Assessing ConnDOT's Portland Cement Concrete Testing Methods Phase II – Field Trials and Implementation

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Final Report

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16. Abstract

This paper presents a description of efforts to disseminate findings from the Phase I study (SPR-2244), provides examples of applied maturity testing and temperature monitoring in Connecticut, reviews several State Highway Agency protocols for using the method, and presents recommendations for future use in Connecticut.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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INTRODUCTION

Background and Significance

In September 2004, Phase I of this study was initiated to investigate why some cured concrete specimens did not attain designed 28-day strength; to evaluate and demonstrate the concrete maturity method to determine real-time, in-place concrete strength; and, to compare several concrete maturity devices for possible ConnDOT applications. The final report was published in March 2007 *(1)*.

In Phase 1, researchers identified when rejections of Portland Cement Concrete (PCC) occur most often (summer months) and what concrete types have been most problematic (types with design strengths > 3,000 psi). By profiling in-place concrete temperatures with concrete temperature measurement systems, it was demonstrated that field-cured specimens do not adequately represent in-place conditions of the structure, as their respective temperature histories differed significantly. The results indicated that the accuracy of estimated PCC compressive strengths by the maturity method strongly depended upon properly determining a representative maturity function *(1)*.

In-place strength estimations by the maturity method were very good when the strength-maturity relationship was developed from the actual material used to pour the structure being monitored. This was thoroughly documented in the Phase 1 report *(1)*. For that reason, the concrete maturity method was recommended for making in-place concrete strength estimations on larger, more critical structures; however, modifications to the procedures contained in ASTM C 1074 were recommended for ConnDOT applications. Finally, concrete temperature profiling with temperature monitoring systems was recommended because it was shown to provide useful data for monitoring the curing of in-place concrete, especially for concreting in hot/cold weather and for mass concreting operations.

During the early stages of the Phase I research, meetings with Connecticut Department of Transportation (ConnDOT) personnel were held to discuss concrete testing issues. Suggestions for better handling of cylindrical test specimens were made, and memoranda were sent to District Construction Offices to clarify specifications for curing and transporting test specimens. In response, District Construction personnel requested a “Concrete Issues” meeting for further discussions. It was suggested that a PCC Specifications Committee be formed to meet regularly to discuss concrete issues. The committee met three or four times and eventually agreed that ConnDOT *Standard Specifications for Roads, Bridges, and Incidental Construction* needed to be revised.

Research Objective

The primary objectives of this study were to disseminate findings from the Phase 1 study; conduct field trials; develop and implement a protocol for using the concrete maturity method for estimating in-place PCC strength; and, implement further PCC temperature profiling.

Literature Review of State Highway Agency Specifications and Procedures

Texas

The Texas Department of Transportation (TexDOT) makes estimations of concrete strength by the maturity method in accordance with Tex-426-A *(2)*. They use the Nurse-Saul TTF maturity index for their strength estimations, with a datum temperature of negative 10 ºC (14 ºF). They use the method for early opening of pavement to traffic, and with approval may use it for determining in-situ strength determinations of structural concrete when there are schedule restrictions.

TexDOT permits the use of the maturity method for concrete pavement in the capacity of early opening to traffic. They also use maturity meters for cold-weather concreting, hot-weather concreting, and for in-situ strength determinations for schedule restrictions *(3)*. They require that the strength-maturity plot for each mixture, with data points, be reviewed and signed by the contractor or his representative, and that it be reviewed by the District Materials Engineer or equivalent. Finally, they require that inspectors be qualified by a TexDOT training program before using the method.

Strength-maturity relationships are required for every mix design evaluated. This is basically developed according to ASTM C 1074 specifications, although there are some differences, such as calculating a logarithmic best-fit curve through the strength-maturity data for estimating concrete strength placed in the field. Note: TexDOT specifications warn engineers to carefully examine the data when R^2 values are less than 0.9.

Applying this procedure to strength-maturity data collected for ConnDOT Class A Modified Concrete presented in Table 1 and Figure 1, the logarithmic best-fit equation would be:

$$\text{Strength} = 1064*\ln(\text{maturity})-5300$$

In this instance, R^2 was equal to 0.98, which suggests a certain degree of reliability for this equation, which is well above the threshold value of 0.9 indicated in Tex-426-A.

TABLE 1. ConnDOT Class A (Modified) Strength-Maturity Data

Sample	Date Broken	Age (days)	Load (lbf)	Strength (psi)	Maturity (°C-Hrs)
A1	10/7/04	2	58217	2059	1139
A2	10/7/04	2	58924	2084	1142
A4	10/8/04	3	72297	2557	1705
A5	10/8/04	3	75577	2673	1679
A8	10/12/04	7	102240	3616	3897
A9	10/12/04	7	101505	3590	3847
A10	10/19/04	14	126952	4490	7650
A11	10/19/04	14	121664	4303	7566
A13	11/2/04	28	133936	4737	14948
A14	11/2/04	28	133200	4711	14812

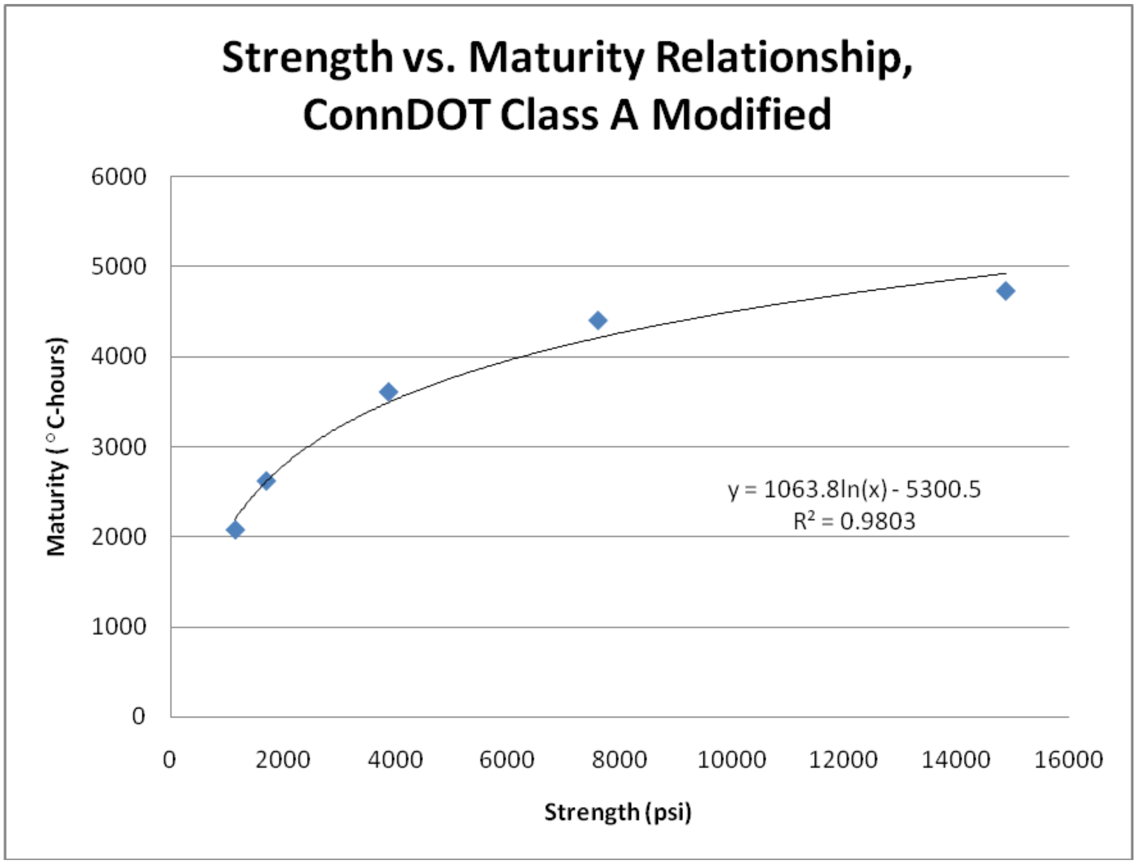

FIGURE 1. Strength-maturity curve for ConnDOT Class A Modified concrete using the Tex-426-A procedure.

In order to determine the necessary maturity for a given strength, the equation (see Figure 1) can be solved for maturity as follows:

$\ln(\text{maturity}) = (\text{Strength} + 5300)/1064$

So, for example, to find the necessary maturity to achieve an estimated strength of 3,000 psi:

$\text{Ln}(\text{maturity}) = (3000 + 5300)/1064 = 7.801$

and, solving for maturity:

$\text{Maturity} = e^{7.801} = 2443\ ^{\circ}\text{C-hours}.$

Inspectors in the field would then know that a minimum maturity of 2,443 °C-hours is needed to achieve a compressive strength of 3,000 psi. Once that target maturity is achieved, they can proceed with the next task, such as removing falsework, shoring, or opening a structure to traffic.

Iowa

The Iowa Department of Transportation's (Iowa DOT) standard specifications *(4)* give contractors the option to use the maturity method for both structural and pavement concretes. For structural concrete, Iowa DOT allows the use of the maturity method for strength determinations for removal of forms and falsework, and for subjecting concrete to exterior loads. For PCC pavements, Iowa DOT provides contractors the option of using the maturity method for determining strengths for opening pavement to traffic. The specification requires that the maturity method be used in accordance with their materials specifications (I.M. 383) *(5)*.

I.M. 383, Testing the Strength of Portland Cement Concrete Using the Maturity Method, outlines Iowa DOT's procedure for using the method. The time temperature factor (TTF) Nurse-Saul concept is specified, and a datum temperature of 14 ºF (-10 ºC) is used there. They measure maturity (M) in ºC-hours, so the equation for measuring maturity becomes:

$$M(^{\circ}C \text{ x hours}) = \Sigma[(T + 10)\Delta t]$$

where,

T is the average concrete temperature during the time interval Δt.

Missouri

In 2000, the Missouri Department of Transportation's (MoDOT) first serious application of the maturity method was used when state officials recognized its potential for a fast-track, ultra-thin whitetopping overlay. They established a strength-maturity relationship with the contractor prior to construction and made in-situ strength estimations throughout construction of the overlay. They used it to make decisions regarding when to saw cut joints and when to open the pavement to traffic *(6)*.

MoDOT developed and has in-place a standard for using the method. Their intent was for contractors to purchase maturity equipment and conduct their own maturity testing *(6)*. The standard covers the method for estimating in-place strengths for pavement or structural applications, and it is basically in accordance with ASTM C 1074, with a few exceptions. One exception is that instead of following initial curing requirements as per AASHTO T 23, it requires that specimens be field-cured for the first 24 hours, demolded at approximately 24 hours, and then standard cured thereafter *(7)*.

Wisconsin

The Wisconsin Department of Transportation's (WISDOT) standard specifications *(8)* and various special provisions permit the use of the maturity method as "…an alternative to compressive strength tests for administering timing of job control functions such as ending the curing period or cold-weather protection periods, opening to service, or removal of forms or false work." WISDOT Construction and Materials Manual (CMM 8.70.4.8) *(9)* requires that data-encrypted sensor devices be used for determining maturity. Specifications for determining the opening strength via the maturity method are included in WISDOT Standard Specifications *(8)*.

In order to use the maturity method, WISDOT specifications require that the contractor develop a strength-maturity relationship for each concrete mix design for which the method is intended to be used. The relationship must be developed from actual concrete used in the field-placement. The contractor is responsible for submitting this relationship to the engineer for approval before the method is incorporated into the work. A new relationship must be developed whenever the mix changes, the average daily temperature changes by 30°F or more, or if estimated strengths by maturity vary from verification compressive strengths by more than 10%.

The WISDOT calibration procedure is similar to the procedure contained in ASTM C 1074, although some modifications are included. The most significant modification relates to how the test specimens are cured, as WISDOT specifications require that specimens be cured "…in conditions similar to which the field concrete will be exposed," whereas the ASTM C 1074 procedure requires that specimens be cured in a water bath or moist room.

WISDOT uses the temperature-time factor (TTF) maturity function for computing the maturity index in accordance with ASTM C 1074. WISDOT's default datum temperature is 32 °F (0 ºC). Alternatively, they permit the use of a mix-specific datum temperature in accordance with Annex A1 of ASTM C 1074.

For pavement concrete, WISDOT uses at least one maturity probe for each 2,000 square yards. For structural concrete, they use at least one probe for each 100 cubic yards. When estimated concrete strengths by means of the maturity method are used for critical operations, WISDOT requires that results be verified with other tests.

WISDOT specifications state that "each workweek the contractor shall provide a set of three verification cylinders to the engineer for each strength/maturity field calibration curve currently in use on the project." They use two cylinder specimens for compressive strength testing, and one for embedding a probe in the center to monitor maturity. They field cure these specimens.

South Carolina

While the South Carolina Department of Transportation does not currently have in-place a procedure for using the maturity method, they do use maturity devices for monitoring temperatures during mass concrete placements. They use them to record temperatures at both the interior and exterior of the structure. Their specification requires that the temperature differential between them be maintained at 35 degrees Fahrenheit or less during curing.

They require that their mass concrete placements be used for pours that have "dimensions of 5 feet or greater in 3 different directions." For circular elements, they interpret this as pours having a diameter of six feet or greater, and a length of five feet or greater *(10)*.

North Carolina

The North Carolina Department of Transportation (NCDOT) uses the maturity method to estimate the compressive strength of concrete pavement to determine whether they will allow traffic or other heavy equipment to travel on it *(11)*. They require a minimum estimated compressive strength of 3,500 psi in terms of the temperature-time factor (TTF) maturity index. They require that a datum temperature of -10 °C be used to calculate the TTF.

NCDOT requires that a strength-maturity relationship be developed for each concrete pavement mix design, and for each mix determine the TTF corresponding to the strength-maturity relationship at 3,500 psi. They require that a new relationship be developed if there are any changes during production, and they require that the relationship be verified during the first day's production and then every ten calendar days thereafter.

DISSEMINATION OF PHASE 1 FINDINGS

On May 17, 2007, a presentation was made titled “An Investigation of Low Strength Concrete Test Results” to a Transportation Research Board (TRB) visitor and staff at the Rocky Hill Laboratory (Figure 2) *(12)*. This presentation focused on the historical analysis of the abovementioned concrete test results, and it described methods of investigating low-strength test results, such as Windsor Probe testing and compression testing of drilled cores.

FIGURE 2. Presentation given to TRB visitor and Central Laboratory staff on May 17, 2007.

Further dissemination was provided via the Department’s Video-on-Demand web site, as the above presentation was added to its Streaming Media Library. Here, users have the ability to view the May 17, 2007, presentation in its entirety by clicking on a link (http://www.ct.gov/dot/spr2252) within the library *(12)*.

Results were regularly presented during PCC Specification Committee meetings. This proved to be an effective platform to present findings, as the committee included several high-ranking employees from the Division of Materials Testing, the Office of

Construction, and the four Construction Districts. This provided valuable feedback from personnel having well over 100 years of combined practical experience. The results presented were well received during the Committee meetings, and the technology was considered for inclusion in ConnDOT specifications.

FIELD TRIALS

Maturity kit demonstrations were provided to field inspectors and contractors working on several high-profile projects. Most notably, they were provided on a few of the contracts included in the I-95 New Haven Harbor Crossing Corridor Improvement Program.

The technology was used on Projects 92-533 and 92-569, which were for widening of I-95 east of the Q-Bridge in East Haven's Frontage Road area. This included deck and parapet wall pours for Bridge No. 180, a deck pour for Bridge No. 5996, and substructure and deck pours for Bridge No. 6610 (See Figure 3). These are listed in Table 2 below.

FIGURE 3. Concrete deck pour for Bridge No. 6610 where maturity probes were embedded on March 29, 2007.

TABLE 2. Concrete Maturity/Temperature Monitoring Locations

Project No.	Bridge No.	Item	Pour Date
92-533	180	Deck	10/23/06
92-533	180	Parapet Walls	11/9/06
92-533	180	Parapet Walls	11/14/06
92-533	5996	Deck	12/11/06
92-569	6610	Abutment #1/ Stem Section #2	12/20/06
92-569	6610	Bearing Pads for Abutment #1	12/21/06
92-569	6611C	Abutment #2, G5 Bearing Pad	3/9/07
92-569	6610	Deck	3/29/07
92-619	169	Piers/Deck	Various
04-128	NA	Truck Escape Ramp	Oct. 2007 to Feb.2008
301-106	NA	Various Elevators/Stairs	November/December 2010

One was for Contract E2, Project 92-619, for the Route 34 ‘Flyover’ Bridge (Figure 4). This was a $99 million, 1,900-foot long, 75-foot high flyover bridge connecting I-95 northbound with Route 34 westbound *(13)*. Consultant inspection, contractor, and ConnDOT District 3 Construction personnel were all given demonstrations of the technology.

FIGURE 4. Route 34 ‘Flyover’ (Bridge No. 169) where concrete maturity and temperature monitoring was demonstrated at Project No. 92-619.

The consultant for the flyover bridge requested a loan of the concrete maturity kit during the winter of 2009. Although they didn't have a formal thermal control plan in-place, they wanted use it to monitor concrete temperatures of concrete pier columns and caps (see Figure 4). The purpose was to determine when to remove insulation during cold weather, and to monitor temperature differentials between the interior and exterior of the pier columns. The consultant indicated that the use of the maturity kit for these purposes was successful. Later, in 2010, the consultant successfully used the maturity kit to monitor temperatures of the 'Flyover' deck (Figure 5) while it was being constructed.

FIGURE 5. Concrete deck for 'Flyover' (Bridge No. 169) on Project No. 92-619.

Project 92-618 utilized a formal thermal control plan for mass concreting operations. These plans were used for pier columns for the Pearl Harbor Memorial Bridge in New Haven.

The thermal control plan limited the temperature differences within the mass pours to a maximum of 35 °F. It included a section entitled "Temperature Monitoring." The plan required that concrete and air temperature be monitored using specified temperature monitoring equipment on an hourly basis.

The consultant identified temperature sensor locations and submitted them to ConnDOT for review. Once these locations were agreed upon, monitoring was conducted by installing two temperature sensors (a primary and backup) at each location. Temperature monitoring continued until completion of the thermal control plan, as agreed upon between the consultant and ConnDOT. The consultant downloaded and logged temperature data and assembled a "daily report of temperature data" for all mass concreting operations. The Project Engineer indicated that the thermal control plan was successful overall, and that the temperature monitoring system worked well. Daily temperature reports generated from the system assured the Project Engineer that thermal control measures were working as planned.

During the 2nd Quarter of 2007, a pre-construction meeting for Project 4-128 was held at the concrete producer's facility. Project 4-128 was for a Truck Escape Ramp (TER) on Route 44 in Avon where Talcott Mountain is traversed (Figure 5) *(14)*. The contractor planned to use the concrete maturity method on the project, and he provided a demonstration of the technology at this meeting. ConnDOT researchers provided an overview of their Phase 1 work to attendees as well. Following the meeting, the contractor wrote a letter to ConnDOT personnel stating that, "As a contractor and long time resident of Connecticut it was reassuring to see that the D.O.T. was open to new technology to better the quality of state resources and the industry in general."

This $3.1 million project received an emergency declaration on October 1, 2007, authorizing the construction of the TER. Construction was completed in less than five months on February 21, 2008. Concrete maturity monitoring was just one of multiple advanced technologies incorporated in the design solution for rapid construction, which was commended for its balance between function and context-sensitivity *(14)*.

FIGURE 6. Truck Escape Ramp (TER) on Route 44 in Avon where Purinton Builders Inc. used the concrete maturity method during construction to complete the work in less than five months. Photo courtesy of Richard Hanley, et al. *(14)*.

Finally, the research team was contacted by a consultant working on Project 301-106 to perform concrete temperature monitoring at several locations for conformance to cold-weather specifications. The purpose of this project was to construct a Component Change Out Shop (CCO) at the New Haven Rail Yard. The Notice to Contractors described the CCO as a multi-story multiuse building that will be the largest facility on the site *(15)*. The research team performed temperature monitoring of the concrete stairs alongside the various elevators inside the building. Temperature monitoring proved successful in verifying that the concrete was insulated sufficiently to keep temperatures above those required in the project specifications.

IMPLEMENTATION

An effort was made to implement the maturity method during PCC Specifications Committee meetings by incorporating its use in revised standard specifications. Progress was made, awareness was raised, and permissive language was added to ConnDOT specifications as a result of these efforts. This report documents how concrete maturity systems were used on several projects for various purposes. Implementation was successful in that regard.

RECOMMENDATIONS

Moving forward, it is recommended that ConnDOT take the next step and adopt a maturity testing procedure similar to that used by TexDOT. It should be used for in-situ strength determinations of structural concrete where there are schedule restrictions. Concrete pavements are not commonly constructed in Connecticut, but for instances where concrete is used, it is recommended that the maturity method be used for early opening to traffic. As part of this research, a draft procedure was prepared and is presented in Appendix A.

It is recommended that a standardized special provision for temperature monitoring be developed. This provision would then be available to ensure that concrete temperatures and temperature differences are not excessive, as per requirements of thermal control plans for mass pours or cold-weather concreting operations. The monitoring system should be capable of measuring and documenting in-place concrete temperatures in accordance with the draft equipment specification contained in Appendix B.

It is recommended that contractors opting to use concrete maturity and/or temperature monitoring be responsible for either performing the monitoring themselves or hiring a consultant that specializes in the technology to do the monitoring for them. The contractor should be required to submit a plan detailing sensor locations, number of sensors, and reporting procedures. They should also be required to submit documentation showing that all personnel performing the testing be qualified by a training program recognized by the Department. Perhaps, in time, a Department certification program could be established to ensure a certain level of individual competence. All plans and lists of qualified personnel should be subject to the review and approval of the Chief of Materials Testing.

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APPENDIX A

Draft Test Procedure for

ESTIMATING CONCRETE STRENGTH BY THE MATURITY METHOD[i,ii]

Connecticut Department of Transportation

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1. SCOPE

1.1 This test method provides a procedure for estimating concrete strength by means of the maturity method. The maturity index is expressed in terms of the temperature-time factor (TTF).

1.2 This practice requires establishing the strength-maturity relationship of the concrete mixture in the laboratory and recording the temperature history of the concrete for which strength is to be estimated.

1.3 The maturity method consists of three steps:

- developing a strength-maturity relationship;
- estimating the in-place strength; and,
- verifying the strength-maturity relationship.

1.4 The values stated in US Customary units are to be regarded as the standard.

2. APPARATUS

2.1 *Maturity Meter*

2.1.1 A commercial battery-powered maturity meter is required to monitor and record concrete temperature as a function of time. The maturity meter must be capable of providing a recording time interval of 20 minutes or less for a 28-day period.

2.1.2 The maturity meter shall be capable of automatically computing and displaying the maturity index in terms of a TTF.

2.1.3 The maturity meter shall have input capability for datum temperature in degrees Fahrenheit.

2.1.4 The same brand and type of maturity meter used to develop and verify the strength-maturity relationship shall also be used in the field.

2.2 Maturity meter calibration shall be verified annually or whenever there is a question of accuracy. This shall be accomplished by placing a randomly sampled maturity sensor in a controlled-temperature water bath and recording whether the indicated result agrees with the known temperature of the water bath. The maturity meter temperature recording device must be accurate to within +/-2 ºF. Verify accuracy at a minimum of three different temperatures, at least 25 ºF apart, reasonably throughout the range anticipated in practice.

3. MATURITY FUNCTION

3.1 The TTF maturity function shall be used as follows:

$$M(t) = \Sigma(T_a - T_o)\Delta t$$

where:

$M(t)$ = the temperature-time factor at age t, ºF-hours;
Δt = a time interval, hours;
T_a = Average concrete temperature during the time interval, Δt, ºF; and’
T_o = datum temperature, ºF.

3.2 A datum temperature of 14 ºF shall be used unless specified otherwise.

4. PROCEDURE TO DEVELOP STRENGTH-MATURITY RELATIONSHIP

4.1 Develop a strength-maturity relationship for every concrete mix design being evaluated by the maturity method.

4.2 *Cylindrical Specimens, Compressive Strengths, and Maturities*

4..2.1 Sample fresh concrete in accordance with ASTM C 172 from a minimum 4-cubic yard batch. The mixture proportions and constituents of the concrete shall be similar to those of the concrete whose strength will be estimated using this practice.

4.2.2 Prepare at least fifteen 6-inch cylidrical specimens according to ASTM C 31.

4.2.3 Test each batch of fresh concrete for concrete temperature (ASTM C 1064), slump (ASTM C 143), and air content (ASTM C 231 or ASTM C 173).

4.2.4 Embed maturity meter temperature sensors to within ½-inch of the centers of at least two additional 6-inch cylindrical specimens prepared, as much as possible, according to ASTM C 31.

4.3 Standard cure the 17 (15 plus 2 with embedded sensors) cylindrical specimens according to ASTM C 31.

4.4 Perform compression tests at ages of 1, 3, 7, 14, and 28 days in accordance with ASTM C 39. Test two specimens at each age and compute the average strength. If the range of compressive strength of the two specimens exceeds 10% of their average strength, test another cylinder and compute the average of the three tests.

4.5 At each test age, record the individual and average strengths from Section 4.5 above, and the respective individual and average maturity indexes from the instrumented specimens read at the time of the compression tests.

4.6 *Strength-Maturity Relationship Plot*

4.6.1 Plot the average strengths as a function of the average maturity values, with data points shown. Using a computer spreadsheet program such as Microsoft Excel, calculate a logarithmic (natural base, ln) best-fit curve through the data. Record the equation of the curve and the R^2 value. The resulting curve is the strength-maturity relationship to be used for estimating the strength of the concrete mixture placed in the field.

Note. When developing the strength-maturity relationship, the spreadsheet software allows the Engineer to develop the corresponding maturity equation that defines the strength-maturity relationship and an R^2 value to fit the strength-maturity relationship. The R^2 value indicates the reliability of the strength-maturity relationship. Expected results should produce an R^2 value of at least 0.90. When the reliability is less than 0.90, the Engineer should carefully examine the data for "outliers," faulty breaks, or faulty maturity readings. The Engineer should use judgment to determine if certain points should be discarded, or retested, or whether the entire strength-maturity relationship should be redeveloped.

4.6.2 The plot of the strength-maturity relationship for each concrete mixture must be circulated and signed by the Contractor or his/her representative and reviewed by the Chief of Materials Testing. Plots must include all data points, logarithmic best-fit equations, and R^2 values.

5. PROCEDURE TO ESTIMATE IN-PLACE STRENGTH

5.1 The Engineer may use discretion to have an inspector present at the concrete producer's plant when placing concrete to be evaluated by the maturity method. Daily verification of batching operations is recommended to ensure adherence to required mix proportions.

Note: Any alteration in mix proportions or source or type of any material, in excess of those tolerable by batching variability, requires the development of a new strength-maturity relationship prior to its use. This includes a change in type, source, or proportion of cement, fly ash, coarse aggregate, fine aggregate, or admixtures. A change in water-to-cementitious material ratio greater than 0.05 requires the development of a new strength-maturity relationship.

5.2 Prior to or at the time of concrete placement, install maturity meters at the frequency specified in the pertinent item of work. Install a minimum of two meters at locations in the structure that are critical in terms of structural considerations or exposure conditions as directed by the Engineer. Place meters 2-4 inches from any formed surface or at mid-depth of the section for sections less than 4 inches. Note: meters may be tied to reinforcing steel but should not be in direct contact with the reinforcing steel or formwork.

5.3 When verification tests are required or when maturity will be used to estimate strength for removal of structurally critical formwork or falsework, or for steel stressing or other safety-related operations, perform specimen strength tests in accordance with Section 6.

5.4 As soon as practical after concrete placement, connect and activate the maturity meter(s). Note: do not disable meters until the required maturity values are achieved. Data collection must be uninterrupted.

5.5 Record the maturity data, and document Required Strength and the Required TTF for the specified Operation.

5.6 When the maturity is at a value that is equal to or greater than the required strength for that concrete mixture, as determined by the strength-maturity relationship, record the maturity value, and when appropriate per Section 5.3, verify the specimen strength in accordance with Section 6.

5.7 Clip the wires at the concrete surface.

6. *Verifying Strength-Maturity Relationship*

Note: specimen strength tests may be included as Verification Tests at the discretion of the Engineer.

6.1.1 Sample fresh concrete in accordance with ASTM C 172 from an actual pour for the project where strength estimations are being made by the maturity method.

6.1.2 The sample must be obtained from a batch of at least 4 cubic yards.

6.2 Make a minimum of four 6-inch cylindrical specimens in accordance with ASTM C 31.

6.2 Test fresh concrete for placement temperature, slump, and air content in accordance with ASTM C 1064, ASTM C 143, and ASTM C 231 or ASTM C 173.

6.3 Embed one sensor in the middle of one of the 6-inch cylindrical specimens. Place the sensor 2-4 inches from any surface. Begin data collection as soon as the meter contacts the fresh concrete. Data collection must be uninterrupted.

6.4 Field cure the specimens for the first 24 hours as per field curing requirements contained in ASTM C 31. In the event the next day is a holiday or weekend, field cure the specimen until the next regular work day. Demold the specimens immediately upon removing them from field curing, and then standard cure them as per ASTM C 31 requirements thereafter.

6.5.1 Perform compression strength tests on two of the specimens when the instrumented specimen achieves the TTF (within 10%) corresponding to the design strength, or when the required TTF of the member is achieved in the field, if estimating strength for removal of structurally critical formwork or falsework or for steel stressing or other safety-related operations. If the two specimen strengths are not within 10% of one another, test the third specimen.

6.5.2 Perform all compression tests in accordance with ASTM C 39.

6.5.3 Record the individual strengths, compute the average of the two or three (if 3 were tested as per Section 6.5.1) specimen strengths, and record the average strength. On the same form, record results of tests performed as per Section 6.2.

6.6 Compare the average strength determined from Section 6.5.3 to the strength predicted by the strength-maturity relationship. The average strength of the specimens must be within the verification tolerance specified for the item of work.

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[i] Test Procedure for Estimating Concrete Strength by the Maturity Method, Tex-426-A, ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/400-A_series/pdfs/cnn426.pdf, Texas Department of Transportation, 2010, Accessed July 29, 2011.

[ii] ASTM C 1074-98

APPENDIX B

Draft Specification for
Concrete Temperature Measurement Systems

Sensors shall be equipped with a battery, clock, temperature sensor and memory unit.

Sensors shall be equipped with unalterable unique identifications numbers and be capable of storing placement notes.

The system shall include a handheld or laptop computer, or reader for downloading sensor data.

Sensor Accuracy:	± 2 °F
Sensor Temperature Range:	23 °F to 185 °F
Minimum Measurement Interval:	1 hour
Minimum Measurement Duration	28 days