Early Age Concrete Acceptance

Final Report

Synthesis Report from Tennessee Technological University | Benjamin J. Mohr, M. Shariful Islam, and Pramashis Kar | June 30, 2024

Sponsored by Tennessee Department of Transportation Long Range Planning Research Office & Federal Highway Administration

DISCLAIMER

This research was funded through the State Planning and Research (SPR) Program by the Tennessee Department of Transportation (TDOT) and the Federal Highway Administration under ***RES2024-06: Early Age Concrete Acceptance.***

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
RES2024-06		

4. Title and Subtitle	5. Report Date
Early Age Concrete Acceptance	June 30, 2024
	6. Performing Organization Code
7. Author(s) Benjamin Mohr, M. Shariful Islam, and Pramashis Kar	8. Performing Organization Report No.
9. Performing Organization Name and Address Tennessee Technological University Box 5015, 1020 Stadium Drive Cookeville, TN 38505	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Tennessee Department of Transportation 505 Deaderick Street, Suite 900 Nashville, TN 37243	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
The Tennessee Department of Transportation (TDOT) is administering more early strength requirements due to accelerated project delivery timelines. Therefore, the main objective of the current study was to establish a non-destructive procedure to predict the strength at an early age. For this, the Nurse-Saul maturity function was considered with a datum temperature of 32 ºF (0 ºC). Locally available materials were collected from East and West areas of Tennessee to produce 8 mixes with 4 types of concrete per TDOT classification, i.e., Class A, D, CP, and X-HES. 4x8 and 6x12 inch cylinders, depending on the TDOT mix class, were prepared to obtain compressive strength at 1, 3, 7, 14, and 28 days. The results revealed that all mixes met the fresh properties (slump, air content, unit weight) and minimum strength requirements. The maturity relationship for each particular class of mix was determined by a logarithmic function from a best fit curve of the strength-maturity data. Field verification of predicted concrete strength was conducted based on the lab-determined strength-maturity relationships at different maturity levels from a commercially available maturity system. For validity of strength-maturity relationship by field data, each logarithmic relationship was plotted along with ±10% boundary conditions and 95% one-sided confidence interval. Field verification results indicated that the strength-maturity relationships can successfully predict the strength at an early age within ±10% boundary conditions. Therefore, the established strength-maturity relationships allow for the prediction of later age strength of different TDOT concrete mixes.

17. Key Words	18. Distribution Statement
NURSE-SAUL MATURITY FUNCTION, TDOT CLASS MIX, STRENGTH-MATURITY RELATIONSHIP, FIELD VERIFICATION	No restriction. This document is available to the public from the sponsoring agency at the website http://www.tn.gov/.

19. Security Class if. (of this report)	20. Security Class if. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	xxx	

Executive Summary

Key Findings

The key findings of this project are listed below:

- The maturity relationship for each particular class of mixes was determined by a logarithmic function showing a best fit curve. The relationship effectively represented the maturity-strength data as indicated by the R^2 values justified by the statistical significance test at 95% confidence level.
- Variations in mix composition (e.g., water-to-cement ratio (w/c), aggregate type and amount, and admixture type and dosage) all influence the laboratory determined strength-maturity relationship. In particular, seasonal changes in admixtures may require additional lab testing,
- Field verification results indicated that the strength-maturity relationships can successfully predict the strength at an early age for later age within ±10% boundary conditions for TDOT Class A, D, CP, and X-HES. In order to accelerate project delivery, including construction payment schedules, the potential strength of concrete can be predicted using the Nurse-Saul maturity function using a datum temperature of 32 ^oF (0 ^oC)

Key Recommendations

The key recommendations are listed below:

- The maturity method is mixture specific as the maturity-strength relationship works only on a particular mix of concrete. If mix proportions or components are changed, a new relationship must be developed for predicting the strength.
- The maturity method may be established using Nurse-Saul function with a datum temperature of 32 ^oF (0 ^oC) for relatively warm weather condition, while a datum temperature of 14 ^oF (-10 ^oC) may be considered for Tennessee as this state often experiences freezing during winter. Maturity curve should be plotted by a best fit logarithmic function with a R^2 value of around 0.90 ensuring the statistical significance test at 95% confidence level. This will allow the strength prediction more confidently.
- Field-based, commercially available maturity systems should be selected after careful consideration, with potential backups in place.
- Since external environmental temperature frequently varies, it is recommended to collect field cylinders and wait 30 to 60 mins under laboratory conditions to equilibrate the cylinder to the room temperature prior to testing compressive strength.

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Chapter 1 Introduction

The typical design strength of conventional concrete is obtained at 28 days. However, there is an increasing need to predict design strength at earlier ages. Often, projects cannot wait to verify if in-place concrete has reached the desired strength, particularly with increased use of accelerated construction schedules. Currently, Tennessee Department of Transportation (TDOT) accepts the design strength of traditional concrete at 28 days and still bases acceptance and payment on 28-day cylinder breaks. However, TDOT is administering more early strength requirements in plans due to accelerated project delivery schedules. Therefore, in order to avoid the above circumstances, TDOT needs to set early-age acceptance criteria that can be used to approve concrete at earlier ages.

The maturity method is an accepted non-destructive procedure for providing dependable early age data for the prediction of later age strength. In this method, a combined effect of the concrete temperature and age on the strength development during its hardening is typically accounted. Concrete temperature is a function of the hydration of cementitious materials along with the influence of the surrounding atmospheric condition. Typically, the temperature is measured in the concrete during its hardening stage using thermocouples or similar sensors, which may be used to calculate the real time maturity index as a function of age. In other words, the maturity method measures the early age temperature of concrete and correlates that data to a measured strength. Once this correlation curve is developed for a particular mix, this correlation can be applied to field situations to improve the overall project delivery schedule by predicting the strength development.

By using the maturity method, it is possible to confidently estimate the field strength of concrete well before the acceptance age (e.g., 28 days) in order to accelerate the overall construction project delivery timelines such as removal of formwork, opening to traffic, and application of partial construction loads. For the verification of predicted strength, concrete cylinders or other specimens can be tested at the indicated time by the maturity method. However, after developing the correlation curve for a particular mix design of concrete, if the proportions are changed, a new curve must be developed. Since TDOT has standard classes of mixes, it may be possible to determine curves over a range of mixes and apply this range to field placement. If done properly, it may be possible to eliminate most destructive field cylinder testing.

Currently, ASTM C1074 (2019) and AASHTO T325 (2022) provide specifications for estimating the concrete strength through the maturity index. Other state DOTs, such as Alabama, Texas, and Oregon, previously established their own specification on the maturity method and successfully utilized this method in the real-life construction projects in order to reduce the overall timeframe of the projects, especially for accelerating the construction schedule. However, TDOT does not have any standard specifications for the maturity method. TDOT needs to set early age acceptance criteria that can be used to approve early strength concrete at the age that it is intended to be in service. The main objective of the current study is to establish the strength-maturity relationships for different TDOT class concrete to predict the strength and to provide TDOT standard specifications on maturity method after verifying the relationship with field data.

Chapter 2 Literature Review

This section reviews the theory behind the maturity method of concrete for estimating the predicted strength of concrete. The primary focus of this Chapter will be on the Nurse-Saul Maturity Function (Temperature-Time Factor Method), to establish the maturity method for TDOT.

2.1 Development of Maturity Method

The maturity method was originally developed in the 1950's (Saul 1951) but was not fully utilized until the 1980's with the publication of the first standard, ASTM C1074 (2019). The strength development of concrete is typically influenced by the temperature during the early ages of the concrete curing process. Therefore, a method can be used to estimate the in-place strength of concrete using the time and temperature profile, which is known as the maturity method (Carino 1991). According to ASTM C1074 (2019), the maturity of the concrete is the development of its physical properties as the hydration of cementitious materials continue with time. ASTM C1074 (2019) also presents two maturity functions: (1) the Nurse-Saul maturity function and (2) the Arrhenius maturity function. For strength predictions based on concrete temperature, the Nurse-Saul maturity function is simple and quick to implement, while the Arrhenius maturity function is suitable for the non-linear strength development of concrete. Most transportation agencies (DOTs) use the Nurse-Saul maturity function due to its simplicity. Moreover, the verification for the Nurse-Saul method through in-place strength is more practical. When a maturity function is used based on the temperature history of a mix to estimate the value, it is called a maturity index. Therefore, using the concept of the maturity method, it is possible to quantify the strength of the concrete regardless of ambient temperature since the internal concrete temperature profile is considered for a particular mix to obtain the strength-maturity relationship. An illustration of the maturity method for concrete cured at cold and hot temperatures is shown in Figure 2-1.

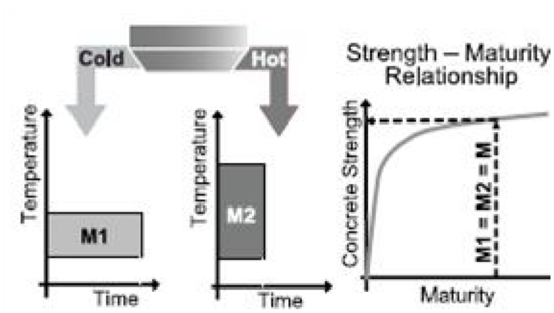


Figure 2-1 Maturity concept (Kaburu et al. 2016).

2.2 Nurse-Saul Maturity Function (Temperature-Time Factor)

In this method, the temperature-time factor has been obtained by a mathematical basis. A typical temperature-time relationship is shown in Figure 2-2. Therefore, this method is also well known as the temperature-time factor method per ASTM C1074 (2019). In this method, a datum temperature is used to calculate the maturity of the concrete as interpreted by Carino (1991). The Nurse-Saul maturity function is defined in Equation 1 from ASTM C1074 (2019):

$$M(t) = \Sigma(T_a - T_0)\,\Delta t \qquad (1)$$

Commented [MB1]: M as a function of t equals the sum of, open parenthesis, T subscript a minus T subscript 0, closed parenthesis, times delta t

where,

$M(t)$ = the temperature-time factor at age t, (ºC-hours),

Δt = a time interval (hours),

T_a = average concrete temperature during time interval, Δt, and

T_0 = datum temperature, °C.

The Nurse-Saul maturity function is the sum of the average temperature for the time interval minus the datum temperature multiplied by the time interval of interest. A schematic of the Nurse-Saul maturity function can be seen in Figure 2-3. The concrete temperature history of the concrete is shown with the curved line, whereas the Nurse-Saul maturity index for each time interval is accumulated in the shaded rectangular blocks.

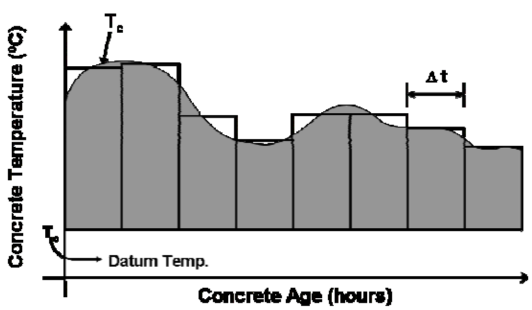


Figure 2-2 Typical temperature-time relationship (Nixon et al. 2008).

Typically, temperature plays a significant role in developing the strength of concrete over time. According to Saul (1951), the datum temperature is the lowest temperature at which concrete gains strength. In that study, a recommended datum temperature was 13.1 °F (-10.5 °C). In contrast, a recommended datum temperature of 14 °F (-10 °C) was determined according to

Carino (1991), Texas DOT (2017), Iowa DOT (2023), and Indiana DOT (2020). ASTM C1074 (2019) provides a procedure to calculate the datum temperature of a particular mix. If no previous data are available, a datum temperature of 14 °F (0 °C) is recommended for Type I cement without admixtures and cured between 32 and 104 °F (0 and 40 °C).

For each particular concrete mix, specimens are monitored for internal temperature while also testing the compressive (or flexural) strength of complementary specimens. Once the temperature-strength relationship is developed for a particular mix, the resulting best-fit curve is the strength-maturity relationship used for estimating the strength of the concrete mix cured under other curing conditions. An example of a relationship between compressive strength and temperature-time factor (maturity) is shown in Figure 2-3, which was obtained using Nurse-Saul maturity function.

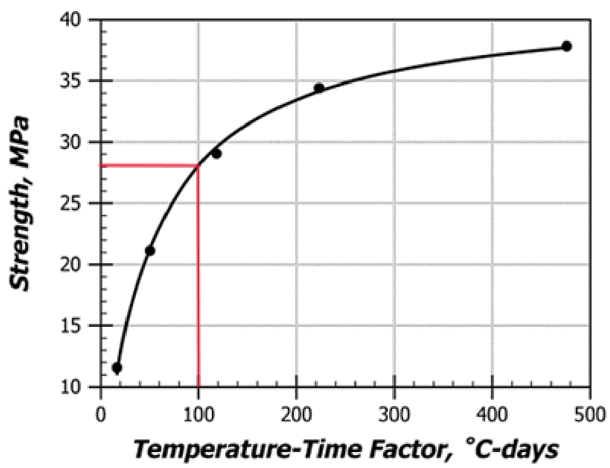


Figure 2-3 Example of a relationship between compressive strength and temperature-time factor, adopted from ASTM C1074 (2019).

The current literature review mainly focuses on the Nurse-Saul maturity function (temperature-time factor method). It was determined that the Nurse-Saul maturity function is simple and quick to implement. Most transportation agencies (such as Indiana DOT, Texas DOT, and Iowa DOT) use the Nurse-Saul maturity function due to its simplicity. See Appendix A for different state DOT practices. Therefore, the Nurse-Saul maturity function is generally thought to be the more practical between these two methods in the field use.

2.3 Development of Maturity Relationship

A minimum of 15 concrete cylinders (or beams) are to be cast per ASTM C1074 (2019). After casting the specimens, thermocouples or temperature sensors are embedded within ±15 mm of the centers of at least 2 specimens according to ASTM C1074 (2019) and other DOT specifications for the maturity method (Texas DOT (2017), Iowa DOT (2023), Ohio DOT (2012), Alabama DOT (2008), as seen in Appendix A. After placing the sensor, it should be connected to a maturity instrument or to a temperature-recording device for obtaining the temperature of the concrete. Water or moist room curing per ASTM C511 (2021) will aid in reducing temperature differences between test specimens.

For lab-based testing, a data logger or similar data acquisition system can be used to monitor multiple specimens simultaneously. Temperature readings should be taken at least every 30 minutes for the first 48 hours and can be extended at later ages. The measuring accuracy for the thermocouple sensors should be ±2 °F (±1 °C) and able to record temperatures in the range of 14 to 194 °F (-10 to 90 °C).

In-situ field monitoring can be accomplished using similar means as lab-based testing. However, there are several commercially available products, including wireless sensors, that automatically calculate maturity values and may be more practical for field conditions.

According to ASTM C1074 (2019), compressive (or flexural) strength testing should be conducted at ages of 1, 3, 7, 14, and 28 days in accordance with ASTM C39 (2023). In certain cases, additional testing may be warranted, such as high early strength mixes. Two specimens should be tested at each age and an average strength should be taken into the account. If the range of compressive strength of the two specimens exceeds 10% of their average values, the third specimen should be tested, and the average of three specimens should be accounted, if a lower value is obtained from a defective specimen, it should be discarded.

After obtaining the strength, a graph should be plotted with an average strength as a function of the average value of the maturity index. The curve should be best-fitted which will represent the strength-maturity relationship that can be used as the calibration for estimating the strength of the concrete mixture cured under the similar temperature conditions.

Chapter 3 Methodology

3.1 Materials

This section contains the information of all the materials such as fine aggregate, coarse aggregate, cementitious materials, and admixtures used to prepare the concrete.

3.1.1 Aggregates

In this study, fine aggregate (FA) and coarse aggregate (CA) were adopted from different regions in Tennessee. Two types of natural sand (NS) were used as fine aggregate denoted as NS-1 and NS-2. For coarse aggregate, #57 crushed limestone and #57 pea gravel were considered. Both FAs and CAs were collected from east and west Tennessee regions, respectively. The specific gravity and absorption capacity of coarse and fine aggregates were determined in accordance with ASTM C127 (2015) and ASTM C128 (2022), respectively. The results are presented in Table 3-1. The sieve analysis was done according to ASTM C136 (2019) and the results are shown in Appendix B, while the fineness modulus is summarized in Table 3-1. Additionally, both as-received the fine and coarse aggregates underwent sieve analysis to ensure compliance with ASTM C33 (2023) gradation requirements (Appendix B). For both fine aggregates, there was slightly over passing #30 sieve (61-64%) than specified value (60%).

Table 3-1 Aggregate properties.

Aggregate	*Specific Gravity (SSD)*	*Absorption Capacity (%)*	*Fineness Modulus*	*Bulk Unit weight (pcf)*
NS-1	2.59 ± 0.01	0.9 ± 0.02	2.59 ± 0.07	99.18 ± 0.04
NS-2	2.57 ± 0.03	1.1 ± 0.06	2.54 ± 0.02	103.40 ± 0.38
#57 crushed limestone	2.70 ± 0.06	1.28 ± 0.01	N/A	99.83 ± 0.50
#57 pea gravel	2.33 ± 0.14	5.71 ± 0.61	N/A	89.80 ± 0.40

Note: N/A indicates not applicable

3.1.2 Cement

For this project, two types of cement ASTM C595 (2023) Type IL and ASTM C150 (2022) Type III cements were used based on their applicability. In Tennessee, ASTM Type I/II cement has almost completely transitioned to ASTM Type IL cement.

3.1.3 Chemical Admixtures

Air entraining admixture (AEA) with the recommended dosage range of 0.125 to 1.5 oz/cwt was used for all the mixes to obtain the desired air content value. High range water reducer (HRWRA) with a recommended dosages of 2-15 oz/cwt was used for Class D-E, X-HES-IL, and X-HES-III mixes to increase the workability of the fresh mix. Accelerator was used only with Class X-HES mixes within the manufacturer’s recommended dosages of 10–45 oz/cwt.

3.2 Experimental Method

This section thoroughly discusses the methodological approach of selecting mix designs and establishing the strength-maturity relationships for four TDOT mix design classes: (1) Class A (for structural or general use), (2) Class D (for bridge decks), (3) Class CP (for paving), and (4) Class X (specialized – high early strength in this research).

3.2.1 Trial Mix Designs

In the initial phase of the study, the trial mix proportions for all candidate concrete mixes were determined based on TDOT specifications, as broadly shown in Table 3-2. A total of 8 mixes were considered, namely A-E, A-W, D-E, D-W, CP-E, CP-W, X-IL, and X-III. Here, 'A', 'D', 'CP', and 'X' represent TDOT class of concrete, while 'E' and 'W' indicate aggregate sources from the East and West regions of Tennessee. Once the candidate mix proportions were selected as seen in Table 3-2, initial trial mixes were started. No supplementary cementitious materials were used in this mix design. Type IL cement was used for all the mixes, except for Class X, designated as X-HES-III. A series of trial batches were done and adjustments made to ensure each mix met TDOT specifications. The final mix design of each batch mix is presented in Table 3-3.

Table 3-2 Initial candidate mix designs.

Mix	FA Type	CA Type	Cement (pcy)	w/c	FA/Total aggregate (%)	Slump (in)	Air Content (%)	Min Strength (psi) @ 28 days
A-E	NS-1	#57 Limestone	564	0.44 (0.45 max)	0.40 (0.44 max)	3 ± 1	6 ± 2	3000
A-W	NS-2	#57 Pea Gravel	564	0.44 (0.45 max)	0.40 (0.44 max)	3 ± 1	6 ± 2	3000
D-E	NS-1	#57 Limestone	620	0.38 (0.40 max)	0.40 (0.44 max)	6-8	7 (4.5-7.5)	4000
D-W	NS-2	#57 Pea Gravel	620	0.38 (0.40 max)	0.40 (0.44 max)	6-8	7 (4.5-7.5)	4000
CP-E	NS-1	#57 Limestone	526	0.44 (0.45 max)	0.40 (0.44 max)	3 ± 1	5 (3-8)	3000
CP-W	NS-2	#57 Pea Gravel	545	0.44 (0.45 max)	0.40 (0.44 max)	3 ± 1	5 (3-8)	3000
X-HES-IL	NS-1	#57 Limestone	714 (Type IL)	0.35	0.44	3 ± 1	6 ± 2	3000 @ 18h
X-HES-III	NS-1	#57 Limestone	620 (Type III)	0.35	0.44	3 ± 1	6 ± 2	3000 @ 18h

Table 3-3 Final mix designs.

Mix	Cement (pcy)	Water (pcy)	FA (pcy)	CA (pcy)	AEA (oz/cwt)	HRWRA (oz/cwt)	Accelerator (oz/cwt)	w/c	FA/Total aggregate
A-E	564	263	1102	1957	0.43	0	0	0.45	0.37
A-W	564	214	1345	1552	0.43	0	0	0.38	0.44
D-E	620	242	1186	1854	0.17	4.92	0	0.39	0.40
D-W	620	236	1183	1609	0.43	0	0	0.38	0.40
CP-E	526	237	1222	1911	0.69	0	0	0.45	0.40
CP-W	546	207	1330	1598	0.43	0	0	0.38	0.43
X-HES-IL	714	228	1285	1705	0.42	7.73	17.18	0.32	0.44
X-HES-III	620	217	1212	1895	1.27	8.59	0	0.35	0.40

3.2.2 Mixing Procedure

All mixes were prepared according to ASTM C192 (2019) in a 3 ft^3 capacity drum mixer, as shown in Figure 3-1. Aggregates were oven-dried and cooled to room temperature prior to use. Moisture corrections were subsequently made to account for moisture contents lower than saturated surface dry (SSD).

(a) (b)

Figure 3-1 (a) Concrete drum mixer and (b) discharged concrete mix.

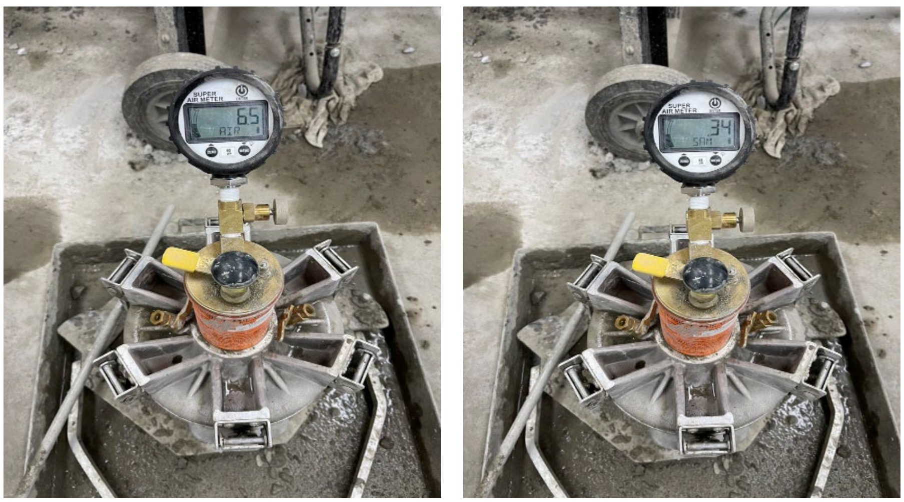
3.2.3 Fresh Property Testing

Slump testing was conducted according to ASTM C143 (2020) and AASHTO T119 (2023), as shown in Figure 3-2. Reported values in Chapter 4 are the average of at least 2 batches for each mix.

Figure 3-2 Slump measurement.

Prior to air content testing, the fresh unit weight was recorded of each mix, according to ASTM C138 (2023) and AAHSTO T121 (2023). The air content of the fresh concrete mix was measured by the Sequential Pressure Method (i.e., Super Air Meter (SAM)) according to AASHTO T395 (2022).

Air content readings were taken at pressures of 14 ± 0.05, 30 ± 0.05, and 45 ± 0.05 psi. Air contents reported in Chapter 4 were taken at the initial pressure reading (Figure 3-3(a)), while SAM numbers represent all ranges of pressures (Figure 3-3(b)).



(a) (b)

Figure 3-3 (a) Air content and (b) SAM readings according to AASHTO T395 (2022).

3.2.4 Development of Strength-Maturity Curve

In this study, ASTM C1074 (2019) was followed to develop the early-age strength relationship with the maturity of concrete. The Nurse-Saul maturity function, shown in Equation 1, was used to determine the maturity (^{o}C-hours) for each class of concrete mixes.

For each of the concrete mixes, 17 cylinders were prepared – 2 for maturity testing and 15 for compressive strength testing at various ages. For Class A, Class D, and Class X mixes, 4x8" cylinders were used, which required two batches of concrete. For Class CP mixes, 6x12" cylinders were used, which required four batches of concrete.

For 2 maturity testing cylinders, once the concrete was properly placed in the cylinder mold, a small plastic straw was positioned vertically to the middle depth of concrete. A K-type thermocouple was subsequently inserted into the straw. After insertion of thermocouple, the wire was labeled and connected to the data logger. Those cylinders containing the thermocouples were sealed with aluminum tape (while plastic cap was used to seal other 15 cylinders) for initial curing as well as to secure the thermocouple, as seen in Figure 3-4. All concrete cylinders were initially cured for 24 hours at 73 ± 5 ^oF (23 ± 3 °C) prior to demolding. Upon demolding, all cylinders were placed in a limewater curing tank at 73 ± 2 ^oF (23 ± 0.5 °C). The dosage of lime (calcium hydroxide) was 3 gm/L in the curing tank.

In this research, a 16-channel data logger was used to simultaneously monitor the 8 concrete mixes (Figure 3-5). The data logger was connected to a computer to continuously monitor the temperature in real-time using a downloadable software that was supplied by the data logger producer. Data were collected over 28 days, until the final set of compressive strength tests were conducted. For the initial 48 hours, the average concrete temperature (T_a) was recorded every 10 minutes. After this period, the recording interval for the average temperature (T_a) was extended to every 30 minutes, providing a detailed profile of the thermal behavior throughout the curing process.

Compressive strength of concrete was initiated at ages of 1, 3, 7, 14, and 28 days for all Class A, D, and CP mixes. For Class X-HES mixes, additional early testing was conducted at 18 hours, followed by the standard intervals of 1, 3, 7, 14, and 28 days. Cylinders were tested by a compression frame having a capacity of 400-kip at a rate of 35 ± 7 psi/sec (0.25 ± 0.05 MPa/sec), according to ASTM C39 (2021) and ASTM C1231 (2023). ASTM C1074 (2019) allows for the testing of 2 cylinders at each age provided the range of their strength values does not exceed 10%. However, in this research, a modified approach was taken such that 3 cylinders were tested at each age and any values exceeding 10% of the average were excluded from further analysis.

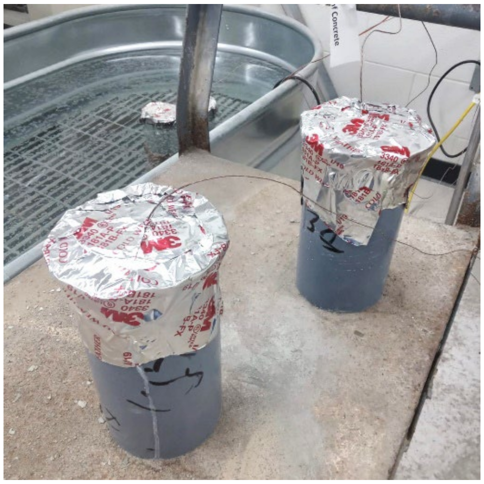


Figure 3-4 Maturity cylinders with embedded sensors during initial curing.

Figure 3-5 A 16-channel data logger for monitoring of 8 different concrete mixes.

3.2.5 Verification of Strength-Maturity Curves in Field Conditions

Once the strength-maturity correlation curve was determined from the laboratory-cured specimens, 11 cylinders from each of the 8 mixes were cast for field verification. 2 cylinders were used to embed the sensor to monitor temperature and maturity, while 9 cylinders were used for compressive strength testing at three different maturity values.

For field verification, a different maturity sensor system was utilized. There are a variety of commercially available maturity sensors available. In this research, a wireless sensor system was used for monitoring of maturity. The cloud-based system could be accessed by any device (i.e., not limited to certain operating systems or devices). Each sensor was connected to a small, reusable transmitter, which then sent data to a 4G receiver to upload data to the cloud server (Figure 3-6(a)). The receiver was located approximately 200 feet from the transmitters, inside a building (Figure 3-6(b)). Maturity sensors embedded in the concrete cylinder and the samples in an external environment are shown in Figure 3-6(c) and 3-6(d), respectively. However, as occurred during the course of this research, even a cloud-based system is subject to security concerns as the vendor server was hacked during the research and all data was lost and not recovered for some mixes.

(a)

(b)

(c)

(d)

Figure 3-6 (a) Maturity sensor connected to transmitter, (b) 4G receiver, (c) maturity sensor embedded in the concrete cylinder, and (d) samples are in an external environment

Once the cylinders were cast with the embedded maturity sensors and each sensor was correlated with the lab-based strength-maturity correlation parameters, data could be monitored in real-time using the associated cloud-based software.

For verification, compressive strength of the field cured cylinders was measured when the associated maturity was approximately 3000, 6000, and 12,000 °C-hours. If the measured compressive strength was within ±10% of the predicted compressive strength, only 2 cylinders were tested for strength. If the measured strength fell outside the ±10% strength window, a third cylinder was strength-tested.

Chapter 4 Results and Discussion

4.1 Fresh Concrete Properties

The fresh properties of all concrete mixes in this study are summarized in Table 4.1. Importantly, the slump and air content for all mixes met the TDOT requirements as outlined in Table 3-2. Additionally, the SAM numbers in this study are below 0.32 for 6 of the mixes, with the exceptions being 2 mixes for Classes D-W and CP-E. The observed unit weights of the mixes vary, reflecting the inherent characteristics of the materials used.

Table 4-1 Fresh concrete properties.

Mix	*Average Slump (in)*	*Average Air Content (%)*	*Average SAM*	*Average Unit Weight (pcf)*
A-E	2.1	6.2	0.27	143.4
A-W	2.6	6.6	0.12	135.6
D-E	4.6	5.5	0.31	144.4
D-W	5.4	6.9	0.65	135.2
CP-E	2.8	5.5	0.54	145.3
CP-W	1.4	6.5	0.16	136.9
X-HES-IL	2.5	6.0	0.18	141.3
X-HES-III	3.1	6.8	0.27	144.3

4.2 Laboratory-Based Strength-Maturity Relationships

Figure 4-1 illustrates the strength-maturity relationship for all mixes, with a datum temperature of 32 ^{o}F (0 °C) cured in a limewater tank at constant temperature per ASTM C511 (2021). The results confirm that all mixes meet the minimum strength requirements as outlined in Table 3.2. A summary of the laboratory-based compressive strength and maturity results is given in Appendix C.

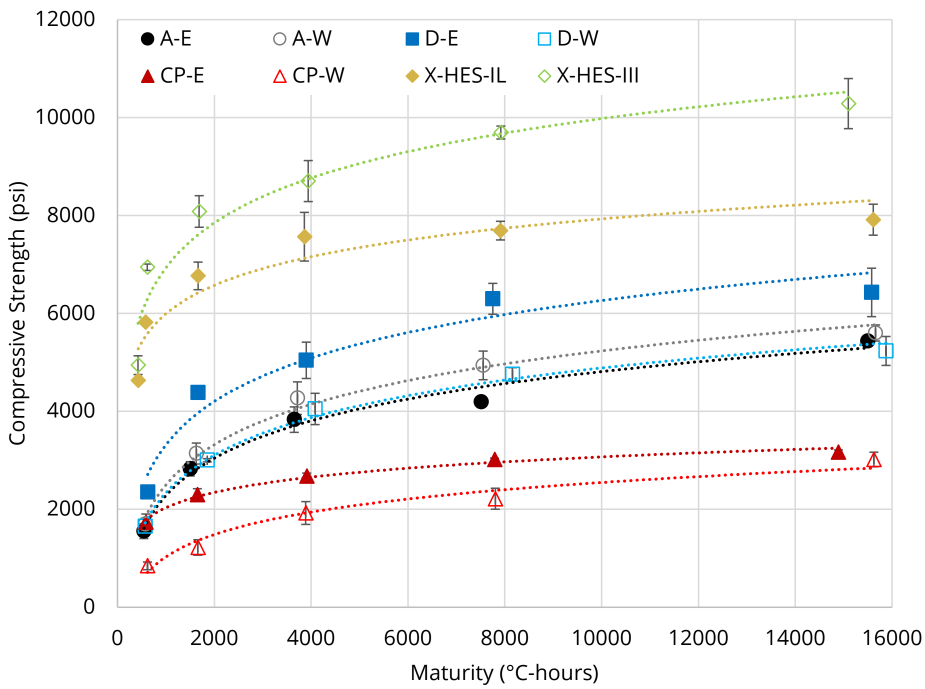


Figure 4-1 Strength-maturity relationships for all 8 mixes (datum temperature = 32 °F (0 °C)).

Figures 4-2 through 4.5 show the relationship for each particular class of mixes, showing a best fit line determined by a logarithmic function. The logarithmic relationship was first observed by Plowman (1956), and is utilized in ASTM C918 (2020) as shown in Equation 2:

S = *a* log(M) + *b* (2)

Commented [MB2]: S equals a times the log of M plus b

where,

S = strength at any given maturity,

M = maturity at given time, and

a, b = maturity parameters determined by best logarithmic fit of strength-maturity data.

The strength-maturity correlation curves for both Class A mixes are shown in Figure 4-2. Both of the mixes showed a similar behavior and obtained a compressive strength of more than 3000 psi at 28 days as per the requirements of TDOT Class A mix. The Class A-E mix had a slightly lower compressive strength compared to the Class A-W mix for all ages up to 28 days. According to the mix design shown in Table 3.3, the w/c ratio for the Class A-E mix (0.45) was higher than that of Class A-W mix (0.38). However, the differences in w/c may be expected to create larger differences in compressive strength than that observed. As such, other factors, such as aggregate type and content, may be expected to factor into the strength-maturity relationship. The parameters “a” and “b” of the logarithmic strength-maturity relationship are summarized in Table 4-2.

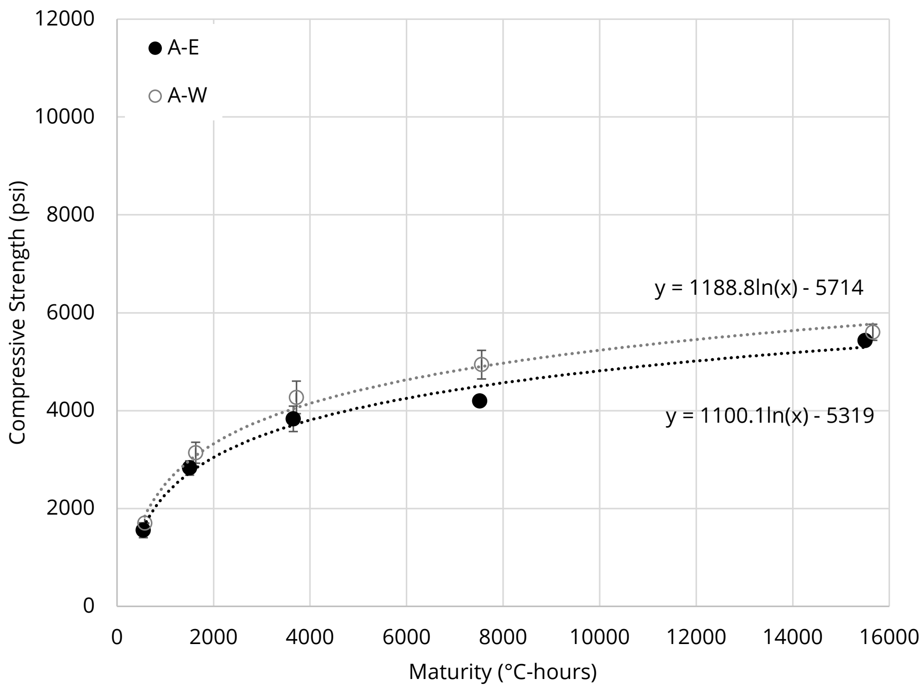


Figure 4-2 Strength-maturity relationship for Class A mixes (datum temperature = 32 °F (0 °C)).

As seen in Figure 4-3, both of TDOT Class D mixes (D-E and D-W) met the criteria for compressive strength as the samples obtained more than 4000 psi at 28 days. Also, it was observed that Class

D-E mix had a relatively higher compressive strength at all ages than that of Class D-W mix. At 28 days, the Class D-E mix had a compressive strength approximately 20% higher than that of the Class D-W mix. According to the mix design shown in Table 3.3, both the Class D-E and Class D-W mixes had a similar w/c ratio. The Class D-E mix also required the addition of HRWRA in order to achieve the specified slump. It was thought that the more angular limestone aggregate contributed to increased interlocking within the microstructure of concrete matrix than that of relatively rounded shape pea gravel (Islam and Siddique, 2017), which led to an increased compressive strength for the Class D-E mix than that of Class D-W mix. This indicates that changes in aggregate type do influence the strength-maturity relationship, along with the use of chemical admixtures, such as HRWRA.

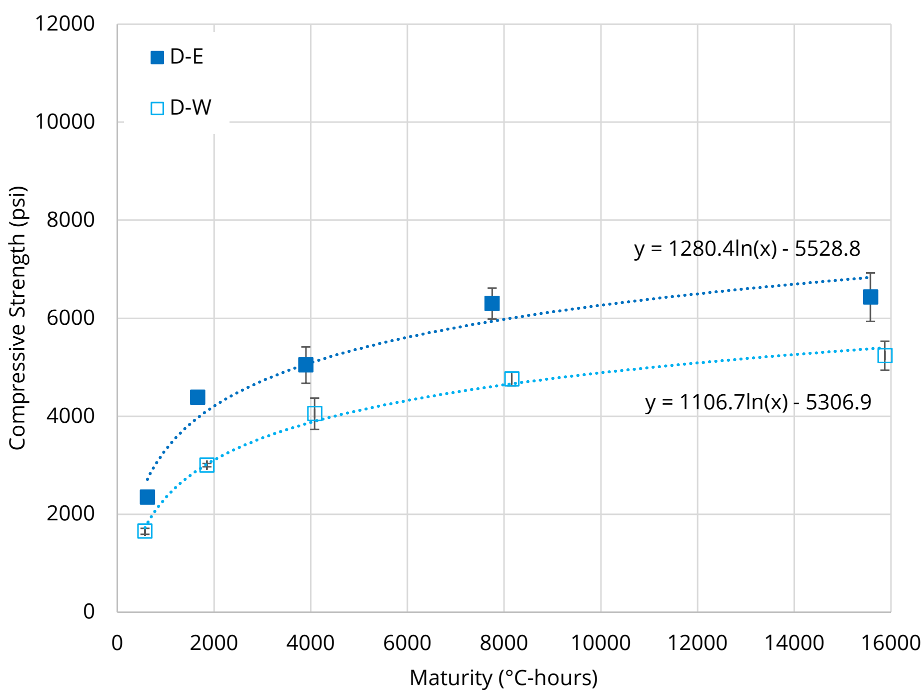


Figure 4-3 Strength-maturity relationship for Class D mixes (datum temperature = 32 °F (0 °C)).

The compressive strength of the Class CP-E mix was higher than that of the Class CP-W mix, as shown in Figure 4-4, despite differences in w/c for the CP-E (0.45) and CP-W (0.38) mixes. Both mixes met the strength requirement of 3000 psi at 28 days for Class CP mixes. Lower strengths, compared to the other mixes tested in this research, can be attributed to the lower cement contents of 526 pcy and 545 pcy for the Class CP-E and CP-W mixes, respectively. Thus, there are competing effects (i.e., w/c, cement content, and aggregate type) influencing the measured compressive strengths.

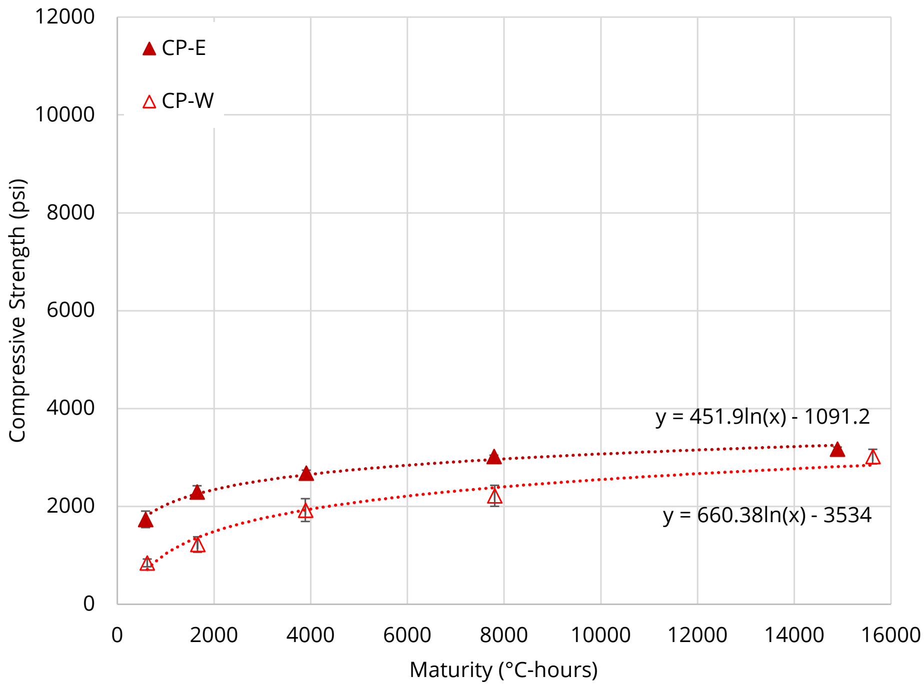


Figure 4-4 Strength-maturity relationship for Class CP mixes (datum temperature = 32 °F (0 °C)).

The maturity-strength relationships for Class X-HES mixes made with ASTM Type IL and Type III are shown in Figure 4-5. For the Class X-HES-III mix, with a w/c of 0.35, it achieved the highest early age compressive strength (4943 ± 191.3 psi) at 18 hours. This rapid strength gain was attributed to the use of Type III cement supplemented with HRWRA. Additionally, the Class X-HES-IL mix reached a compressive strength of 4630 ± 17.3 psi at 18 hours, benefiting from the highest cement content in the current study at 714 pcy and a lower w/c of 0.32. Both Class X-HES mixes met the requirements for obtaining a strength of at least 3000 psi at 18 hours per TDOT class X-HES concrete. Overall, the Class X-HES-III mix achieved a compressive strength over 10,000 psi at 28 days, while the Class X-HES-IL mix obtained a compressive strength of approximately 8000 psi at 28 days. Differences in the strength-maturity relationships for the Class X-HES mixes are primarily attributed to several factors, including cement content and chemical admixtures (accelerator in particular).

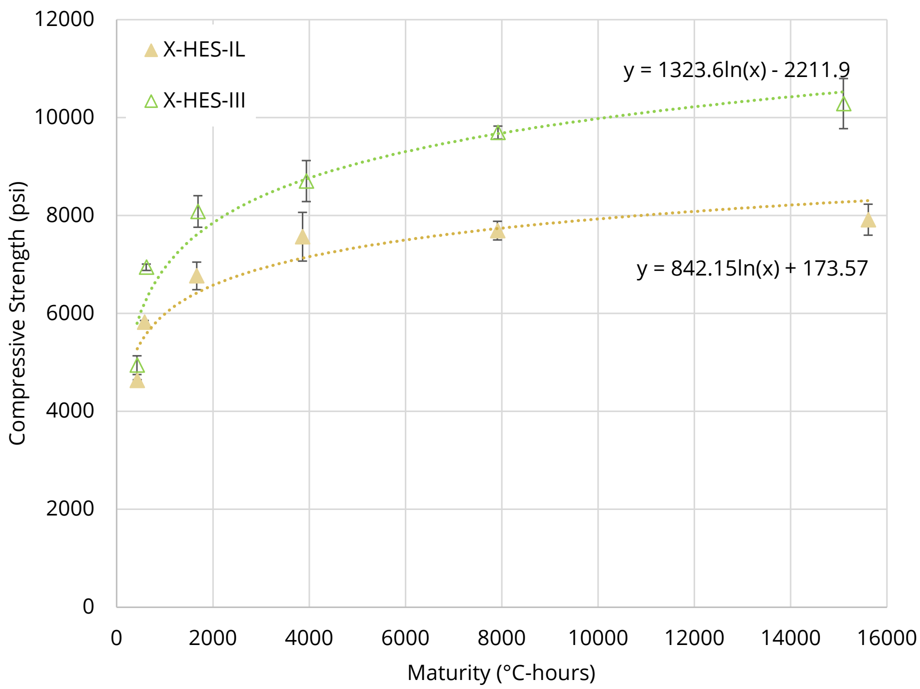


Figure 4-5 Strength-maturity relationship for Class X-HES mixes (datum temperature = 32 °F (0 °C)).

After obtaining the strength-maturity curves for all mixes, a regression analysis was conducted using a statistical software, SPSS Statistics, in order to observe the significance of these relationship at a 95% confidence (α) level. A summary of the maturity function parameters is shown in Table 4-2. Based on the results, it can be said that at all the mixes had a significance (α) value of less than 0.05, indicating all these mixes had a statistically significant relationship at 95% confidence (α) level.

Table 4-2 Summary of strength-maturity relationship parameters.

Mix	*a*	*b*	*R^2*	*Sig. (a)*	*Significance at 95% confidence level*
A-E	1114.2	-5458.7	0.98	0.001	Yes
A-W	1188.8	-5714.0	0.99	0.000	Yes
D-E	1280.4	-5528.8	0.95	0.005	Yes
D-W	1106.7	-5306.9	0.99	0.000	Yes
CP-E	451.9	-1091.2	0.99	0.001	Yes
CP-W	660.38	-3534.0	0.97	0.003	Yes
X-HES-IL	842.15	+173.57	0.88	0.005	Yes
X-HES-III	1323.6	-2211.9	0.93	0.002	Yes

4.3 Field Verification of Strength-Maturity Relationships

As discussed in Section 3.2.5, the strength-maturity relationship was verified for each mix under field conditions. While the curing temperature under laboratory conditions was 73 ^{o}F (23 ^{o}C), field verification specimens were subjected to exterior temperatures ranging from approximately 48 to 95 ^{o}F (9 to 35 ^{o}C) as well as variations in relative humidity (i.e., wetting and drying).

At different maturity values, cylinders were pulled for compressive strength testing. For each mix, strength was typically measured at three different maturity values and plotted on the existing figures as shown in Figures 4-6 through 4-13. In addition to the strength-maturity relationship curves presented in Section 4.2, each logarithmic relationship is plotted (solid line) along with ±10% boundary conditions (short-dashed lines), which are used by many states as acceptance criteria. In addition, a one-sided confidence interval of 95% (red, long-dashed line) is also plotted per ASTM C918.

According to the results (Figures 4-6 through 4-13), all field data for different types of mixes were within ±10% boundaries of the strength-maturity relationship curves, except the Class D-E mix at maturity level 12,000 ^{o}C-hours. The difference in field and lab-based data for the Class D-E mix at around 12,000 ^{o}C-hours was -11.56%, which was very close to the lower (-10%) boundary of the best fit curve.

Similarly, the difference for the Class D-E mix was -5.21% when considering the 95% lower boundaries per ASTM C918 (2020). Note that a one-sided confidence interval of 95% (lower bound) indicates the field data should be above this boundary. Also, a slight discrepancy was found for A-E mix at around 4000 and 12,000 maturity (^{o}C-hours) as the difference between the field data and 95% confidence level data was around -1.50%.

However, in order to identify the reason for lower field strength of D-E mix, the air content of fresh concrete for field verification was analyzed and indicated an approximately 1% higher air content for the field concrete. This could explain the slightly lower strengths of the Class D-E field mixes compared to the lab-based mixes. All other mixes showed differences of lab and field air contents less than 0.5%. It is well known that increased air contents lead to lower compressive strengths. This research also appears to indicate that changes in air content do not necessarily impact temperature/maturity, though more research is needed to determine the extent of this variable impacting the strength-maturity relationship.

A summary of the percent differences between field verification strengths and lab-based estimated strengths is shown in Table 4-3 and Table 4-4, while the detailed field data were summarized in Appendix D.

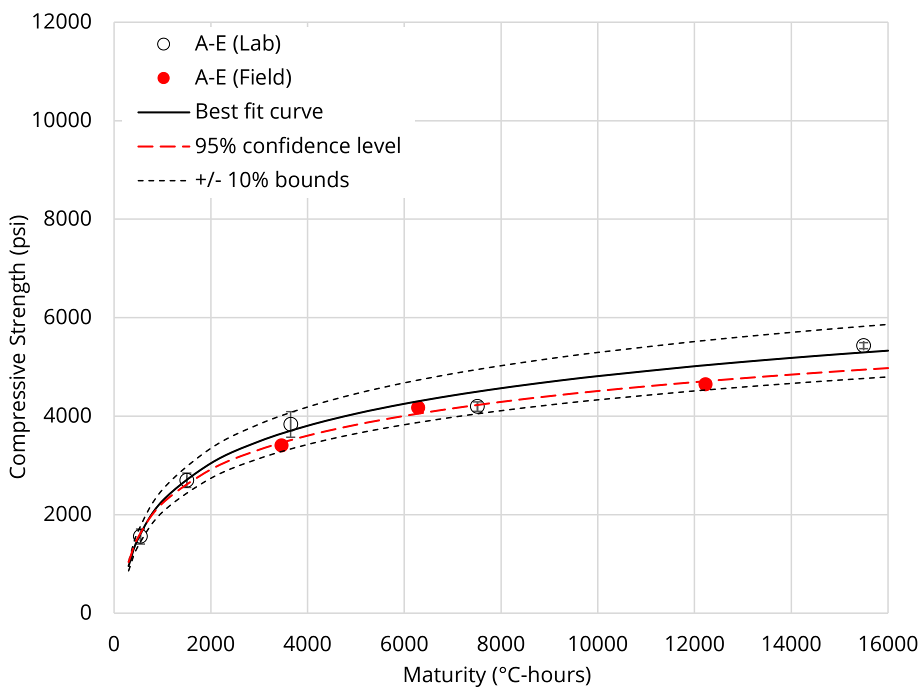


Figure 4-6 Field verification for Class A-E mix.

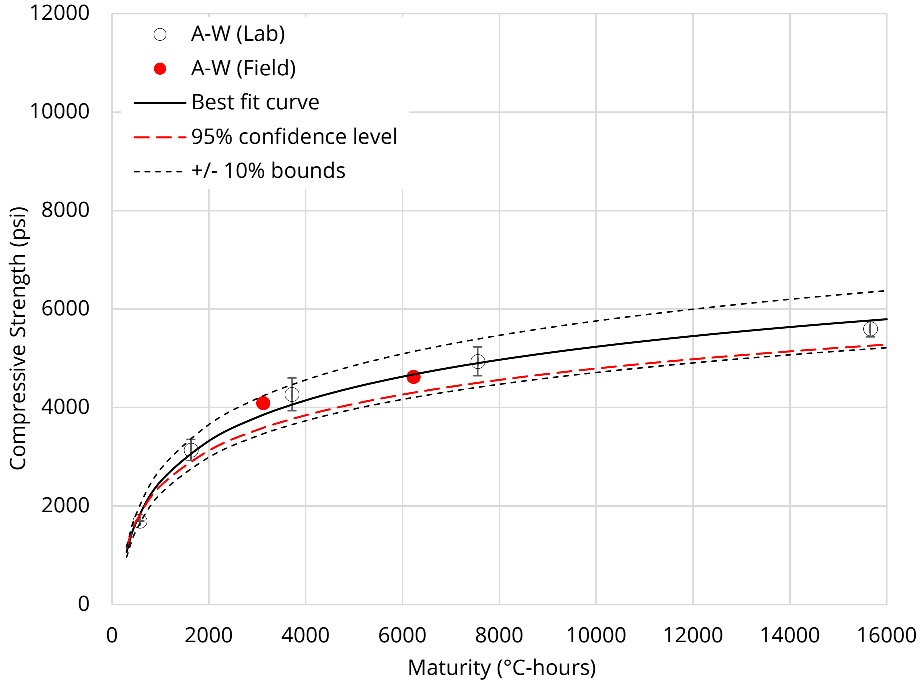


Figure 4-7 Field verification for Class A-W mix.

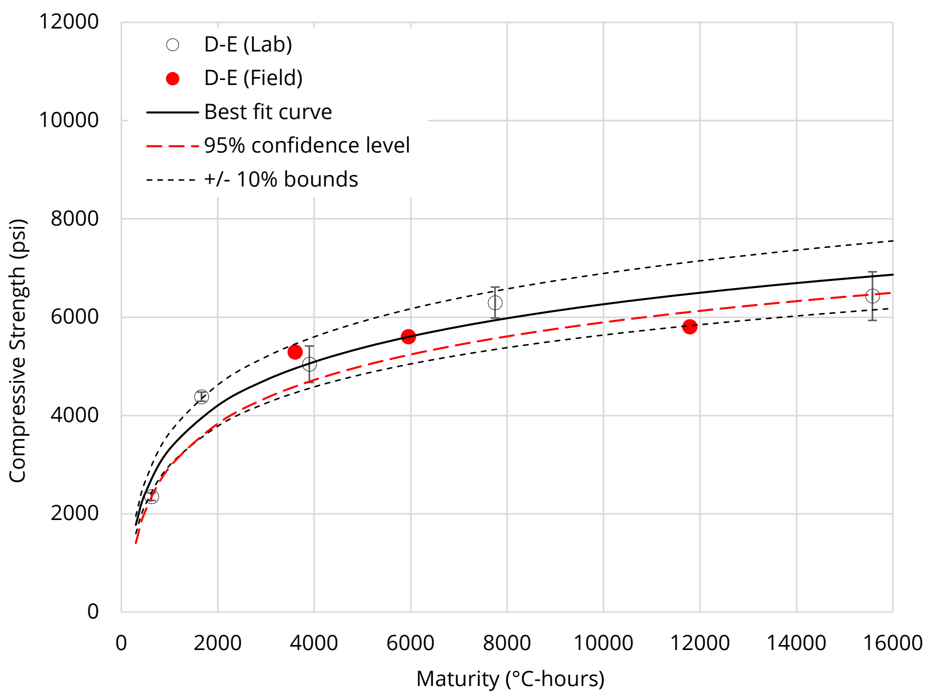


Figure 4-8 Field verification of Class D-E mix.

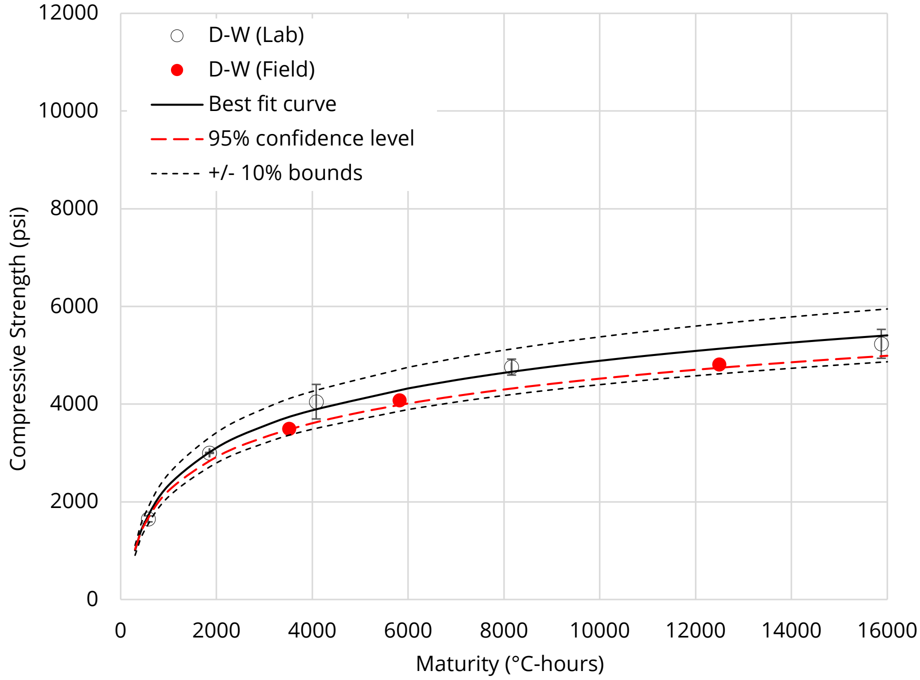


Figure 4-9 Field verification of Class D-W mix.

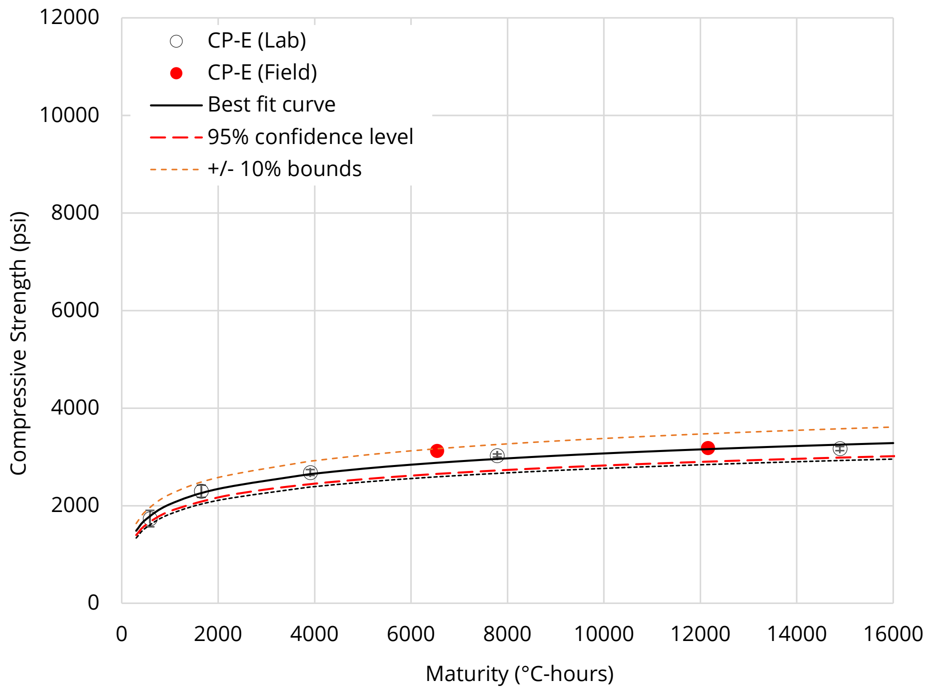


Figure 4-10 Field verification of Class CP-E mix.

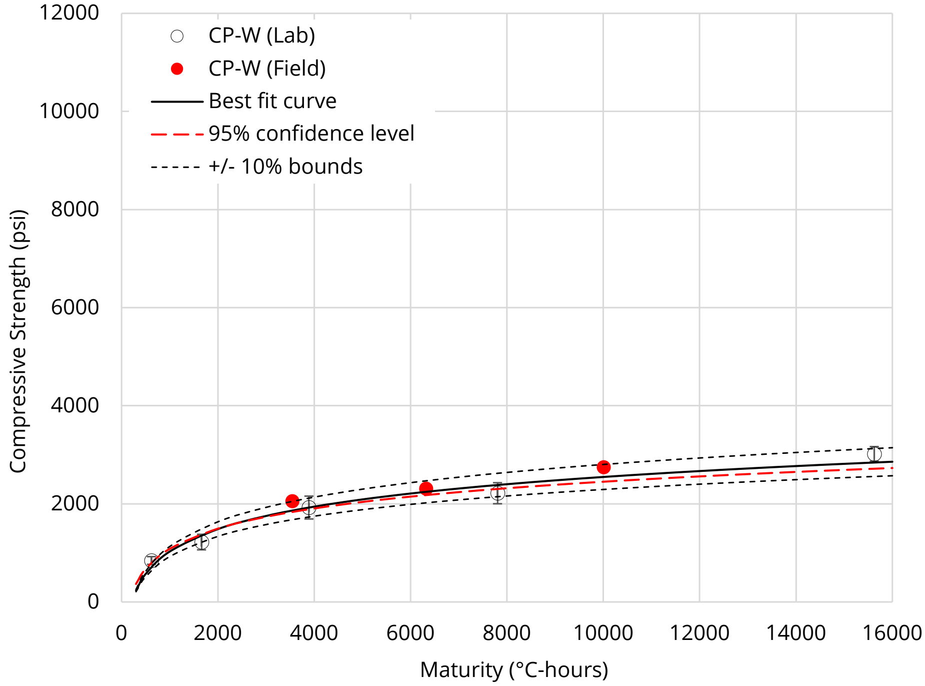


Figure 4-11 Field verification of Class CP-W mix.

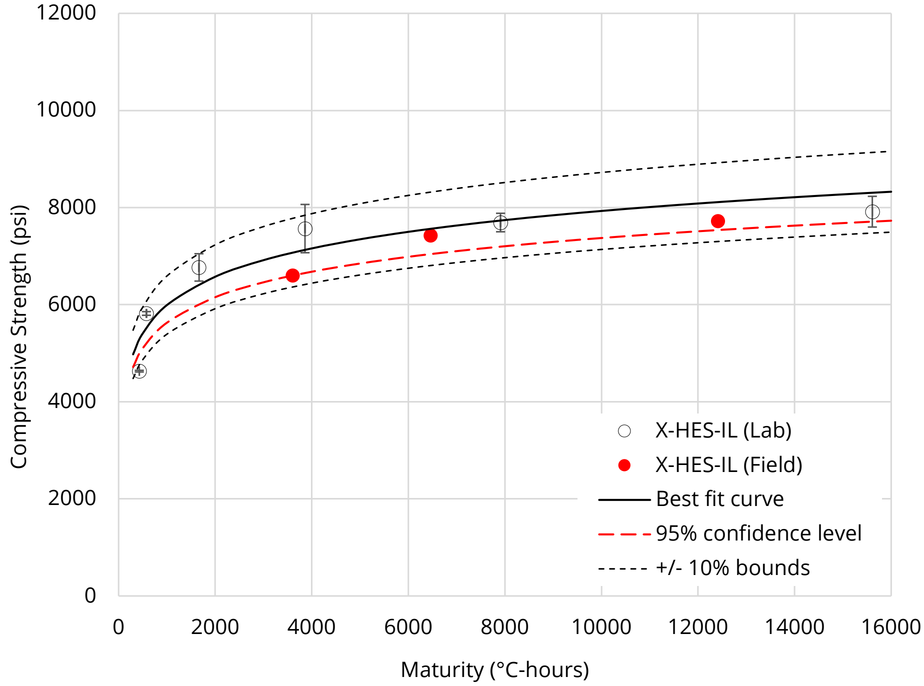


Figure 4-12 Field verification of Class X-HES-IL mix.

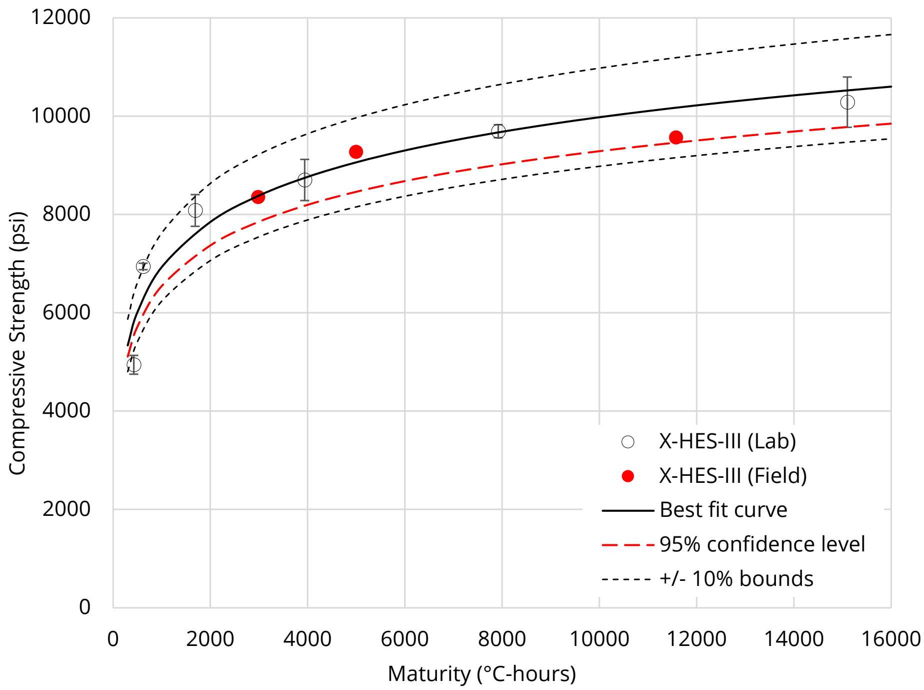


Figure 4-13 Field verification of Class X-HES-III mix.

Table 4-3 Percent difference between field data and best fit logarithmic relationship,

Mix	*Difference between field data and best fit curve within ± 10% boundaries (%)*		
	Early Ages (<7d)	*Middle Stage (7-14d)*	*Later Ages (14-28d)*
A-E	-7.0	-3.01	-8.33
A-W	+5.95	-1.01	N/A
D-E	+6.25	+0.04	-11.56
D-W	-6.68	-5.19	-6.37
CP-E	N/A	-7.81	+0.79
CP-W	+9.31	+2.73	+7.21
X-HES-IL	-7.10	-1.80	-5.04
X-HES-III	-0.22	+2.32	-6.29

Note: Negative values represent average field strength lower than the best-fit predicted strength. Acceptable data should be within ±10%. N/A represents data that were not available due to maturity server outages.

Table 4-4 Percent difference between field data and 95% confidence interval, per ASTM C918.

Mix	*Difference between field data and 95% confidence level curve (%)*		
	Early Ages (<7d)	*Middle Stage (7-14d)*	*Later Ages (14-28d)*
A-E	-1.56	+3.00	-1.35
A-W	+7.05	+13.41	N/A
D-E	+13.20	+6.61	-5.21
D-W	+0.46	+2.31	+1.46
CP-E	N/A	+15.15	+8.82
CP-W	+13.22	+7.89	+12.59
X-HES-IL	+0.03	+5.20	+2.40
X-HES-III	-0.06	+8.70	+1.13

Note: Negative values represent average field strength lower than the 95% confidence interval for the predicted strength. Acceptable data should be positive numbers. N/A represents data that were not available due to maturity server outages.

4.4 Summary of Maturity Method for Use by Tennessee Department of Transportation

As evidenced in the previous sections, the maturity method has shown applicability for predicting the strength of concrete based on temperature measurements. Furthermore, the maturity method has the potential to accelerate construction schedules by allowing contractors and/or

TDOT to accept concrete at early ages, provided that the strength-maturity predictions match those previously determined. Proposed language has been published for Supplemental Specifications – 600SS of the Standard Specifications for Road and Bridge Construction (rev. 12/19/2022). Subsection 604.15.D has been added as follows:

> ***D. Maturity Method***
> *Strength of concrete in-place may be estimated by the Standard Practice for Estimating Concrete Strength by the Maturity Method AASHTO T325 and Departmental procedures for critical activities. (open pavement to traffic, removing forms, post tension, shipping, cold weather). The Department will break a set of cylinders made from the pour in question to verify the strength-maturity relationship, the concrete will be accepted on the basis of the 28 day strength as defined by the strength-maturity relationship. If the cylinders break within 10% of the estimated strength based on the strength-maturity relationship, the concrete will be accepted on the basis of the 28 day strength as defined by the strength-maturity relationship. If the cylinders break outside of the 10% tolerance, the 28 day cylinders will be broken and the concrete will be accepted per* ***604.15.B****.*

Based on the results of this research, the above language appears to capture all necessary aspects of early age concrete acceptance. In particular, the 10% variability appears to be in line with the field verification phase on this research. While the 95% confidence level outlined in ASTM C918 may be more accurate (i.e., accounting for magnitude of differences in field/lab strengths compared to just average values), that method does require some more technical knowledge and may be more difficult to implement in the field.

Therefore, the 10% bounds are suggested for acceptance (similar to many other states). Because the 10% variability at very early ages is typically very small, it may be suggested to begin acceptance around 3 days. While earlier acceptance testing would still be permitted, the contractor should ensure that an appropriate number of cylinders are made, in order to possibly test at later ages for acceptance.

The primary caveat would be that each concrete mix would need to have an established strength-maturity curve developed prior to field acceptance. Under most situations, this would require a particular contractor and/or ready-mix producer to have established mix proportions well in advance of the concrete pour.

Chapter 5 Future Research

Research presented in the previous chapters represented 8 preliminary mixes as a verification of the maturity method for use in the acceptance of concrete at early ages. While the procedures involved capture variability in concrete mix designs, more research is suggested to investigate the influence of other mix components as well as more extreme environmental conditions.

For the Class D mixes in this research, a HRWA was used in order to improve the slump of the Class D-E mix, as compared to the Class D-W mix, which did not require any water reducer. While the need for the water reducer is primarily attributed to the increase aggregate angularity of the crushed limestone compared to the rounder pea gravel, there was a fairly large difference in the strength-maturity behavior of the Class D mixes. As expected, the use of high range water reducer did increase the strength of the Class D-E mix. Whether or not impact translates across over mixes is yet to be seen. Potentially there is a relationship to be estimated between the amount of water reducer used and the increase in strength. It has yet to be seen whether this also applies to other water reducers, particularly mid-range. It may be possible to model the influence of water reducers on the strength-maturity behavior in order to minimize or eliminate the need for correlation curves to be determined with even the slightest change in admixture dosage. While it is noted that high range water reducer addition did impact the strength-maturity relationship, it is unknown if other chemical admixtures change the maturity behavior in similar ways. Particularly of interest is the impact of air entrainers, accelerators, and retarders.

Specifically, AEA addition needs further investigation. During this research, initially, the AEA dosage remained constant between the lab and field measurements. However, it was noted that some of the field mixes showed much higher or lower strengths than expected. Upon further investigation, it was determined that the expected air contents were lower or higher than expected, respectively. This was attributed to environmental conditions, particularly temperature upon mixing. When the temperatures were further controlled to be similar to that previously, air entraining admixtures dosages returned to the same as used before and air contents were very similar (less than 0.5% difference) for the new field concrete. It is important to investigate how these changes in air content and/or air entraining admixture dosage rates will impact the use of a singular strength-maturity relationship over the course of varying seasons.

Many concrete mixes contain some amount of supplementary cementitious materials (SCMs), such as fly ash, slag, silica fume, and/or metakaolin. The replacement of portland cement with any of these SCMs would be expected to significantly impact the strength-maturity relationship. Some of these materials, such as a fly ash, tend to be fairly variable in chemical composition, impacting property development. In theory, a ready-mix producer could utilize the existing strength-maturity relationship for a particular mix, but unbeknownst to the producer, a change in material composition may cause issues.

The same may be true for portland cement composition. While the composition does not typically change much for a given cement manufacturer, it would be interesting to assess whether the same concrete mix (same strength-maturity relationship) could be utilized in varying locations that may use different cement manufacturers.

The research presented in this report already indicates that aggregate type does impact maturity. Additional research may be warranted, identifying additional aggregate sources and/or changes in the aggregate content for particular mixes.

Ultimately, the goal of any future research should be the expand the catalog of strength-maturity relationships within the state of Tennessee.

Chapter 6 Conclusions and Recommendations

The Nurse-Saul maturity function was used for establishing the strength-maturity relationship at a datum temperature of 0 °C per ASTM C1074. Field verification was conducted to assess the portability of lab-determined strength-maturity relationship under varying environmental conditions. The following conclusions were drawn based on the maturity method developed for different TDOT Class (A, D, CP, X-HES) concrete:

- The results confirmed that all mixes met the fresh properties (slump, air content, unit weight) and minimum strength requirements established by TDOT for each concrete class.
- The Nurse-Saul maturity function with a datum temperature of 0 °C was used for all maturity testing. ASTM C1074 was followed for laboratory-based testing. Concrete cylinders were cured at 23 ± 1 °C, while the compressive strength test was measured at 1, 3, 7, 14, and 28 days with at least 2 cylinders. If any individual cylinder exceeded ± 10% of the average compressive strength, the 3rd cylinder must be tested. For any high early strength mixes, additional cylinders should be tested at ages earlier than 1 day.
- Lab-based strength-maturity relationships must be established for each concrete mix if early age acceptance is warranted. Field mixes must contain the same mix proportions and materials in order to be correlated to the strength-maturity correlation curves. Minor changes in materials and/or proportions can significantly change the strength-maturity relationship. It is recommended that TDOT expand its catalog of established strength-maturity relationships to increase the use of the maturity method across the state.
- Field verification was conducted on the predicted strength based on the strength-maturity relationship at different maturity level for similar lab mixes. A secured cloud-based server system was used to obtain the maturity data for the field verification, where the embedded sensors in the cylinder transferred the data through the transmitter to a receiver using a 4G connection. However, it is recommended that TDOT thoroughly investigate any maturity system for potential vulnerabilities and develop a backup plan in case of system failure.
- All field testing was conducted at temperature above approximately 50 °F (10 °C) (and up to 95 °F (35 °C)), Further field maturity verification is recommended at lower temperatures to replicate conditions that may be present in cold weather concrete placements.
- For validity of strength-maturity relationship by field data, each logarithmic relationship was plotted along with ±10% boundary conditions and a one-sided confidence interval of 95% (lower bound) per ASTM C918 (2020). While ASTM C918 procedures may be more accurate by taking into account statistical variations, the ±10% boundary conditions are likely to be more easily incorporated in field conditions. Most states that have accepted the maturity method appear to use the ±10% bounds. It is recommended that TDOT continue to use of these bounds in future maturity acceptance.

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Appendix A State DOT Practices

Table A-1 Adoption of maturity method by state DOTs.

State DOT	*DOT Specification/ Publication/ Test Method*	*Title/Citation*	*Link*
Alabama	Yes	ALDOT Testing Manual, ALDOT-425, Maturity method to determine early-age strengths of concrete	https://www.dot.state.al.us/publications/materials/testingmanual/pdf/Pro/ALDOT425.pdf
Alaska	Research does not appear to be adopted by DOT	Project AUTC #107052, Study of Concrete Maturity Method in Very Cold Weather (Appendix C – Draft standard)	https://scholarworks.alaska.edu/bitstream/handle/11122/7456/Dong_Concrete-Maturity-in-Cold-Weather_Final11.23.pdf
Arizona	Yes	ADOT Testing Manual, ADOT 318a, Estimating the Development of Concrete Strength by the Maturity Method	https://apps.azdot.gov/files/materials-manuals/materials-testing/ariz-318a.pdf
Arkansas	Could not be located	N/A	N/A
California	Yes	Standard Specifications, Section 40-1.03L Use of the Maturity to Determine Opening to Traffic Concrete Strength	https://dot.ca.gov/-/media/dot-media/programs/construction/documents/policies-procedures-publications/cpd/cpd22-6-attachment-3.pdf
Colorado	Yes	Colorado Procedure 69-18, Standard method for estimating the in-place concrete strength by a maturity method	https://www.codot.gov/business/designsupport/materials-and-geotechnical/manuals/2018-fmm/cps/CP-60s/14-cp-69-18
Connecticut	Research does not appear to	Project SPR-2252, Report CT-2252-F-12-3, Assessing	https://rosap.ntl.bts.gov/view/dot/24287

	be adopted by DOT	ConnDOT's portland cement concrete testing methods phase II – field trials and implementation (Appendix A – Draft test procedure)	
Delaware	Yes	Standard Specifications for Road and Bridge Construction, Section 503.03.7	https://deldot.gov/Publications/manuals/standard_specifications/pdfs/2016/2016_standard_specifications_08-2016.pdf
Florida	Yes	Florida Method 3-C1074, Estimating the strength of high early strength concrete using the maturity method	https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/materials/materials/administration/resources/library/publications/fstm/methods/fm3-c1074.pdf
Georgia	Could not be located	N/A	N/A
Hawaii	Could not be located	N/A	N/A
Idaho	Could not be located	N/A	N/A
Illinois	Could not be located	N/A	N/A
Indiana	Yes	Indiana Test Method 402-20, Strength of portland cement concrete pavement (PCCP) using the maturity method utilizing the time temperature factor methodology	https://www.in.gov/indot/doing-business-with-indot/files/402_testing.pdf
Iowa	Yes	Iowa Test Method 383, Estimate of portland cement concrete strength by maturity method	https://www.iowadot.gov/erl/current/im/content/383.htm
Kansas	Yes	Kansas Test Method KT-44, Method of testing the strength of portland cement concrete using the maturity method	https://www.ksdot.gov/Assets/wwwksdotorg/bureaus/burConsMain/Connections/ConstManual/2018/KT-44.pdf

Kentucky	Yes	Kentucky Method 64-322-08, Estimating Concrete Strength by the Maturity Method	https://transportation.ky.gov/Materials/Documents/KM322_08.pdf
Louisiana	Yes	Special Provision 902 High Early Strength Concrete – Maturity Meter Cheat sheet	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Materials_Lab/TPM_Vol_I_Part_II/902%20High%20Early%20Strength%20Concrete%20-%20Use%20of%20Maturity%20Meter.pdf
Maine	Could not be located	N/A	N/A
Maryland	Research does not appear to be adopted by DOT	Project SP708B4K, Report MD-11-SP708B4K, Implementation of the concrete maturity meter for Maryland	https://rosap.ntl.bts.gov/view/dot/23578
Massachusetts	Could not be located	N/A	N/A
Michigan	Yes	MDOT Standard Specifications for Construction, Section 603	https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Business/Construction/Standard-Specifications-Construction/2020-Standard-Specifications-Construction.pdf
Minnesota	Yes	MNDOT Maturity Method Procedure – Estimating Concrete Strength by the Maturity Method	https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=18268941
Mississippi	Yes	MDOT Concrete Field Manual, Section 9.2	https://mdot.ms.gov/documents/Materials/Standards/Manuals/MDOT%20Concrete%20Field%20Manual%20v20180907.pdf
Missouri	Yes	MoDOT Standard Specifications for Highway Construction, Section 507	https://www.modot.org/sites/default/files/documents/2021%20Missouri%20Standa

		Strength of Concrete Using the Maturity Method.	rd%20Specific%20-%20MHTC%20%28Oct%202021%29.pdf
Montana	Yes	MDT Standard and Supplemental Specifications for Road and Bridge Construction, Section 501.03.13	https://www.mdt.mt.gov/other/webdata/external/const/specifications/2020/SPEC-BOOK/2020-SPEC-BOOK-V1-2.pdf
Nebraska	Yes	NEDOT Maturity Curve Method of Development - Certification	https://dot.nebraska.gov/media/ti0oflr5/method-development-maturity-curve.pdf
Nevada	Could not be located	N/A	N/A
New Hampshire	Could not be located	N/A	N/A
New Jersey	Research does not appear to be adopted by DOT	FHWA/NJ-2001-017 Tech Brief, Development of maturity protocol for construction of NJDOT concrete structures.	https://www.nj.gov/transportation/business/research/reports/FHWA-NJ-2001-017-TB.pdf
New Mexico	Yes	NMDOT Standard Specifications for Highway and Bridge Construction, Section 510.3.5.2	https://www.dot.nm.gov/infrastructure/plans-specifications-estimates-pse-bureau/standards/
New York	Yes	Maturity Methodology: ITEM 555.04010011 – High Early Strength Concrete with Non-chloride Accelerator for Substructure Element Replacement	https://www.dot.ny.gov/spec-repository-us/555.04010011.pdf
North Carolina	Yes	NCDOT Standard Specifications for Roads and Structures, Section 700-13	https://connect.ncdot.gov/resources/Specifications/2024StandardSpecifications/2024%20Standard%20Specifications%20for%20Roads%20and%20Structures.pdf
North Dakota	Yes	NDDOT Standard Specifications for Road and Bridge Construction, Section 550.04	https://www.dot.nd.gov/divisions/environmental/docs/supspecs/2023%20Standard%20Specifications.pdf
Ohio	Yes	ODOT Supplement 1098, Procedure for estimating	https://www.dot.state.oh.us/Divisions/ConstructionMgt/

		concrete strength by the maturity method.	Specification%20Files/1098_12312012_for_2013.PDF
Oklahoma	Could not be located	N/A	N/A
Oregon	Yes	ODOT Standard Specifications for Construction, Sections 00559.60, 00755.60, 00756.60	https://www.oregon.gov/odot/Business/Specs/2021_STANDARD_SPECIFICATIONS.pdf
Pennsylvania	Yes	PA Test Method No. 640: Estimating Concrete Compressive Strength by the Maturity Method.	https://www.dot.state.pa.us/public/PubsForms/Publications/PUB_19/Pub%2019%20Ch%2010.pdf
Rhode Island	Yes	RIDOT Standard Specifications for Road and Bridge Construction, Section 607.2.2	https://www.dot.ri.gov/business/bluebook/docs/Compilation_of_Approved_Specifications_02-21.pdf
South Carolina	Could not be located	N/A	N/A
South Dakota	Could not be located	N/A	N/A
Tennessee	Yes	TDOT Standard Operating Procedures (SOP 4-4), Appendix G	https://www.tn.gov/content/dam/tn/tdot/hq-materials-tests/standard-operating-procedures/SOP_4-4.pdf
Texas	Yes	TxDOT Test Procedure, Tex-426-A Estimating concrete strength by the maturity method.	https://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/400-A_series/pdfs/cnn426.pdf
Utah	Yes	UDOT Standard Specifications for Road and Bridge Construction	http://udot.utah.gov/go/2024standards
Vermont	Could not be located	N/A	N/A
Virginia	Could not be located	N/A	N/A
Washington	Yes	WSDOT Standard Specification for Road, Bridge, and Municipal Construction, Section 5-05.3(17)	https://www.wsdot.wa.gov/publications/manuals/fulltext/m41-10/ss.pdf

West Virginia	Yes	WVDOT Materials Procedure, MP 601.04.21 Use of the Maturity Method for the Estimation of Concrete Strength on WVDOH Projects	https://transportation.wv.gov/highways/mcst/Material%20Procedures/601.04.21_2012-05-23%20(1).pdf
Wisconsin	Yes	WIDOT Standard Specifications, Section 870	https://wisconsindot.gov/rdwy/cmm/cm-08-70.pdf
Wyoming	Mention of new Testing Method and Special Provision as of 2021, but cannot be located	N/A	N/A

Appendix B Gradation of Aggregates

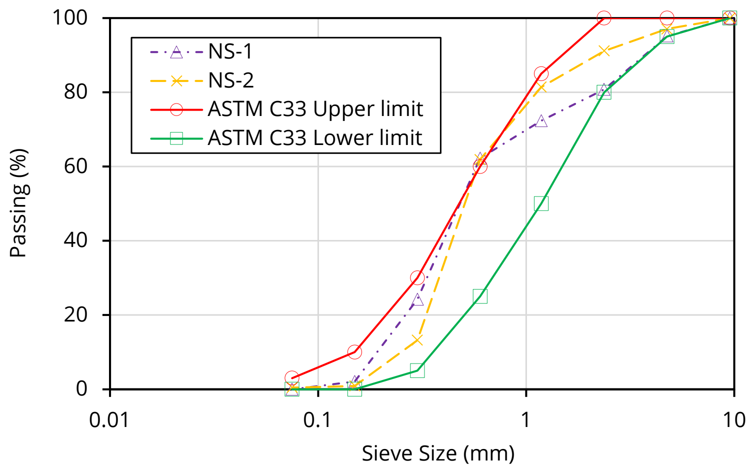

Figure B-1 Gradation of fine aggregates.

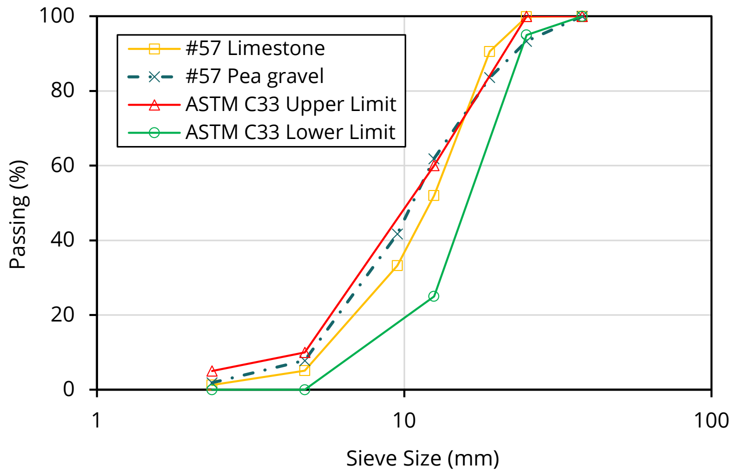

Figure B-2 Gradation of coarse aggregates.

Appendix C Compressive Strength and Maturity for Laboratory Data

Note: Values were excluded if greater than 10% difference from average, as discussed in Section 3.2.4, or were due to an obviously defective specimen, per ASTM C1074 (2019).

Table C-1 Compressive strength results obtained from laboratory for Class A-E.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	1525	1422	1721	1556	152
3	2659	2911	2911	2827	146
7	3988	3976	3532	3832	260
14	4126	4262		4194	96
28	5393	5480	5425	5432	61

Table C-2 Maturity values obtained from laboratory for Class A-E (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	*Sample 2*		
1	544	546	545	1
3	1503	1505	1504	1
7	3648	3655	3652	5
14	7507	7518	7512	8
28	15489	15504	15496	11

Table C-3 Compressive strength results obtained from laboratory for Class A-W.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	1692	1706	1692	1697	8
3	3247	2893	3278	3139	214
7	3886	4454	4470	4270	333
14	5089	5126	4602	4939	292
28	5540	5786	5475	5601	164

Table C-4 Maturity values obtained from laboratory for Class A-W (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	*Sample 2*		
1	572	577	574	3
3	1623	1635	1629	9
7	3706	3728	3717	16
14	7540	7566	7553	18
28	15655	15664	15659	6

Table C-5 Compressive strength results obtained from laboratory for Class D-E.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	2293	2403		2348	778
3	4317	4449		4383	93
7	4701	4991	5438	5043	371
14	6522	6832	6076	6477	380
28	6080	7185		6632	781

Table C-6 Maturity values obtained from laboratory for Class D-E (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	*Sample 2*		
1	622	624	623	1
3	1659	1665	1662	4
7	3894	3905	3899	8
14	7741	7763	7752	16
28	15553	15601	15577	34

Table C-7 Compressive strength results obtained from laboratory for Class D-W.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	1670	1583	1700	1651	601
3	2975	2990	3040	3002	34
7	4415	3914	3821	4050	320
14	4914	4683	4676	4758	164
28	5435	5374	4895	5234	296

Table C-8 Maturity values obtained from laboratory for Class D-W (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (oC-hours)*	*Standard Deviation (oC-hours)*
	Sample 1	*Sample 2*		
1	571	575	573	3
3	1851	1857	1854	4
7	4079	4085	4082	4
14	8158	8159	8158	1
28	15878	15872	15875	4

Table C-9 Compressive strength results obtained from laboratory for Class CP-E.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	1616	1855		1735	169
3	2344	2155	2391	2297	125
7	2679	2622	2741	2827	60
14	3051	3006	2997	3018	29
28	3141	3200		3170	42

Table C-10 Maturity values obtained from laboratory for Class CP-E (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	Sample 2		
1	593	578	585	10
3	1656	1645	1651	8
7	3916	3901	3908	11
14	7804	7772	7788	22
28	14932	1485	14892	57

Table C-11 Compressive strength results obtained from laboratory for Class CP-W.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
1	763	919	855	846	79
3	1333	1109		1221	158
7	2090	1760		1925	233
14	2368	2065		2217	214
28	2848	3127	3079	3018	149

Table C-12 Maturity values obtained from laboratory for Class CP-W (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	*Sample 2*		
1	626	613	619	9
3	1670	1649	1660	15
7	3910	3869	3889	29
14	7842	7766	7804	54
28	15678	15570	15624	76

Table C-13 Compressive strength results obtained from laboratory for Class X-HES-IL.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
0.75 (18hr)	4618	4643		4631	17
1	5792	5846		5820	38
3	6926	6442	6933	6767	282
7	8006	7667	7028	7567	497
14	7797	7806	7472	7692	191
28	8139	7691		7915	316

Table C-14 Maturity value obtained from laboratory for Class X-HES-IL (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	*Sample 2*		
0.75 (18hr)	429	428	429	0
1	577	576	576	1
3	1665	1662	1664	2
7	3864	3858	3861	4
14	7914	7907	7911	5
28	15619	15601	15610	12

Table C-15 Compressive strength results from laboratory for Class X-HES-III.

Age (days)	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
0.75 (18hr)	5079	4809		4944	191
1	6990	6898		6944	65
3	7719	8200	8330	8083	322
7	9000	8408		8704	419
14	9753	9787	9544	9695	132
28	10875	10026	9957	10286	512

Table C-16 Maturity value obtained from laboratory for Class X-HES-III (T_0 = 32 °F (0 °C)).

Age (days)	*Maturity (°C-hours)*		*Average Maturity (°C-hours)*	*Standard Deviation (°C-hours)*
	Sample 1	Sample 2		
0.75 (18hr)	423	426	425	2
1	615	619	617	3
3	1686	1690	1688	3
7	3939	3941	3940	1
14	7922	7917	7920	3
28	15097	15099	15098.	1

Appendix D Compressive Strength and Maturity for Field Verification

Note: Values were excluded if greater than 10% difference from average, as discussed in Section 3.2.4, or were due to an obviously defective specimen, per ASTM C1074 (2019).

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class A-E.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
3459	29	3425	3391	3408	24
6285	38	4066	4287	4176	156
12224	72	4517	4777	4647	184

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class A-W.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
3119	55	4167	4019	4093	104
6234	76	4689	4561	4625	91

Note: Compressive strength was not recorded at approximately 12,000 °C-hours due to maturity server outage.

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class D-E.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2	Sample 3		
3601	8	4993	5461	5407	5287	256
5954	10	5148	5820	5839	5602	394
11788	74	5801	5807		5804	4

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class D-W.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2	Sample 3		
3511	29	3471	3519		3495	33
5820	93	4415	3898	3915	4076	294
12489	302	4887	4737		4813	107

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class CP-E.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
6826	65	3030	3299	3164	190
12154	124	3116	3253	3184	97

Note: Compressive strength was not recorded at approximately 3,000 °C-hours due to maturity server outage.

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class CP-W.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
3541	18	1980	2128	2054	105
6322	41	2327	2290	2309	26
10009	50	2751	2741	2746	6

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class X-HES-IL.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
3602	24	6644	6559	6601	60
6462	41	7576	7277	7428	212
12411	69	7615	7829	7722	151

Compressive strength at field maturity values of approximately 3000, 6000, and 12,000 °C-hours for Class X-HES-III.

Average Maturity (°C-hours)	*Standard Deviation (°C-hours)*	*Compressive Strength (psi)*		*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
		Sample 1	Sample 2		
2980	40	8101	8615	8358	24
4995	40	9152	9400	9276	41
11570	21	9594	9546	9570	69