimens representative of reinforced deck portions. In implementing paste efficiency principle, during the casting of the bridge deck, standard specimens were prepared and cured in the laboratory. UPV measurements are obtained both from the deck and the standard specimens at 7, 14, 28, and 90 days. The decrease in field UPV from the standard specimens shows the increase in permeability of the deck concrete.

The lab-deck specimens are designed to allow the investigation of the effects of improper casting and curing procedures on permeability. Specifically, the effect of two errors, namely segregation (over vibrating) and poor curing are documented. This is accomplished by forcing segregation by over vibrating during casting a pair of lab-deck specimens. These specimens were cured properly. Second pair of lab-deck specimens is prepared with good casting but improper curing practice. A third pair of lab-deck specimens with good casting and curing practice is prepared as control specimens. Measured UPV and permeability are compared for each pair of lab-deck specimens.

All six lab-deck specimens are reinforced with epoxy coated steel reinforcement, which are spaced and tied similar to a typical reinforced bridge deck. Rebar details are 16-milimeter bars at 200-milimeter centers at top and bottom and 10-milimeter bars at 290-milimeter centers only at the top. The reinforcement layers are assembled on chairs with specific heights in order to position the layers accurately along the deck depth. A top cover of 75 millimeters and a bottom cover of 40 millimeters were provided as standard cover for reinforcement.

The samples for this research are based on concrete grade D from MDOT's 1996 Standard Specifications for Construction. Concrete mix per cubic meter consisted of 390 kg cement, 650 kg sand, 1055 kg coarse aggregate and 158 kg water. One cubic meter of the mix also included 104 ml of air entraining and 261 ml of retarding chemical admixture. Fresh concrete tests showed a slump of 100 mm, air content of 7% and unit weight was measured as 2250 kg/m³.

Different groups of specimens are tested in this study. The first group includes 150x300 mm cylindrical specimens labeled LDIII-A, the second group includes 100x200 mm cylindrical specimens labelled LDIII-B, and lab-deck specimens. The lab-deck specimens are grouped into three as LDIII-CON, designating control lab-deck specimens, LDIII-CUR designating the uncured specimens, and LDIII-VIB designating the over-vibrated specimen. The core samples are extracted from lab-deck specimens and labeled LDIII-C- (CON or CUR or VIB). Direct air permeability and indirect, RCPT and absorption measurements are performed on the core specimens at 28th and 90th days.

EXPERIMENTAL RESULTS AND DISCUSSION

The concrete strength is measured from standard 150 mm cylinder specimens as 39 Mpa at 28 days and 47 Mpa at 90 days. The elasticity modulus at 28 days was 36 Gpa and at 90 days 35 Gpa. The specimens are moist cured for 28 days only and later kept in ambient lab condition which resulted in desorption of moisture from the specimens. The decrease in elasticity modulus and a rapid increase in strength between the 28th and 90th days with decreasing specimen moisture content is consistent with results reported in the literature. Poisson's ratio was measured as 0.251.

The UPV measurements on the lab-deck specimens and the standard specimens are given in Table 2. The 28th day UPV measurements are conducted with the specimens in a saturated state. Decrease in UPV is observed as expected from the 28th day onwards due to the standard specimens losing moisture. The control and the over-vibrated lab-deck specimens are only cured for 7 days wrapped in wet burlap. The UPV was measured on the surface of lab-deck specimens using indirect transducer arrangement as shown in Fig. 1.

Table 2. UPV Measurements on Lab-deck and Standard Specimens

Specimen Label	Indirect UPV (m/sec)							
	07 days		14 days		28 days		90 days	
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
LDIII-CON	4331	0.96	4400	1.69	4440	1.34	4489	2.44
LDIII-VIB	4472	3.59	4395	2.05	4437	1.41	4462	1.85
LDIII-CUR	4256	4.02	4347	1.84	4391	2.00	4397	3.80
LDIII-B	4703	1.02	4784	1.09	4823	1.22	4764	1.05

In Table 2, comparing the mean UPV measurements show that the standard specimens have the highest UPV. Additional observation is the UPV measured on control lab-decks is faster than the UPV measured on uncured lab-decks.

A more descriptive means of observing curing error is by looking at the probability density function (PDF) charts drawn for the UPV measurements at 7th, 14th, 28th and 90th days shown in Fig. 2 (a-d). The reduction of the mean UPV value and the flattening of the PDF is interpreted as the loss of concrete soundness. This flattening is observed in Fig. 2(c) and (d) from the comparison of UPV measurements on the control and uncured lab-deck specimens at 28th and 90th day. Same observation cannot be made on 7th day and 14th day UPV measurements shown in Fig. 2(a) and (b). One reason may be lack of reliable 7th day UPV measurements on the lab-deck specimens due to high attenuation of the ultrasonic waves. From the UPV measurements

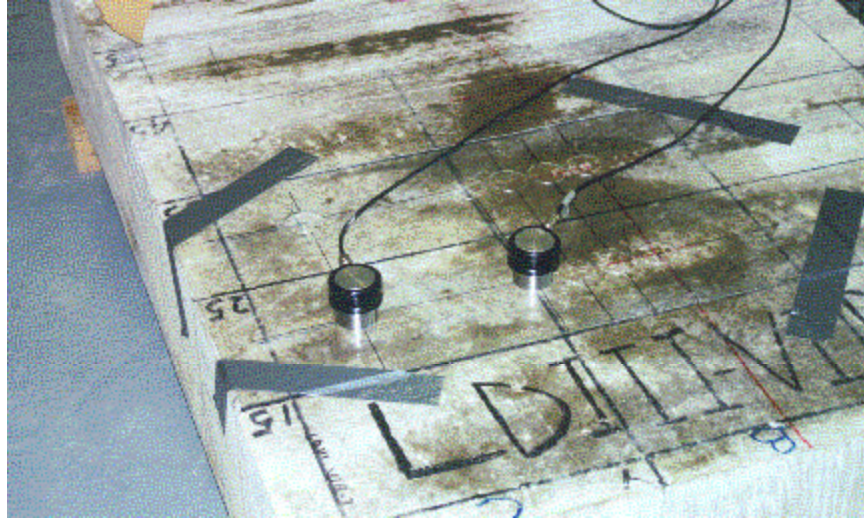


Figure 1. Indirect UPV Measurements on Lab-deck Specimens

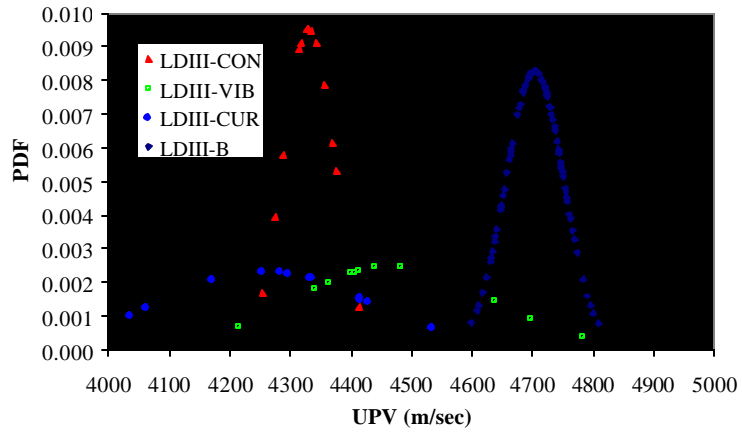
shown in Fig. 2 the quantification of the loss of concrete soundness is described by a parameter we defined as the “Paste Quality Loss (PQL)”. PQL parameter is in principle computed in a similar manner to eq. (6) and amplified by the dispersion of measurements described by the PDF. The PQL parameter is computed using the formula below:

$$PQL = \frac{\Delta V}{V_s} \frac{0.95}{P(\mathbf{m} - 2a \leq X \leq \mathbf{m} + 2a)} \quad (11)$$

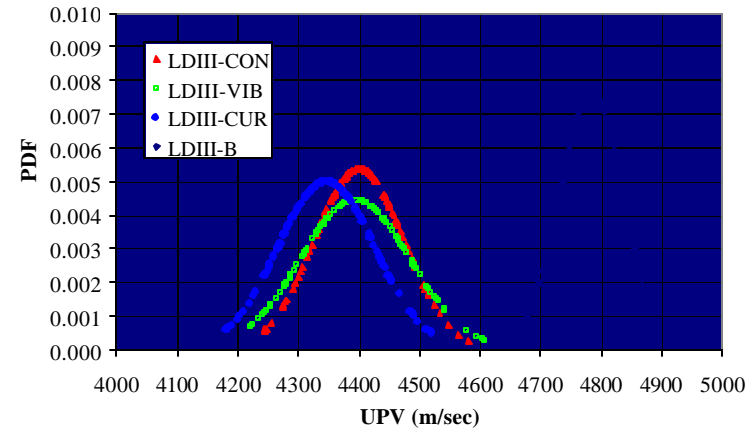
where, P is the cumulative PDF of field UPV, μ is the mean of field UPV measurements, and 'a' is the standard deviation of standard specimen UPV measurements.

In eq. (11), 0.95 corresponds to the cumulative PDF of UPV measurement on standard specimens integrated between two standard deviations around the mean. PQL increases with a decrease in field UPV as well as with the increase in the flattening of the PDF of field measurements. Using the 90th day UPV measurements the PQL of 8.6% and 16.4% is computed for the control and uncured lab-deck specimens respectively. The data obtained from the over-vibrated deck specimen does not show any loss of soundness with a PQL value of 7.8%. The PQL computed at the 28th day is 8% for control and 10.4% for the uncured lab-deck specimens.

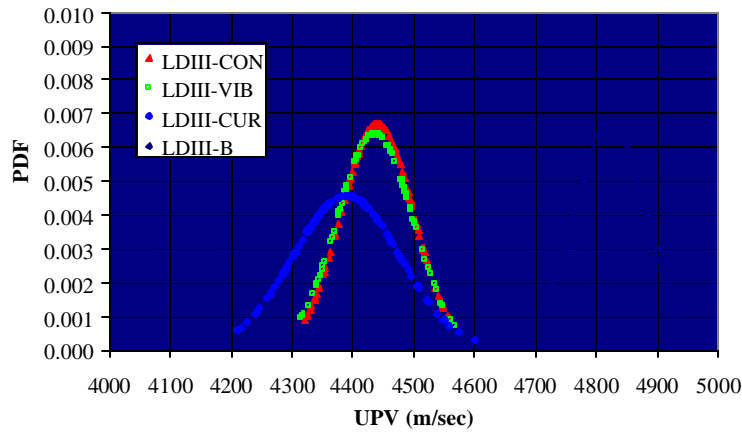
The relationship between UPV and concrete soundness is verified by various permeability tests. These tests are performed on the standard specimens and on the cores obtained from the lab-deck specimens. The tests are direct air permeability, RCPT and absorption. Air permeability tests are conducted by sealing the specimens in a cell, after being dried in the oven to a constant weight. A stream of air is applied to the upstream face of the specimen by opening a source valve. On achieving a steady state, both upstream and downstream pressures are recorded. The flow rate through the specimen is determined by measuring the pressure drop across a calibrated orifice that was located downstream from the sample. Permeability is calculated from the measured flow rate through the specimen. The RCPT test is described in ASTM C 1202 and absorption test is described in ASTM C 642-90. The results shown in Tab. 3 for the 28th and 90th day tests clearly demonstrate the increase in permeability (loss of soundness) of the uncured lab-deck specimens. Standard specimens show the lowest or benchmark permeability values. The conductivity values measured from the RCPT is elevated due to the presence of chemical admixtures in the concrete mixture.



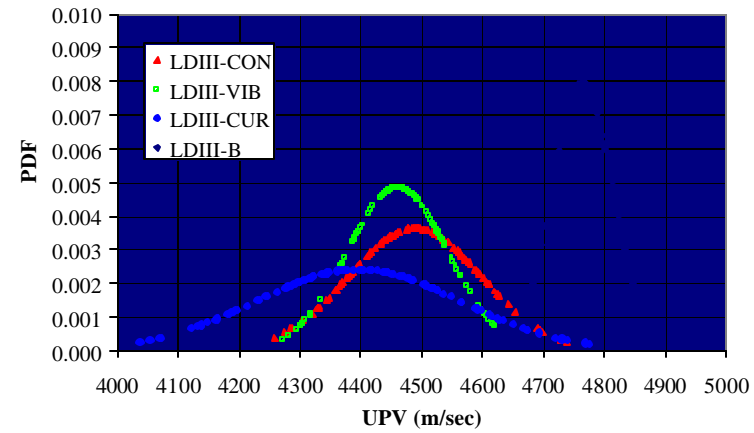
(a) 07 days



(b) 14 days



(c) 28 days



(d) 90 days

Figure 2. PDF of UPV Measurements on Lab-Deck and Standard Specimens

Table 3. Permeability Test Results

Specimen	RCPT (Colombs)				Porosity (%)				Air Permeability ($m^2 \times 10^{-16}$)			
	Mean		COV (%)		Mean		COV (%)		Mean		COV (%)	
	[28]	[90]	[28]	[90]	[28]	[90]	[28]	[90]	[28]	[90]	[28]	[90]
LDIII-C-CON	7968	7252	12	16	5.05	4.83	7	8	1.87	1.36	15	12
LDIII-C-VIB	7418	8106	16	15	5.74	4.97	7	9	1.89	1.72	27	19
LDIII-C-CUR	9401	9922	24	8	6.39	6.26	11	9	5.26	3.80	17	0
LDIII-B	7400	5890	1	7	4.98	4.06	13	7	1.06	0.82	7	3

CONCLUSIONS

The research goal is the development of a health-monitoring tool for the quantification of soundness of field concrete. The tool developed for the purpose relies on UPV measurements obtained from field concrete. The UPV measured on field concrete is compared to the UPV measured on concrete specimens prepared using the field mix and cured in the laboratory in a standard fashion. The health-monitoring tool utilizes the PDF of the UPV measurements on field concrete as well as the standard specimens. The quantification of the loss of soundness of field concrete is defined in a parameter called the “Paste Quality Loss (PQL).”

In order to evaluate the health-monitoring tool specimens are prepared representative of portions of bridge decks. Some decks are uncured while some are over-vibrated and some cast and cured in a proper fashion as control specimens. The PQL parameter conclusively quantified the loss of soundness of the uncured specimen. Comparing the 28th day and 90th day PQL values for the uncured lab-deck indicates as expected a loss of soundness with age. Field implementation of the health-monitoring tool is being initiated.

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