FINAL REPORT

U.F. Project No: 00098299
FDOT Project No: BDK75-977-62

SLAB REPLACEMENT MATURITY GUIDELINES

Mang Tia
Larry Muszynski
Ohhoon Kwon

April 2014

Department of Civil and Coastal Engineering
Engineering School of Sustainable Infrastructure and Environment
College of Engineering
University of Florida
Gainesville, Florida 32611-6580

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation or the U.S. Department of Transportation.

Prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.

SI (MODERN METRIC) CONVERSION FACTORS (from FHWA)

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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
kip	kilo poundforce	4.45	kilo newtons	kN
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO 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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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 International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Slab Replacement Maturity Guidelines		5. Report Date April 2014 6. Performing Organization Code
7. Author(s) Mang Tia, Larry Muszynski & Ohhoon Kwon		8. Performing Organization Report No. 00093785
9. Performing Organization Name and Address Department of Civil and Coastal Engineering Engineering School of Sustainable Infrastructure & Environment University of Florida 365 Weil Hall – P.O. Box 116580 Gainesville, FL 32611-6580		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDK75-977-62
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report 01/17/12 – 4/16/14 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation and the Federal Highway Administration

16. Abstract

This study investigated the use of maturity method to determine early age strength of concrete in slab replacement application. Specific objectives were (1) to evaluate effects of various factors on the compressive maturity-strength relationship of concrete at early age, (2) to develop appropriate test procedures for applying maturity method to predict early age strength of concrete, and (3) to validate the accuracy of the prediction of maturity method using the proposed test procedures.

The maturity method using the Arrhenius maturity function was found to be quite reliable and convenient for use in predicting the early-age compressive strength of concrete in replacement slab application. Some limitations of maturity-strength prediction, such as the strength loss due to high curing temperature and insufficient moisture, supply were observed in the laboratory studies. However, these limitations were observed at the later age of the concrete when the compressive strength reached around 3,000 to 3,500 psi, and thus the observed limitations did not have any negative effect on the early-age-strength prediction of the concrete in the replacement slab.

Using the strength of the protection specimens as strength determination of the in-place concrete is unreliable and may result in over-prediction of its strength. The maturity method using the Arrhenius maturity function is recommended for use to estimate the early-age compressive strength of concrete in slab replacement application. A testing protocol for the generation of maturity-strength curve for prediction of early-age compressive strength of concrete was recommended. The concrete used in the replacement lab must have exactly the same water-cement ratio, mix ingredients, and fresh concrete properties as those of the laboratory concrete used to develop the maturity curve. In the event that differences in fresh concrete properties, with more than ±1 inch in slump and/or ±1 % in air contents, are observed between the actual concrete used at the project site and the concrete which has been used to develop the maturity-strength curve, the maturity-strength curve should not be used to make strength predictions without proper adjustments of the predicted strengths due to effects of the variations in the fresh concrete properties.

17. Key Words	18. Distribution Statement
Maturity Method, Concrete Slab Replacement, Arrhenius Function, Temperature Sensor, Compressive Strength, High Early-Age Strength, Fresh Concrete Properties, Curing Condition, Activation Energy, Strength Prediction.	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	168	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

A compilation of this nature could not have been completed without the help and support of others. The Florida Department of Transportation (FDOT) is gratefully acknowledged for providing the financial support for this study. The FDOT Materials Office provided the additional testing equipment, materials, and personnel needed for this investigation. Sincere thanks and appreciation are extended to the Project Manager, Mr. Michael Bergin, for providing his technical coordination and expert advice throughout the project. Sincere gratitude is extended to Ms. Katie Bettman of FDOT District 2 Materials Office, Mr. Daniel Haldi of FDOT District 5 Materials Office, and Messrs. Richard DeLorenzo and Harvey DeFord of the FDOT Materials Office for their invaluable expert advice and help on this project.

EXECUTIVE SUMMARY

Background and Problem Statement

Replacing concrete slabs on highway facilities requires a contractor to close the lane, remove cracked and shattered concrete slabs, place new concrete in the repair area, and reopen the lane to traffic within a 10-to-12 hour window. According to Section 353 of the FDOT Standard Specifications for Road and Bridge Construction, concrete specimens are required to have 24-hour compressive strength of 3,000 psi, and 2,200 psi prior to allowing traffic on the new pavement. The specification requires making a minimum of four cylindrical specimens and curing the specimens by identical conditions used in curing the replacement slab. However, the testing procedure poses the following challenges:

(1) Testing concrete cylinder requires a testing laboratory to be available at early morning hours on-site, thus adding cost to the project.

(2) The measured strength of the concrete specimens may not represent the actual strength of the concrete in the replacement slab.

For these reasons, the maturity method has been recommended to estimate strength of in-place concrete as an alternative by many state DOTs including Florida DOT. Although the maturity method is a proven method for indicating concrete strength for normal concrete placement and has the potential to be used to determine concrete strength for early opening to traffic, some limitations for the maturity method have been reported in previous research as follows:

(1) A different curing temperature can produce different maturity-strength relationship and can result in the different prediction of long-term strength of concrete.

(2) A sufficient amount of surface moisture is required for appropriate hydration of cement in the concrete in order for the maturity method to give accurate prediction of strength.

(3) Variations in fresh concrete properties, such as entrained air, moisture content, and unit weight, can cause substantial variation in the strength of the concrete and thus maturity-strength relationship.

For these reasons, ASTM C1074 specifies that a new maturity-strength relationship has to be developed for each different concrete mixture and a sufficient amount of moisture must be supplied during the curing process. Also, a standard curing temperature, 73˚F, is recommended as a reference temperature. However, the proposed limitations and recommendations by other studies are mostly based on long-term maturity-strength prediction for normal concrete. Clear guidance and guidelines have not been established for the use of the maturity method to predict strength for high early strength concrete at the early age of 4 to 8 hours.

Objectives of the Study

The primary objectives of this study were to evaluate the effects of various factors on the strength–maturity relationship and to determine if the maturity method can be used to determine early age strength of high early strength concrete to facilitate concrete slab replacement. Specific objectives were as follow:

(1) To evaluate effects of various factors on the compressive maturity-strength relationship of concrete at early age.

(2) To develop appropriate test procedures for applying maturity method to predict early age strength of concrete.

(3) To validate the accuracy of the prediction of maturity method using the proposed test procedures.

Findings from the First Set of Laboratory Experiments

The main objectives of the first set of laboratory experiments were to evaluate the effectiveness of four different concrete maturity measuring systems, namely Humboldt, Command Center, Intelli-Rock, and COMA meter, under various curing temperatures and to select the most appropriate one to be used in the maturity-strength prediction. The differences between the results from 6″×12″ specimens and those from 4″×8″ specimens were also evaluated to determine the most effective specimen size to be used for the rest of the study.

Based on the consideration of accuracy, resolution, response time, and convenience of use, it was decided to use the Command Center maturity system for measuring the temperature history of the concrete, and to use 4″×8″ concrete specimens for maturity-strength calibration in the second set of experiments and field studies.

Findings from the Second Set of Laboratory Experiments

The main objectives of the second set of experiments were to evaluate the possible effects of different curing environments on the predicted strength of concrete from the maturity method and to determine the most appropriate procedure to be used to obtain accurate predicted strength of concrete. Two maturity functions, namely the Nurse-Saul and Arrhenius maturity functions, were evaluated. The effects of variation of fresh concrete properties on the predicted strength of the concrete were also evaluated to achieve the goal of the second set of experiments.

The Arrhenius maturity function with an activation energy of 33,500 J/mol was chosen for maturity-strength prediction as it showed consistent maturity-strength relationships developed by various groups of specimens cured under various conditions. It was also found that different curing conditions did not have any significant effect on the Arrhenius maturity-strength relationships at early age while variation in fresh concrete properties could have substantial effects on the maturity-strength relationships. Based on the results of laboratory experiments, ASTM C143, and ASTM C231 specifications, it is recommended that when the actual concrete used at the project site has a different water-cement ratio, or has fresh concrete properties different by more than ±1 inch in slump and/or ±1 % in air content from those of the concrete used in developing the maturity-strength relationship, the developed maturity-strength relationship should not be used to make maturity-strength prediction without making proper adjustments to the predicted strength to account for the changes in the fresh concrete properties.

Based on the findings from the second set of experiments, a testing protocol for the generation of maturity-strength curve for prediction of early-age compressive strength of concrete used in slab replacement project was recommended.

Findings from the Field Study

The main objective of the field study was to evaluate the effectiveness and reliability of the proposed maturity method for prediction of concrete strength at early age for slab replacement application. The maturity-strength curves developed from the field-sampled concrete were compared to the maturity-strength curve developed from the laboratory-prepared concrete to see how close the laboratory concrete can simulate the actual concrete used at the project site. Also, the predicted strength of the in-place concrete at different locations of the replacement slab were compared to the actual strength of the protection specimens to evaluate the reliability of using the strength of 4″×8″ cylindrical specimens as the estimated strength of the concrete in the slab.

The results of the field study indicate that the maturity-strength prediction showed great accuracy when the same concrete preparation time were applied for both concrete batches, namely the concrete batch used to develop maturity-strength curve and the other batch used in the replacement slab. When more or less time has been taken to place the concrete at the project site than the estimated preparation time which was applied to the concrete batch used to develop the maturity-strength relationship, it is recommended to adjust the maturity-strength relationships by adding or subtracting the amount of maturity index (equivalent age) caused by the time difference.

In both field studies, the protection specimens showed higher strength than the strength of the concrete at the slab corner at the time to open the slab to traffic. Thus, using strength of the protection specimens as strength determination is unreliable and may result in over-prediction of concrete strength and result in too early opening of the replacement slab to traffic.

Conclusions and Recommendations

The maturity method using the Arrhenius maturity function was found to be quite reliable and convenient for use in predicting the early-age compressive strength of concrete in replacement slab application. Some limitations of maturity-strength prediction, such as the strength loss due to high curing temperature and insufficient moisture, supply were observed in the laboratory studies in this research project. However, these limitations were observed at the later age of the concrete when the compressive strength reached around 3,000 to 3,500 psi, and thus the observed limitations did not have any negative effect on the early-age-strength prediction of the concrete in the replacement slab.

The maturity method using the Arrhenius maturity function and using the monitored temperature of the in-place concrete at the mid edge of the concrete slab is recommended for use to estimate the early-age compressive strength of concrete in slab replacement application. In the event that there is extra waiting time before the concrete is placed, the maturity-strength relationships should be adjusted by adding or subtracting the amount of maturity index (equivalent age) caused by the time difference. However, this recommended adjustment in the maturity-strength curve is applicable only when the delay does not cause any problem in the proper placement of the concrete.

In the event that the actual concrete used at the project site has a different w/c or has different fresh concrete properties with more than ±1 inch in slump and/or ±1 % in air contents as compared with the concrete which has been used to develop the maturity-strength curve, the maturity-strength curve should not be used to make strength predictions without proper adjustments of the predicted strengths due to effects of the variations in the fresh concrete properties.

However, if the developed maturity curve is to be used to make maturity-strength prediction, it is recommended that an additional 200 psi be added to the target compressive strength of the in-place concrete for every 1% increase in air content or for every 1 inch increase in slump of the fresh concrete. The adjusted target strength of the concrete would then be used to determine the adjusted required equivalent age of the in-place concrete before opening to traffic.

It is recommended that a follow-up laboratory study be conducted to establish the appropriate adjustments to the maturity-strength curves to account for the effects of variations of fresh concrete slump, air content, and water-cement ratio, so that the maturity method could be effectively used for determination of the strength of in-place for these various conditions.

TABLE OF CONTENTS

page

LIST OF TABLES

LIST OF FIGURES

Figure page

CHAPTER 1
INTRODUCTION

1.1 Background

Replacing concrete slabs on highway facilities requires a contractor to close the lane, remove cracked and shattered concrete slabs, place new concrete in the repair area, and reopen the lane to traffic within a 10 to 12 hour window. To minimize the effect of the repair work, work is generally started at night time and done by next morning, which includes curing of the placed concrete. According to Section 353 of the FDOT Standard Specifications for Road and Bridge Construction, concrete specimens are required to have a 24-hour compressive strength of 3,000 psi, and 2,200 psi prior to allowing traffic on the new pavement. In order to test the strength of the replacement slab, the specification requires making a minimum of four cylindrical specimens and curing the specimens by identical conditions used in curing the replacement slab (Freiesleben-Hansen and Pedersen, 1997; Nixon et al., 2008). However, the testing procedure poses the following challenges:

- Testing concrete cylinder requires a testing laboratory to be available at early morning hours on-site, thus adding cost to the project.
- The measured strength of the concrete specimens may not represent the actual strength of the concrete in the replacement slab. Difference in compressive strength at early age between 4″×8″ cylinders and cores was found to reach as high as 20 % (Mohsen et al., 2004).

For these reasons, the maturity method has been recommended to estimate strength of in-place concrete as an alternative, or verification method, in most state DOTs including Florida DOT (Bagheri-Zadeh et al., 2007). The concept of concrete maturity was first introduced by Saul in 1951. He defined "maturity of concrete" as "age multiplied by the average temperature above freezing that a slab has maintained." Based on this definition, he further developed the law for relationship between concrete strength and maturity: "Concrete of the same mixture at the same maturity has approximately the same strength whatever combination of temperature and time goes to make up that maturity." Since then, many studies on maturity have been done by other researchers and Saul's law for maturity has been confirmed and proven to be a useful tool to predict concrete strength.

1.2 Problem Statement

Although the maturity method is a proven method for indicating concrete strength for normal concrete placement and has the potential to be used to determine concrete strength for early opening to traffic, some limitations for the maturity method have been reported in previous research as follows:

- Different curing temperature can produce different maturity-strength relationship and can result in the different prediction of long-term strength of concrete (Wade et al., 2006).
- In order to increase the accuracy of the maturity method, a sufficient amount of surface moisture is required for appropriate hydration of concrete (Tank and Carino, 1991).
- Fresh concrete properties such as entrained air, moisture content and unit weight affect the strength of the concrete and thus maturity-strength relationship (Carino and Malhotra, 1991).

For these reasons, ASTM C1074 specifies that a new maturity-strength relationship has to be developed for each different concrete mixture and sufficient amount of moisture must be supplied during the curing process. Also, a standard curing temperature, 73˚F, is recommended as a reference temperature. However, the proposed limitations and recommendations by other studies are mostly based on long-term maturity-strength prediction for normal concrete. Clear guidance and guidelines have not been established for the use of the maturity method to predict strength for high early strength concrete at the early age of 4 to 8 hours.

1.3 Objectives

The primary objectives of this study are to evaluate effects of various factors on the strength–maturity relationship and to determine if the maturity method can be used to determine early age strength of high early strength concrete to facilitate concrete slab replacement.

Specific objectives are as follow:

- To evaluate effects of various factors on the compressive maturity-strength relationship of concrete at early age.
- To develop appropriate test procedures for applying maturity method to predict early age strength of concrete.
- To validate the accuracy of the prediction of maturity method using the proposed test procedures.

1.4 Scope of Study

This study investigates the effects of various curing conditions and variation of fresh concrete properties on the prediction of concrete strength at early age using the maturity method. As shown in Table 1-1, two curing variables (Curing Temperature and Curing Type) were used to simulate the various curing conditions for slab replacement projects in Florida. The four maturity systems considered are currently most widely used in Florida. The effects of the fresh concrete properties that may have an effect on the application of maturity method were also investigated. With the numerous variables considered, this research is aiming to develop an appropriate procedure for the use of maturity method for determining early strength of concrete in replacement slabs to determine time for opening to traffic.

Table 1-1. Parameters Considered in the Study

Curing Temperature	Curing Type	Types of Maturity Systems	Fresh Concrete Properties
• 113˚F • 73˚F • 43˚F • Ambient Temperature	• Exposed to the air • Wrapped with Burlene • Soaked in water	• Command Center • Intelli-Rock • Coma meter • Humboldt maturity meter	• Fresh concrete temperature • Slump • Air Content • Unit weight • Setting Time

1.5 Research Approach and Methodology

The schematic diagram of the research approach is shown in Figure 1-1. In achieving the set objectives in this study, the following tasks were performed:

1.5.1 Preparation of Concrete in the Laboratory

A thorough review of past and current literature was conducted on the theory and practice of maturity method for concrete, state of the practice for Early-Opening-to-Traffic (EOT) slab replacement, materials and construction specifications in use, and guidelines for use of maturity method for slab replacement.

1.5.2 The First Set of Experiments

The main objective of the first experimental design was to evaluate the effectiveness of different temperature sensors (or data loggers) under various curing environments and to select the most appropriate one to be used in the maturity method for concrete. The differences between the results from 6″×12″ cylinders and those from 4″×8″ cylinders were determined to find the most efficient specimen size for the second set of experiments and field study that were planned in this research.

Two different concrete mix designs were used. The mix designs for these two concrete mixes represent typical concrete mixes which have been used in slab replacement applications in Florida.

1.5.3 The Second Set of Experiments

The second experimental design aimed to evaluate the possible effects of different placement and curing environments on the predicted strength of concrete from the maturity method and to determine the most appropriate procedure to be used to obtain accurate strength prediction of concrete.

The temperature sensor and specimen size which were determined to be the most effective in the first set of experiments were used. Also, three different concrete mix designs were used. The mix designs for these three concrete mixes represent typical concrete mixes which have been used in slab replacement application in Florida.

1.5.4 Field Study

The developed strength prediction procedure using the maturity method was applied to actual slab replacement projects in Florida to evaluate its effectiveness and reliability. The recorded temperature histories at different locations of actual slabs were used to calculate the equivalent age or the temperature-time function (TTF) and the prediction of strength was made by a laboratory developed maturity curve for the concrete used in the actual slab. A total of two field studies were performed.

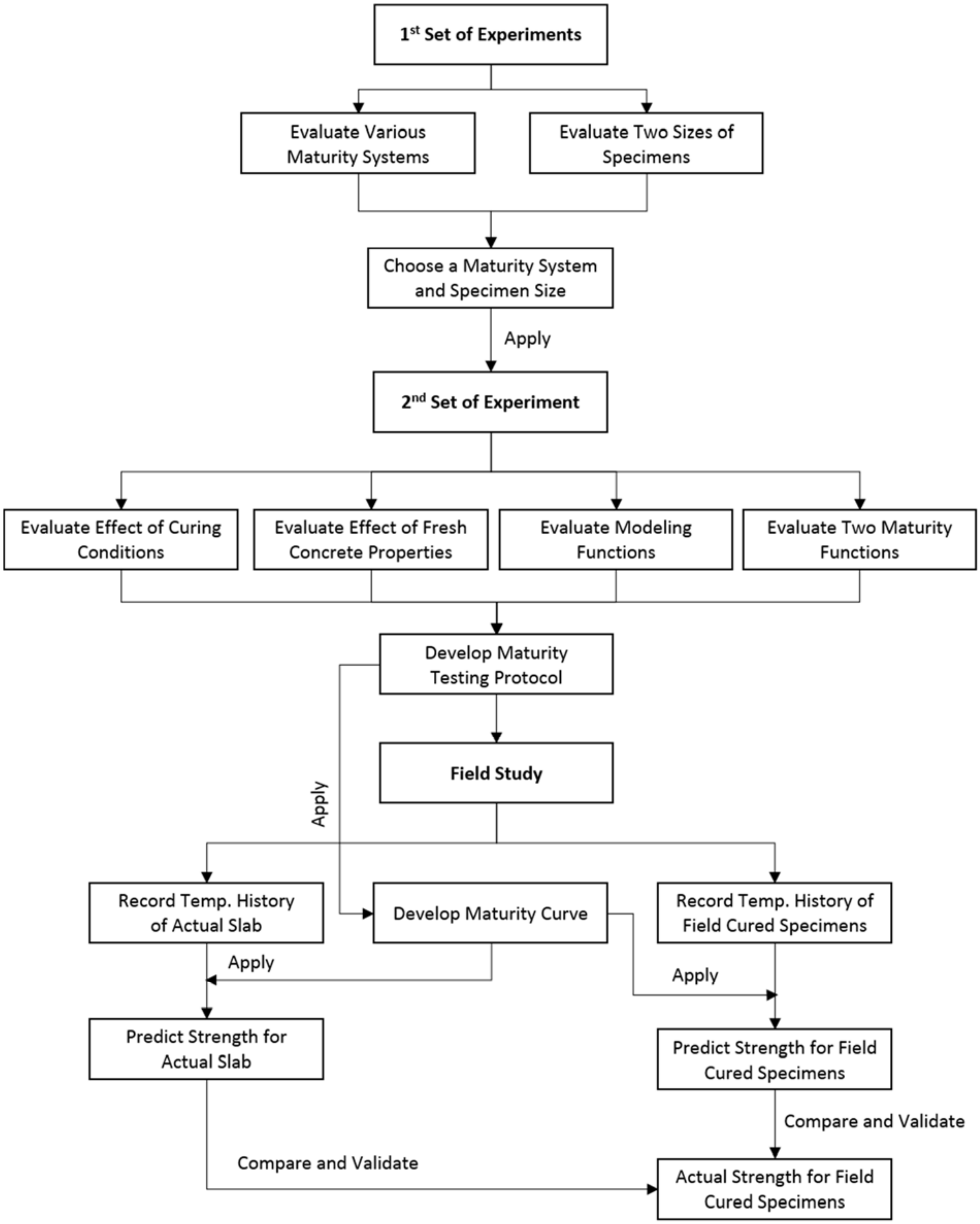


Figure 1-1. Schematic diagram for the research approach.

CHAPTER 2
LITERATURE REVIEW

2.1 Slab Replacement Project

Slab replacement is one of the typical methods used to repair severely deteriorated concrete slabs with relatively low project costs as compared with the other repair solutions such as overlay and reconstruction (Tia and Manakhoom, 2008). According to the slab replacement guideline developed by California Department of Transportation in 2004, slab replacement needs to be applied for the following concrete slab conditions:

- When slabs have 2 or more corner breaks.
- When slabs have cracked into three or more pieces with interconnected cracks developing between cracks or joints.
- When slabs have longitudinal or transverse cracks with 13 mm or more crack width
- When slabs have cracks having 150mm or more spalling and loss of concrete from the crack centerline.
- When slabs have defects due to lack of support such as settlement, base failure and excessive curling.

In many highway agencies, to replace deteriorated concrete slabs, transportation is often restricted, and thus this repair work always aims to be done within a very short time window.

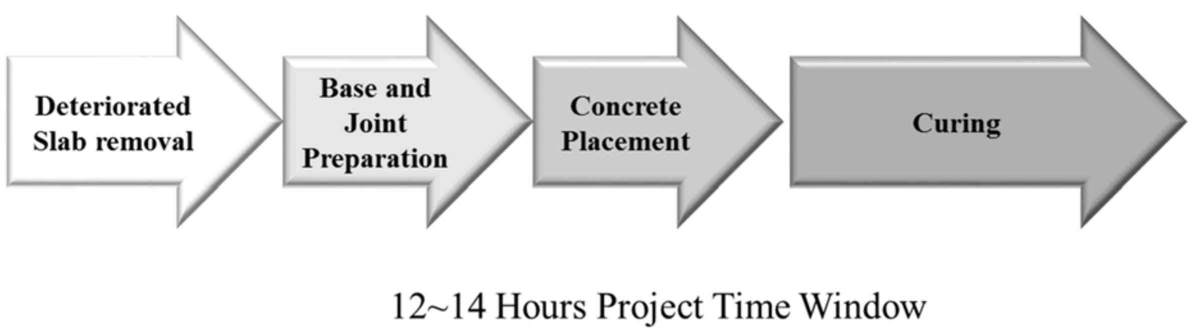


Figure 2-1. Process of slab replacement project.

Figure 2-1 shows the schematic of the process of a slab replacement project conducted by the Florida Department of Transportation. According to the four phases in Figure 2-1, the phase which dictates project time window is the curing of the placed concrete. Therefore in most slab replacement, high-early-strength concrete mix designs, which meet FDOT criteria for the replaced concrete slab requiring to have more than 2,200 psi of compressive strength prior to allowing traffic on the new pavement, have been used.

2.2 Strength Prediction with Maturity Method

In 1949, McIntosh found that the rate of concrete strength gain is highly related with the curing temperature and assumed that "the rate of hardening at any moment is directly proportional to the amount by which the curing temperature exceeds the datum temperature." With the concept of basic age used as a concrete hardening index, he defined that the trend of basic age versus compressive strength are very similar in the range of curing temperature from 60˚F to 200˚F.

To predict strength of concrete, Nurse introduced temperature-time factor (TTF) in 1949 and Saul proposed a maturity-strength prediction which is known as the Nurse-Saul maturity method.

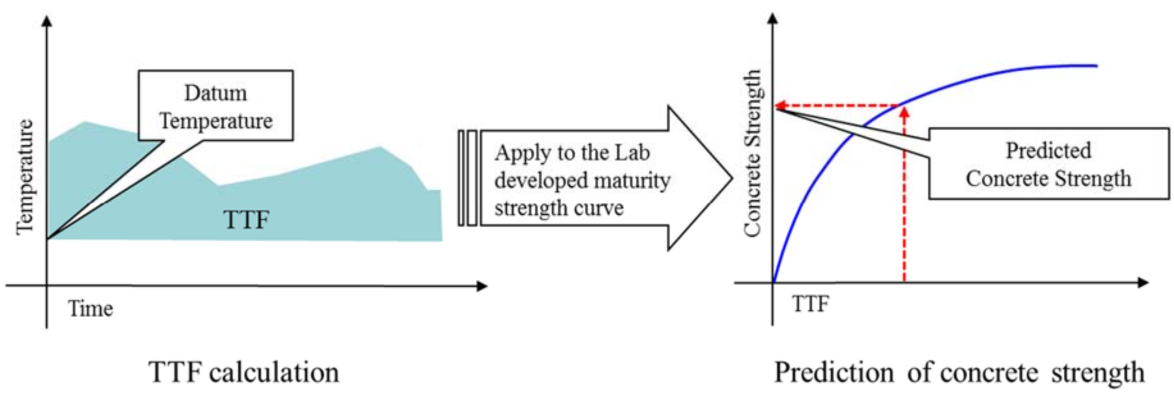


Figure 2-2. Diagram showing concept of the maturity method.

As shown in Figure 2-2, TTF can be calculated as a function of concrete temperature and time. Strength prediction can be made by applying calculated TTF to the lab developed maturity-strength relationship with the notion that the same concrete mixtures will have the same strength at the same point of maturity.

Though the maturity method has been proven to be relatively simple and accurate in the prediction of concrete strength throughout various previous studies, it is not widely applied in actual road way projects. According to a previous study, 29 states out of a considered 32 states did not have any guidelines for the application of maturity-strength prediction (Tepke and Tikalsky, 2007). Thus, for the last decade, strength prediction by maturity method has been recommended for use mainly by the Federal Highway Administration (FHWA).

2.2.1 Nurse-Saul Maturity Function

The Nurse-Saul maturity function, which was originally proposed by Nurse and Saul in 1951, uses TTF as a maturity index. Because of its simplicity and fairly accurate strength prediction, many previous researchers recommended the use of this maturity function. The following equation shows the calculation of TTF using the concrete temperature history in the Nurse-Saul maturity function:

$$M(t) = \sum (T_a - T_0)\,\Delta t \tag{2-1}$$

Where,

	M(t)	=	Maturity index (˚F×hours), or temperature-time factor (TTF),
	Δt	=	Time interval (days or hours),
	T_a	=	Average concrete temperature during time interval, ΔT, (˚F),
	T_o	=	Datum temperature, (˚F).

2.2.2 Arrhenius Maturity Function

The Arrhenius maturity function, which was developed by Freiesleben-Hansen and Pedersen in 1977, is based on the rate of chemical reaction in concrete. Equivalent age is used in this maturity function as a maturity index. The following equation shows the calculation of equivalent age:

$$t_e = \sum e^{-Q\left(\frac{1}{273+T_a} - \frac{1}{273+T_s}\right)} \Delta t \tag{2-2}$$

Where, t_e = Equivalent age at a specified temperature, T_s,
Q = Apparent activation energy, or activation energy divided by universal gas constant (8.3144 J/mol·K),
T_a = Average concrete temperature during time interval, ΔT, (˚C),
Δt = Time interval (days or hours),
T_s = Specified temperature (˚C).

2.3 Comparisons of Maturity Functions

The TTF used in the Nurse-Saul maturity function as a maturity index can be transformed to an equivalent age at a specified reference temperature (Carino et al., 1983). As a result, both Nurse-Saul and Arrhenius maturity functions use the same maturity index and equivalent age.

$$t_e = \sum \frac{(T_a - T_0)}{(T_s - T_0)} \Delta t \tag{2-3}$$

$$t_e = \sum \alpha \, \Delta t \tag{2-4}$$

Where, α = Age conversion factor

Equation 2-4 shows the basic form of both maturity functions with the use of an age conversion factor. Thus, it can be seen that both maturity functions use the same idea that for concrete to reach the same strength under different curing temperatures, it must have the same equivalent age (Wade et al., 2006; Nixon et al., 2008). The only difference between these two maturity functions is the use of different age conversion factors.

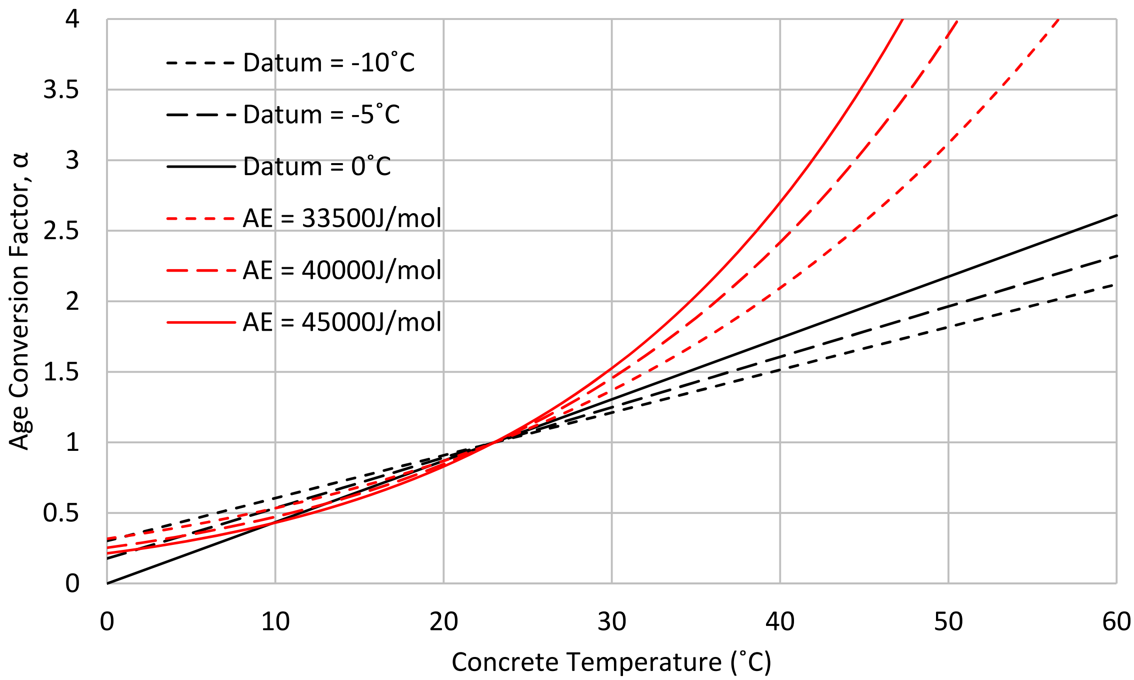


Figure 2-3. Comparison of age conversion factors for both maturity functions (Wade et al., 2006).

Figure 2-3 shows relationships between age conversion factor and concrete curing temperature for both maturity functions. The Nurse-Saul maturity function uses an age conversion factor that has a linear relationship with concrete curing temperature. On the other hand, the Arrhenius maturity function uses a nonlinear relationship between age conversion factor and concrete curing temperature. Carino reported that the nonlinear age conversion factor used in the Arrhenius maturity function gives better fit to the nonlinear concrete hydration rate under different curing temperatures, and thus Arrhenius maturity function gives better prediction of concrete strength (Carino and Malhotra, 1991). On the other hand, other studies have recommended the consideration of both maturity functions because concrete hydration rate is mainly affected by mix design, and some mix designs show better fit to the linear age conversion factor used in the Nurse-Saul maturity function under certain curing conditions.

2.4 Limitations of Maturity Method

According to the previous studies conducted by other researchers, some factors that affect concrete hydration, such as curing temperature, curing humidity, and fresh concrete properties, cause inaccurate maturity-strength prediction.

2.4.1 Effect of Curing Temperature

In 1962, Alexander and Taplin found that different curing temperatures have an effect on the maturity-strength relationship. They developed maturity-strength curves under different curing temperatures, 41˚F (5˚C), 70˚F (21˚C), and 108˚F (42˚C) from a single mixture with the Nurse-Saul maturity function.

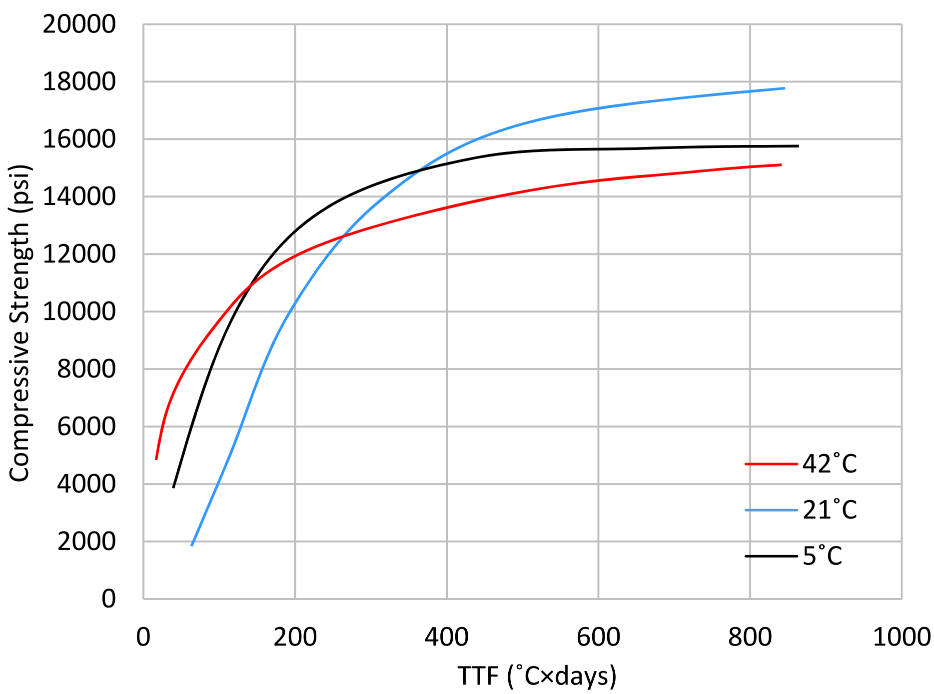


Figure 2-4. Comparison of maturity-strength curves developed by Nurse-Saul maturity function under different curing temperatures (Alexander and Taplin, 1962).

According to the maturity concept, the three developed maturity-strength curves should have identical trend. However each maturity-strength curve had distinctly different trends as shown in Figure 2-4. At early age, the specimens cured under lower temperature showed lower strength while the specimens cured under higher temperature showed higher strength at the same maturity. On the contrary, at late age, the specimens cured under higher temperature showed lower strength while the specimens cured under lower temperature showed higher strength at the same maturity. In 1968, Verbeck and Helmuth confirmed this phenomenon and named it "crossover effect." They found that the crossover effect is mainly affected by initial curing temperature. The strength of concrete exposed to the higher temperature at early age is greater than the strength of concrete exposed to the lower temperature and the TTF calculated by the Nurse-Saul maturity function cannot explain the different rate of chemical reaction of the concrete at different curing temperatures. In addition, impermeable hydration product around cement grains can be made due to the rapid hydration of concrete at the high curing temperature and which results in long-term strength loss. Verbeck and Helmuth concluded that rapid hydration rate and long term strength loss under high curing temperature causes the crossover effect (Wade et al., 2006). In 1984, Carino developed similar maturity-strength curves with the Arrhenius maturity function under three different curing temperatures, 54˚F (12˚C), 70˚F (21˚C), and 90˚F (32˚C) from a single concrete mixture.

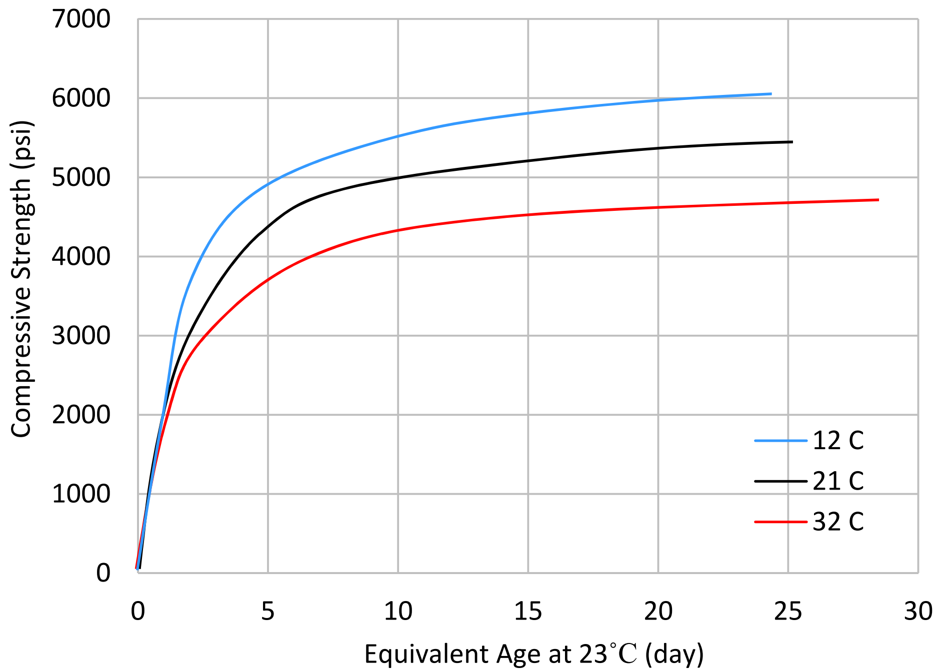


Figure 2-5. Comparison of maturity-strength curves developed by Arrhenius maturity function under different curing temperatures (Carino and Malhotra, 1991).

Figure 2-5 shows the developed maturity-strength curves in his study. It can be seen that at early age, the three curves show a relatively identical trend. However, at the equivalent age of 1 day or later, significant strength losses on the concretes cured under higher curing temperature are detected.

Previous studies conducted by other researchers found that neither Nurse-Saul nor Arrhenius maturity function can perfectly account for the rate of strength development under different curing temperature (Guo, 1989; Tank and Carino, 1991, Wade et al., 2006; Nixon et al., 2008). However, according to the result of Carino's experiments, Arrhenius maturity function may give more accurate strength predictions at early age.

2.4.2 Effect of Moist Curing

In 1928, Gonnerman and Shuman conducted experiments to evaluate the effect of different moist curing time on the strength development of concrete. They generated strength versus time plots under same temperature but different moist conditions. According to the results of their study, specimens cured under moist condition for longer time had higher long-term strength and the strength difference between moist cured specimens and air cured specimens was more than 3,500 psi for one-year strength. However, there was no strength difference observed between the specimens cured under different moist conditions at the early age (Gonnerman and Shuman, 1928).

The observed strength loss may occur due to insufficient moisture supply for proper cement hydration and also can be observed on the maturity versus strength plots. In 1991, Carino found that similar strength loss occurred in the maturity-strength relationship and concluded that "If concrete dries out, strength gain ceases but the computed maturity value continues to increase with time." Since strength loss results in inaccurate maturity-strength prediction, ASTM C 1074 specification (2004) recommended a sufficient amount of moisture to be supplied for accurate in-place concrete strength prediction.

2.4.3 Effect of Fresh Concrete Properties

2.4.3.1 Water-to-cement ratio

ASTM C 1074 specified that the same concrete (with the same water-to-cement ratio and fresh concrete properties) must be produced in the laboratory in order to predict accurate, in-place concrete using the maturity method. However, it is hard to produce exactly the same concrete in the laboratory because actual moisture content of the aggregates cannot be accurately accounted for during batching of concrete. This variation in moisture content affects the water-to-cement ratio of the concrete, which in turn affects the compressive strength of concrete.

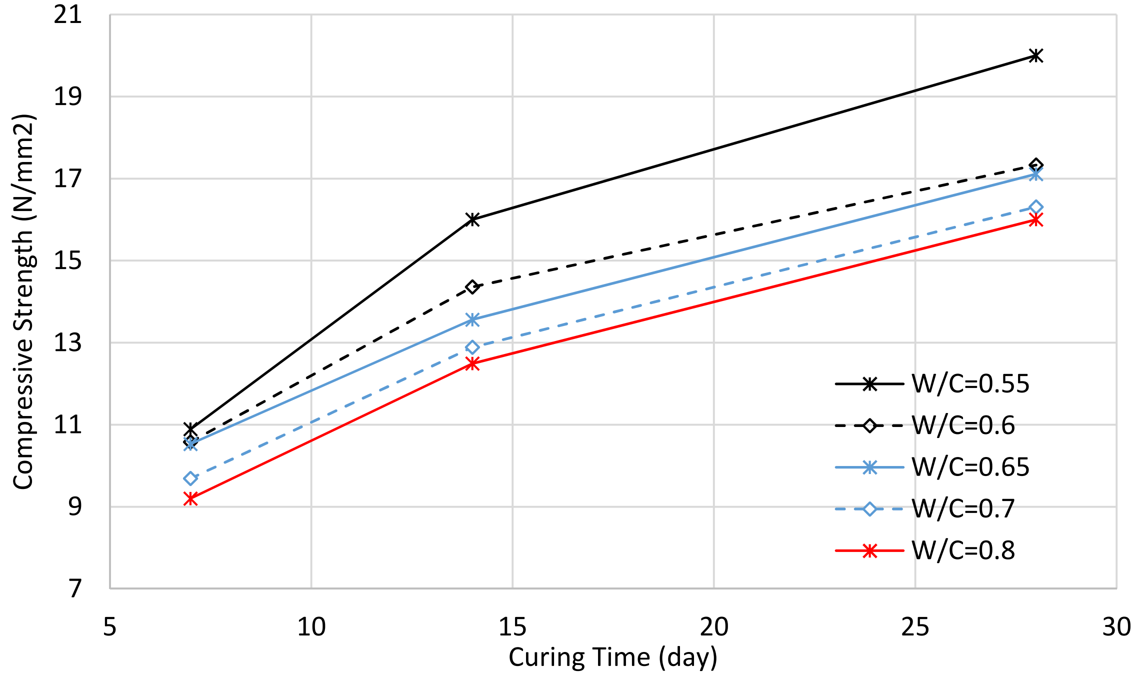


Figure 2-6. Effect of water-to-cement ratio on the compressive strength (Alawode and Idowu, 2011).

It is well-known that compressive strength in concrete mixtures decreases with addition of more water. In 2011, Alawode and Idowu conducted experiments to determine the effect of water-to-cement ratio on compressive strength. They produced concrete mixtures having different water-to-cement ratios in the range of 0.55 to 0.8 by controlling the amount of water. They concluded that the mixture having higher water-to-cement ratio showed lower unit weight and higher slump value. As shown in Figure 2-6, compressive strength increases by decreasing water-to-cement ratio.

2.4.3.2 Air content

Air content in fresh concrete can be varied using different materials involving several chemical reactions (Nixon et al., 2008). Table 2-1 shows the effects of various factors on air content, which in turn affect the compressive strength of the concrete. (Wilson and Kosmatka, 2011).

Table 2-1. Effect of Concrete Materials and Production Practices on Air Entrainment

Material/Practice	Change	Effect on Air Content
Cement	Increase in Cement Content	Decrease
	Increase in Fineness	Decrease
	Increase in Alkali Content	Increase
SCMs	Fly Ash (With High Carbon)	Significant Decrease
	Silica Fume	Significant Decrease
	Slag with Increasing Fineness	Decrease
	Metakaolin	No Change
Aggregate	Increase in Maximum Size	Decrease
	Sand Content	Increase
Chemical Admixtures	Water Reducers	Increase
	Retarders	Increase
	Accelerators	No Change
	High-Range Water Reducers	Increase
Water-to-Cement Ratio	Increase Water-to-Cement Ratio	Increase
Slump	Increase in Slump up to 6 in	Increase
	High Slump (> 6 in)	Decrease
	Low Slump (< 3 in)	Decrease
Production	Increased Mixer Capacity	Increase
	Mixer Speeds to 20 rpm	Increase
	Mixer Time	Increase
Transport and Delivery	Transport	Decrease
	Long Hauls	Decrease
	Retempering	Increase
Placing and Finishing	Belt Conveyors	Decrease
	Pumping	Significant decrease

The effect of air content has already been shown by previous research. For every 1 % increase in total volume of air, a 5 % decrease in compressive strength can be expected (Mindess et al., 2003). Figure 2-7 shows the relationship between volume of air and 28-day compressive strength for concrete at three different cement content levels. It can be seen that at all cement contents, the compressive strength generally decreases with increasing volume of air under the same slump value.

These strength variations, due to the different fresh concrete properties such as moisture and entrained air content, can also be observed in the maturity-strength curves (Nixon et al., 2008). Hence, in order to predict accurately the compressive strength of concrete using the maturity method, the maturity-strength curve must be developed using the same fresh concrete properties as the in-place concrete.

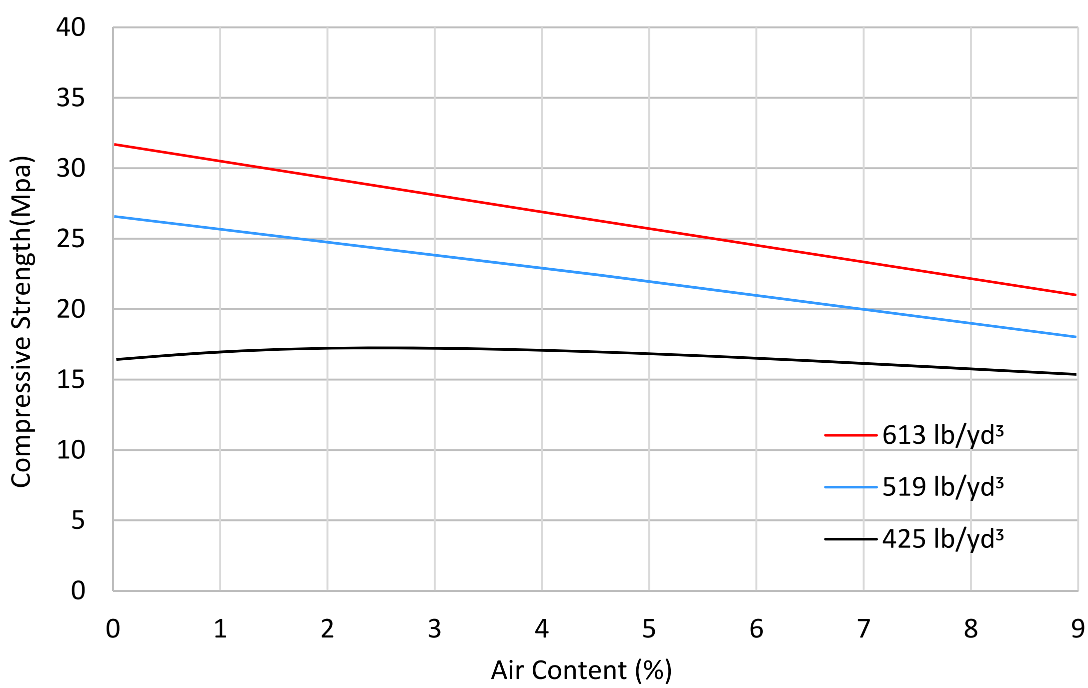


Figure 2-7. Relationship between air content and 28-day compressive strength (Cordon, 1946).

2.5 Functions for Modeling Maturity-Strength Relationships

In order to predict accurate concrete strength using the maturity method, it is important to develop appropriate maturity-strength curves that show an identical trend with the actual strength versus maturity index plots. ASTM C 1074 states that each concrete mix design has a unique maturity-strength relationship, and a common equation that can explain all the unique maturity-strength relationships is required for modeling the maturity-strength relationships. In previous research work, several types of equations have been proposed by different researchers to model the maturity-strength relationships. The most widely used equations are exponential, hyperbolic, and logarithmic functions, and will be presented in the following sections.

2.5.1 Modified Exponential Function

In 1956, Nykanen proposed an exponential equation which mostly depended on the w/c ratio of the concrete (Nixon et al., 2008). The equation did not fit the actual strength data very well. As a result, Freiesleben-Hansen and Pederson proposed a modified exponential function in 1977. Their modified exponential equation has shown good fit to many researchers' maturity-strength data sets, especially at an early age (Carino and Malhotra, 1991). ASTM C 1074 recommends using the modified exponential equation for modeling maturity-strength relationship of concrete. Freiesleben-Hansen and Pederson's modified exponential equation is as follows:

$$S = S_u e^{-\left(\frac{\tau}{M}\right)^{\beta}} \tag{2-5}$$

Where,

Where,	S	=	Compressive strength (psi),
	S_u	=	Limiting compressive strength (psi),
	M	=	Maturity index (˚C×hours or hours),
	τ	=	Characteristic time constant (hours), and
	β	=	Shape parameter.

2.5.2 Modified Hyperbolic Function

The modified hyperbolic function was suggested by Carino in 1991. He introduced an offset of maturity, M_0, to account for the fact that strength development does not begin until the maturity reaches a certain point. It has also been shown by other studies that the modified hyperbolic function fits well for various concrete mix designs. ASTM C 1074 recommends using the modified hyperbolic function for modeling maturity-strength relationships as well. The modified hyperbolic function is as follows:

$$S = S_u\left(\frac{k(M-M_0)}{1+k(M-M_0)}\right) \tag{2-6}$$

Where, M_0 = Maturity when strength development is assumed to begin (˚C×hours or hours), and

k = Rate constant (1/[˚C×hours] or hours).

2.5.3 Logarithmic Function

Plowman proposed the logarithmic function in 1956 for modeling maturity-strength relationships. Because of the simplicity of this function, it is the most widely used for generating maturity-strength curves. Illinois Department of Transportation (IDOT) IM-383 and Texas Department of Transportation (TXDOT) Tex-426-A guidelines recommend using the logarithmic function to develop maturity-strength relationships (Nixon et al., 2008). However, some limitations of the logarithmic equation were discovered by previous studies, and thus this function was not recommended by ASTM C 1074 specification.

- The relationship predicts ever-increasing strength with increasing maturity.
- The linear relationship is not valid at very early maturities.
- Only intermediate maturity values result in an approximately linear relationship between strength and the logarithm of maturity (Carino and Malhotra, 1991).

The logarithmic function is as follows:

$$S = a + b \log M \tag{2-7}$$

Where,	a	=	Constant (psi), and
	b	=	Constant (psi/hours or psi/[˚C×hours])

CHAPTER 3
PREPARATION OF CONCRETE SPECIMENS

3.1 Introduction

In order to develop appropriate testing protocol for the application of maturity method to slab replacement projects, more than 1,500 cylindrical specimens from three different mix designs and for various curing conditions were produced and tested. In this chapter, the mix designs, mix ingredients, and procedures for preparation of the concrete specimens are described. Fresh concrete tests used to evaluate the characteristics of the concrete mixtures, and compressive strength tests on the hardened concrete are also described.

3.2 Concrete Mix Designs

Three different concrete mix designs were used for two different sets of laboratory experiments. Two mix designs, namely Mix #1 and Mix #2, were used to evaluate different maturity systems in the first set of experiments. The two mix designs used for the first set of experiments and an additional mix design, namely Mix #3, were used to evaluate the effect of different curing conditions on the maturity-strength relationship in the second set of experiments.

Table 3-1. Mix #1 Used in the First and Second Sets of Experiments (for 1 yd^3 of Concrete)

Name	Product Name	Quantity	Specification
Cement	Type I/II Cement	850 LB	AASHTO Type I/II
Coarse Aggregate	#57 Stone	1,720 LB	
Fine Aggregate	Silica Sand	983 LB	
Air Ent Admixture	Darex AEA	1.0 OZ	AASHTO M 154 - AEA
Type D Admixture	WRDA 60	25.5 OZ	AASHTO M 194 - Type D
Type F Admixture	Adva 120	38.3 OZ	AASHTO M 194 - Type F
Type E admixture	Daracel	384.0 OZ	AASHTO M 194 - Type E
Water	Water	32.0 GA	

Table 3-2. Mix #2 Used in the First and Second Sets of Experiments (for 1 yd^3 of Concrete)

Name	Product Name	Quantity	Specification
Cement	Type I/II Cement	850 LB	AASHTO Type I/II
Coarse Aggregate	#57 Stone	1,720 LB	
Fine Aggregate	Silica Sand	983 LB	
Air Ent Admixture	Darex AEA	1.0 OZ	AASHTO M 154 - AEA
Type D Admixture	WRDA 60	25.5 OZ	AASHTO M 194 - Type D
Type F Admixture	Adva 120	38.3 OZ	AASHTO M 194 - Type F
Type E admixture	Daracel	384.0 OZ	AASHTO M 194 - Type E
Water	Water	32.0 GA	

Table 3-3. Mix #3 Used in the Second Sets of Experiments (for 1 yd^3 of Concrete)

Name	Product Name	Quantity	Specification
Cement	Type I/II Cement	850 LB	AASHTO Type I/II
Coarse Aggregate	#57 Stone	1,775 LB	
Fine Aggregate	Silica Sand	999 LB	
Air Ent Admixture	Darex AEA	6.8 OZ	AASHTO M 154 - AEA
Type D Admixture	WRDA 60	8.5 OZ	AASHTO M 194 - Type D
Type F Admixture	Adva 120	68.0 OZ	AASHTO M 194 - Type F
Type E admixture	Daracel	382.5 OZ	AASHTO M 194 - Type E
Water	Water	32.0 GA	

All three concrete mix designs represent typical concrete mix designs which have been used in slab replacement application in Florida. Tables 3-1, 3-2, and 3-3 show the mix designs for Mixes #1, #2, and #3, respectively.

3.3 Preparation of Concrete Ingredients

3.3.1 Cement

In accordance with the mix designs, two different Type-I/II Portland cements from two cement manufacturers, CEMEX and Suwannee American Cement were used to produce the concrete mixtures. Table 3-4 shows the physical properties of both cements as measured by the cement manufacturers and their corresponding AASHTO/ASTM Type I/II cement specification limits.

Table 3-4. Physical Properties of the Type I/II Cements Used

	CEMEX	Suwannee	Specification Limit
Loss on Ignition	0.5 %	2.4 %	<= 3.0
Autoclave Expansion	0.04 %	0.06 %	<= 0.8
Time of Setting (Initial)	172 min	104 min	>=60
Time of Setting (Final)	260 min	215 min	<=600
3-Day Compressive Strength	3,127 psi	3,889 psi	>=1,450
7-Day Compressive Strength	4,892 psi	5,084 psi	>=2,470

3.3.2 Aggregate

Silica sand and #57 Oolite limestone were used as fine and coarse aggregates. Both aggregates were obtained from the CEMEX batch plant in Gainesville where they produce slab replacement concrete. The physical property tests were conducted in the lab for each set of laboratory experiments. Table 3-5 and 3-6 show the test results for both the fine and coarse aggregates.

Table 3-5. Physical Properties of the Fine Aggregate Used

	First set of lab experiments	Second set of lab experiments
SSD Specific Gravity	2.615	2.478
Apparent Specific Gravity	2.623	2.488
Bulk Specific Gravity	2.610	2.471
Absorption	0.177	0.274

Table 3-6. Physical Properties of the Coarse Aggregate Used

	First set of lab experiments	Second set of lab experiments
SSD Specific Gravity	2.423	2.422
Apparent Specific Gravity	2.592	2.578
Bulk Specific Gravity	2.317	2.323
Absorption	4.569	4.258

In order to measure the exact amounts of moisture content for both aggregates, the silica sand was oven-dried by placing the sand in an 110˚C oven for over 24 hours. Also, the #57 stone was soaked in water for 20 hours and then drained for 50 minutes. Based on the differences between the obtained moisture contents and specified moisture contents at SSD condition for both fine and coarse aggregates, the amount of mixing water was adjusted in the batching of ingredients for the concrete mixtures.

3.3.3 Admixtures

Four different types of admixtures were used in each concrete mix design to produce the concrete mixes in this slab replacement project. They are as follows:

- Air Entraining Admixture: It was used to stabilize microscopic air bubbles in concrete and thus durability of the concrete can be improved
- Type D Admixture: It was used to reduce water and retard the setting time. Thus, the right consistency and retarding of setting time could be achieved.

- Type E Admixture: It was used to reduce water and accelerate the rate of concrete hydration. Thus, early strength development of concrete could be achieved.

- Type F Admixture: Similar to the Type D admixture, it was used to reduce water and greater amount of water can be reduced.

Table 3-7. Admixtures Used in the Laboratory Experiments

Type	Product Name	Producer
Air Entrained Admixture	Darex AEA	W.R Grace Co.
Type D Admixture	WRDA 60	W.R Grace Co.
Type F Admixture	ADVA 120 (Mix #1 and #3) ADVA 140M (Mix #2)	W.R Grace Co.
Type E Admixture	Daracel	W.R Grace Co.

Table 3-7 shows the product names and producers of the different admixtures used in the laboratory study. All four types of admixtures were diluted in the water used to produce the concrete mixtures right before adding the water to the other mix ingredients.

3.4 Temperature Sensor Installation

As part of the first set of experiments, temperature sensors from Humboldt,

Command Center and Intelli-Rock maturity systems were compared to each other for their accuracy and efficiency. Since concrete cylinders do not have the same temperature at different locations, all temperature sensors were pre-installed in the middle of both, 4″×8″ and 6″×12″ cylinder molds before concrete was placed.

As shown in Figure 3-1, the temperature sensors were firmly fixed in the middle of the molds, and thus would not be displaced during pouring and vibrating of concrete. Thus, appropriate comparisons between the measurements made by different sensors can be made in the first set of experiments.

Figure 3-1. Pre-installed temperature sensors in the 4″×8″ cylinder molds.

3.5 Tests for Fresh and Hardened Concrete

In accordance with ASTM specifications, fresh and hardened concrete tests were performed for every concrete batch. All test results were used to develop and compare among the various maturity-strength curves developed under various curing conditions.

3.5.1 Time of Set

In order to determine the overall time frame for making and testing concrete specimens in the laboratory, initial and final setting time tests were performed for all mix designs. The setting time test was conducted in accordance with ASTM C191 specification. Mortar specimens were obtained by sieving the fresh concrete mixtures through a No. 4 sieve and the penetration test was performed in a temperature controlled room, maintaining a temperature of 73˚F (23˚C). Since the concrete mix designs used for this research were designed to get high early strength, penetration tests were performed every 5 minutes after an elapsed curing time of 1 hour. The results of the setting time test for all three mix designs were used to determine the time to remove the cylinder mold and to run the compressive strength test. Figure 3-2 shows the Humboldt Acme Penetrometer and mortar container used in the setting time test in this research.

Figure 3-2. Humboldt Acme penetrometer and mortar container.

3.5.2 Slump

Concrete slump tests were performed to determine the consistency of the fresh concrete mixture. The tests were performed for every separate batch in accordance to the ASTM C143 specification. The slump test was performed as soon as the concrete mixtures were produced because slump decreases as time passes. The test results were used to control the quality of each fresh concrete mixture and to evaluate the effect of slump on the maturity-strength relationship.

3.5.3 Air Content

Concrete air content tests were performed to determine the amount of air in the concrete for every separate batch. All test procedures were performed in accordance with the ASTM C231 specification. A Type B pressure meter was used to measure the percent of volume of air. Since air content decreases with the passing of time, the air content test was performed as soon as the slump test was finished.

3.5.4 Unit Weight

Concrete unit weight tests were performed to determine the density of the fresh concrete. In accordance with the ASTM C138 specification, all measurements were made using the Type B pressure meter and calculated by the equation below:

$$D = (M_c - M_m)/ V_m \tag{3-1}$$

Where, M_c = Weight of the measure holding the concrete
M_m = Weight of the empty concrete measure
V_m = Volume of the measure (0.247 ft^3)

The results of the unit weight test were reported in units of pcf and done 10 minutes after production of the fresh concrete mixture. The test results were used to evaluate the effect of fresh concrete properties on the maturity-strength relationship.

3.5.5 Concrete Mixture Temperature

In accordance with ASTM C1064, fresh concrete temperature was measured for each batch. As high mixture temperature can result in strength loss in hardened concrete, the measurement of the fresh concrete temperature was used to check whether it was within the normal range. The temperature of fresh concrete was measured within 5 minutes after completing the concrete mixture. The results were reported with an accuracy of 1˚F.

3.5.6 Compressive Strength

Though maturity method can be applied for predicting different types of concrete strengths, only compressive strength tests were performed in this study as FDOT has a single criterion of compressive strength to determine the time to open the replaced concrete slab to traffic. As part of the second set of experiments, compressive strength tests were performed on all concrete mixes to develop and compare maturity-strength curves under various curing conditions. All compressive strength test procedures were performed in accordance with the

ASTM C39 standard. Because of the characteristic of high early strength concrete used in this study, the compressive strength tests were performed at early curing times. Table 3-8 shows the elapsed curing times when the compressive strength tests were tested.

Table 3-8. Curing Times for Testing Compressive Strength

Curing Temperature	Compressive Strength Testing Time
Ambient, Standard Temperature (73˚F)	4, 6, 8, 24, 168 hours
High Curing Temperature (113˚F)	3, 4, 6, 8, 24, 168 hours
Low Curing Temperature (43˚F)	7, 10, 13, 24, 48, 168 hours

An average value of the three test results of the specimens was used for each testing time. When an individual strength has a significant level of deviation (more than 10 % of the average strength), an average value of the other two test results was used. The two flat surfaces of each cylinder were evenly ground by using a diamond wheel grinder before the specimens were tested for their compressive strengths.

CHAPTER 4
FIRST SET OF LABORATORY EXPERIMENTS

4.1 Laboratory Experiment Design

4.1.1 Main Objective

The main objective of the first set of laboratory experiments was to evaluate the effectiveness of different maturity systems under various curing temperatures and to select the most appropriate one to be used in the maturity-strength prediction for the rest of the study. The differences between the results from 6″×12″ cylinders and those from 4″×8″ cylinders were evaluated to determine the most effective specimen size to be used in the second set of experiments and the field studies planned for this project.

4.1.2 Maturity Measuring Systems

Since this study aims to propose the most appropriate maturity-strength prediction guidelines for a slab replacement project, different maturity measuring systems must also be evaluated. Four commonly used maturity measuring systems were evaluated in this set of experiments.

4.1.2.1 Humboldt Concrete Maturity Meter

The Humboldt 4101 concrete maturity meter is one of the most commonly used multi-channel maturity meters in the U.S. Figure 4-1 shows a picture of the Humboldt maturity meter. Up to four "T" type thermocouple wires can be connected to the maturity meter and RS-232C cables can be connected from the maturity meter to a computer to download the collected data. The Humboldt maturity meter records temperature every half an hour for the first two days and then every hour for the rest of the time. The range of temperature reading is from -10˚C to 90˚C with 1˚C of temperature resolution. The maturity meter meets ASTM C 1074 specification and can calculate both the Nurse-Saul and the Arrhenius maturity functions. For the Nurse-Saul maturity function, a datum temperature with a range of -20˚C to 60˚C can be input into the meter. For the Arrhenius maturity function, a reference temperature with a range of 0˚C to 40˚C and activation energy with a range of 0 KJ/mol to 200 KJ/mol can be programmed.

Figure 4-1. Humboldt 4101 maturity meter with thermocouple wires.

4.1.2.2 Command Center Maturity System

The Command Center maturity measuring system consists of self-powered, self-recorded temperature sensor and manufacturer-supplied software. The recorded temperature history and the computed maturity index can be downloaded, whenever the data needs to be used, by connecting the sensors to either a Command Center pocket computer or to any computer where the Command Center maturity software has been installed. The Command Center maturity system generates the Nurse-Saul maturity function from the collected temperature data and the input datum temperature. The Command Center maturity system has a temperature recording range of -10˚C to 85˚C and a temperature resolution of 0.5˚C. It can record temperature at specified time intervals ranging from every 1 to 225 minutes, which can be set through the Command Center software. In addition, the start time of data recording can be pre-programmed into the sensors, so that it is not required to activate sensors when placing concrete in the field. A picture of a Command Center temperature sensor is shown in Figure 4-2.

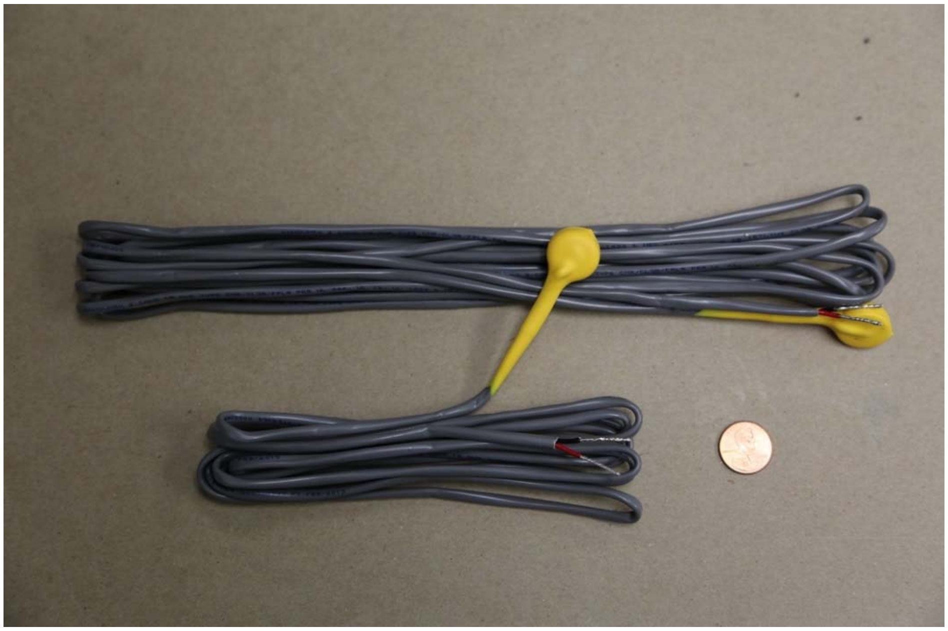


Figure 4-2. Command Center temperature sensors.

4.1.2.3 Intelli-Rock Maturity System

Similar to the Command Center maturity system, the Intelli-Rock maturity measuring system consists of self-powered and self-recorded temperature sensors, a data reader and manufacturer supplied software. Figure 4-3 is a picture of the temperature sensor and data reader used for this system. The recorded temperature history and the maturity index can be downloaded by connecting the data reader to the sensor. Once the data are downloaded to the reader, the display panel shows all the information and useful plots of downloaded data. It can provide two maturity functions, namely Nurse-Saul and the Arrhenius, and several time intervals of temperature readings can be chosen by selecting from 22 different types of temperature sensors. In addition, if other time intervals are required, the supplier can program the sensors to meet those needs. The sensor has a measurement range of -5˚C to 85˚C and 1˚C temperature resolution. Any datum temperature for Nurse-Saul maturity function, and any activation energy for Arrhenius maturity function, can be programmed into the sensor by connecting the data reader to a sensor.

Figure 4-3. Temperature sensor and hand-held reader of the Intelli-Rock maturity system.

4.1.2.4 COMA Meter

The COMA (COncrete MAturity) meter is a convenient method for measuring the maturity of newly cast concrete by equivalent age according to the Arrhenius method. Figure 4-4 shows a picture of the COMA meter. The principle operation of a COMA meter is described in the product information sheet as follows:

A glass capillary contains a liquid for which the rate of evaporation varies with temperature according to the Arrhenius equation, which is the same function that is used to determine maturity of concrete from the temperature history.

Figure 4-4. COMA meter.

The closed capillary is placed on a card with a scale indicating maturity in equivalent age at reference temperature of 20˚C. By reading the position of the liquid in the capillary on the scale, the equivalent age can be obtained. The measured equivalent age by COMA meter is the same as the calculated equivalent age with a fixed activation energy of 40 KJ/mol.

Currently, two types of COMA meters are available for measuring equivalent age of concrete. COMA-5, which has a scale of 0 to 5 days of equivalent age, is recommended to be used in the high early strength concrete. COMA-14, which has a scale of 0 to 14 days of equivalent age, is recommended to be used in other types of concrete.

4.1.3 Curing Conditions

The following three different curing conditions were used for the first set of experiments:

- 73˚F in curing tank (standard curing condition)
- 113˚F in environment-control chamber
- Ambient condition in lab

Since ASTM specification C192 specifies that "concrete specimens shall be moist-cured at 73˚F ±3.5˚F", 73˚F water curing environment was used as a standard curing condition. The 113˚F curing chamber condition was designed to make an extremely hot curing condition to resemble the historically highest temperature recorded in Florida, 109˚F at Monticello in 1931. An ambient curing room was also used to simulate the variation of air temperature in the field.

4.1.4 Concrete Specimens

A total of two batches of concrete were produced and tested in this set of experiments. For each batch of concrete, the following concrete specimens were tested.

- Ten (10) 6″×12″ cylindrical specimens to be instrumented

  a) Only the ambient condition in the lab was used for curing. Each specimen was instrumented separately with one of the five different temperature sensors.
  b) Two replicate specimens were used for each of the five types of maturity measuring systems.

- Twenty eight (28) 4″×8″ cylindrical specimens to be instrumented

  a) Each specimen was instrumented separately with one of the five different temperature sensors.
  b) The specimens instrumented with the first four temperature sensors were placed in the three curing conditions.
  c) The specimens instrumented with the Coma meter were placed only in the last two curing conditions.
  d) Two replicate specimens were used per condition.

- Fifteen (15) 4″×8″ cylindrical specimens to be tested for compressive strength

  a) These specimens were cured in the curing tank at 73˚F
  b) Three specimens were tested for compressive strength at each of the following five curing times: 4, 6, 8, 24, 168 hours.
  c) It is to be noted that since high early-strength concretes are used in this study, 7 day strength was adequate for characterization of the ultimate strength of the concrete. 7 day strength was chosen to be used instead of 28 day strength in order to shorten the time of the experiment.

4.2 Evaluation of the Effectiveness of Maturity Systems

This section presents the test results and findings from the first set of experiments which evaluated the effectiveness of different maturity systems to be used in the maturity method for predicting concrete strength. Two different concrete mix designs were used in this set of experiments. Since the results from the two concrete mix designs gave similar trends and findings, only the results from the first concrete mix design are discussed in this chapter. The results from the second concrete mix design are presented in Appendix A.

4.2.1 Comparison of Recorded Temperature Histories

The temperature data as recorded by the different sensors from the same concrete mix design under the same curing condition were plotted and observed to see how they compared to one another. Figure 4-5 shows the comparison of temperature-time plots of the concrete specimens cured under ambient lab condition as recorded by the Humboldt, Command Center and Intelli-Rock temperature sensors. The temperature-time plot of the ambient laboratory environment during the testing period was also shown in this figure. It appears that the temperatures as recorded by the Humboldt maturity meter are 2 to 5˚F higher than those recorded by the Command Center and Intelli-Rock temperature sensors, while the temperatures recorded by the Command Center and Intelli-Rock temperature sensors were similar to one another.

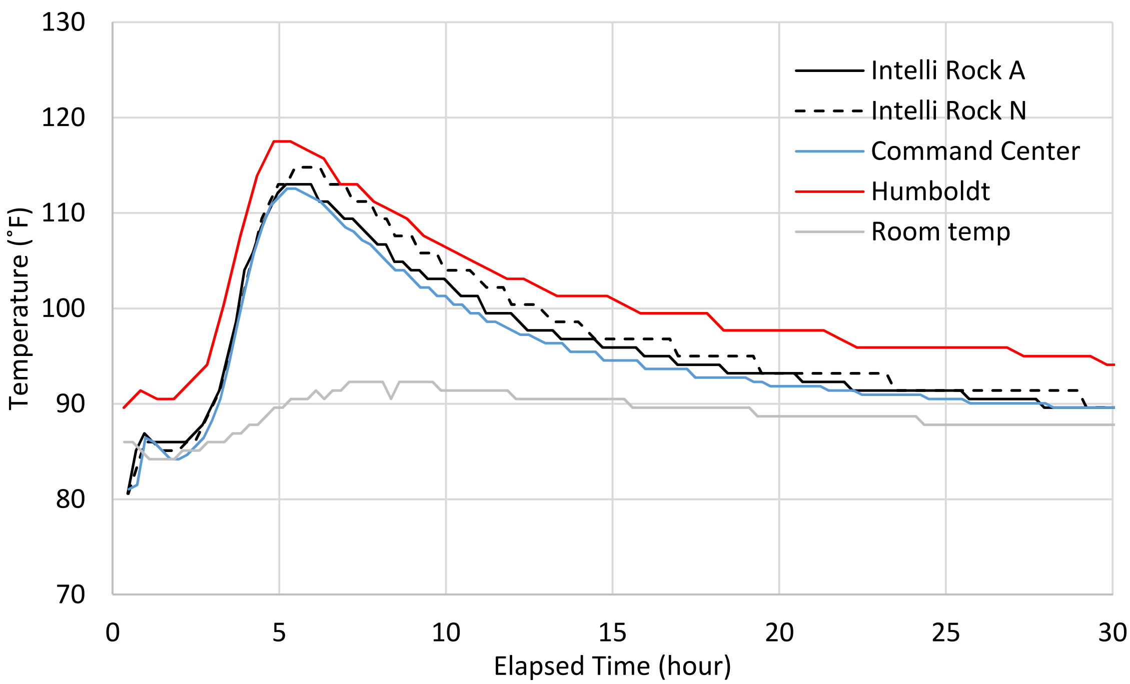


Figure 4-5. Temperature-time plots of 4″×8″ concrete specimens cured under ambient laboratory condition.

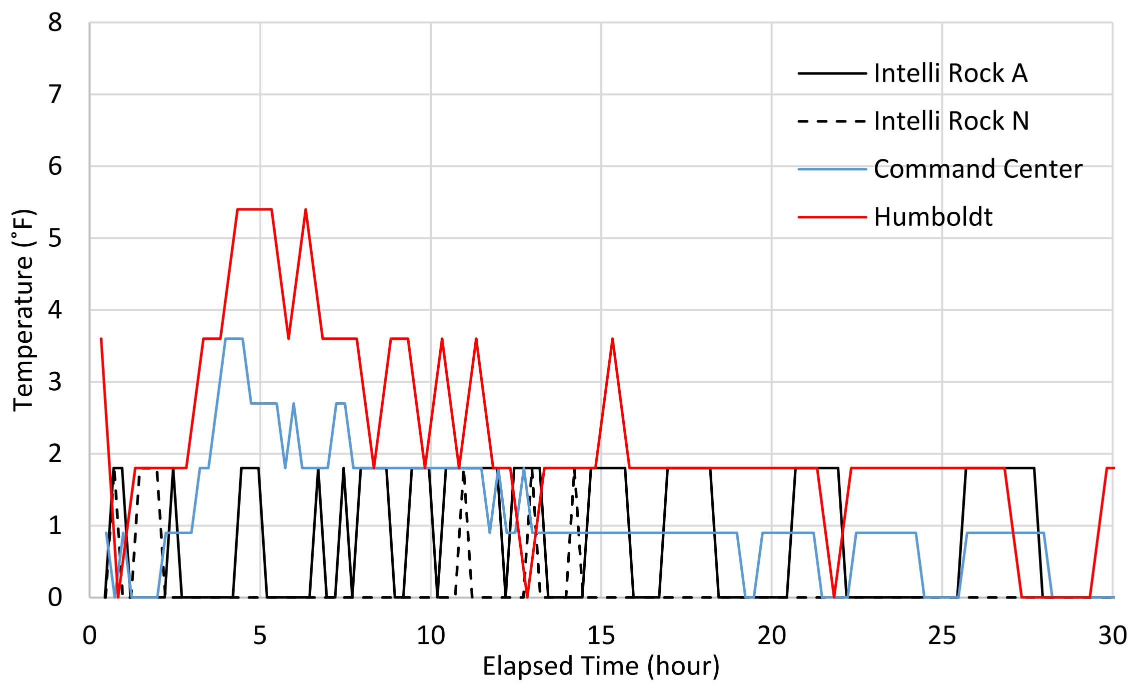


Figure 4-6. Variations of temperature measurements from same temperature sensors cured under ambient laboratory condition.

Figure 4-6 shows the variations of temperature measurements from two identical temperature sensors. It can be seen that the temperature data from the Humboldt maturity meter had greater variations than those from the other sensors.

Figure 4-7 shows the comparison of temperature-time plots of the concrete specimens cured in the 113˚F environment-control chamber as recorded by the different maturity meters. The temperature-time plot of the environment-control chamber during the testing period was also shown in this figure. Similarly, it appears that the temperatures as recorded by the Humboldt maturity meter are 2 to 4˚F higher than those recorded by the Command Center and Intelli-Rock temperature sensors.

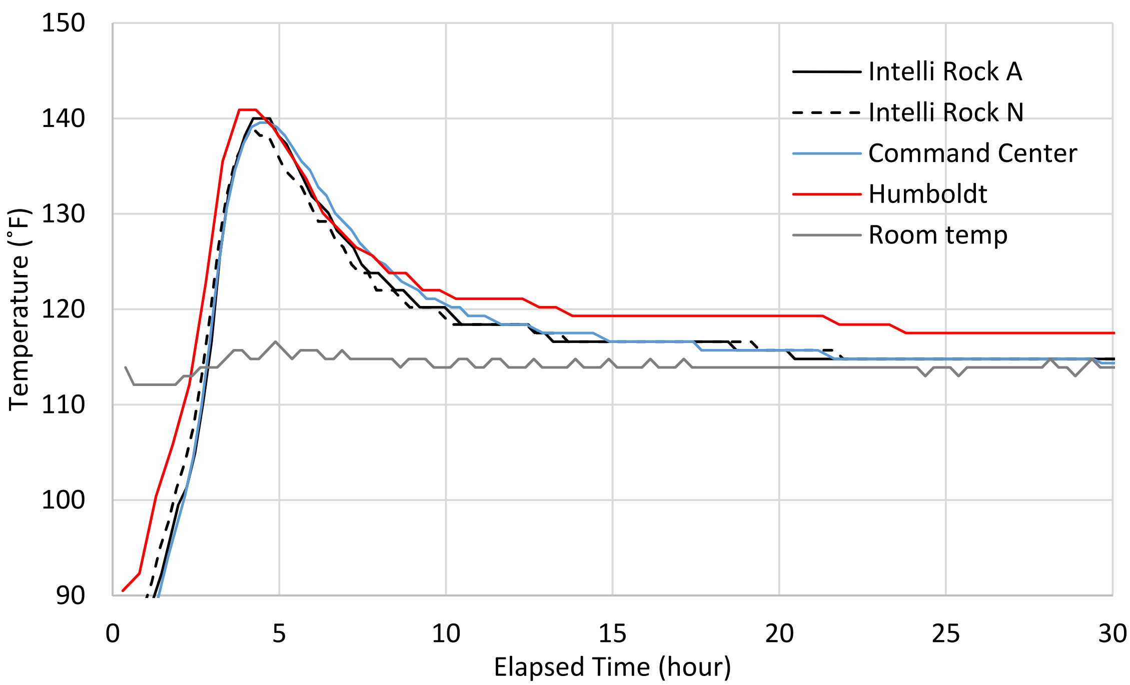


Figure 4-7. Temperature-time plots of 4″×8″ concrete specimens cured in 113˚F environment-control chamber.

Figure 4-8 shows the variations of temperature measurements from two identical temperature sensors. It can be seen that all types of temperature sensors show some temperature variation in the recorded data, but the temperature data from the Humboldt maturity meter had slightly bigger variations than those from the other sensors.

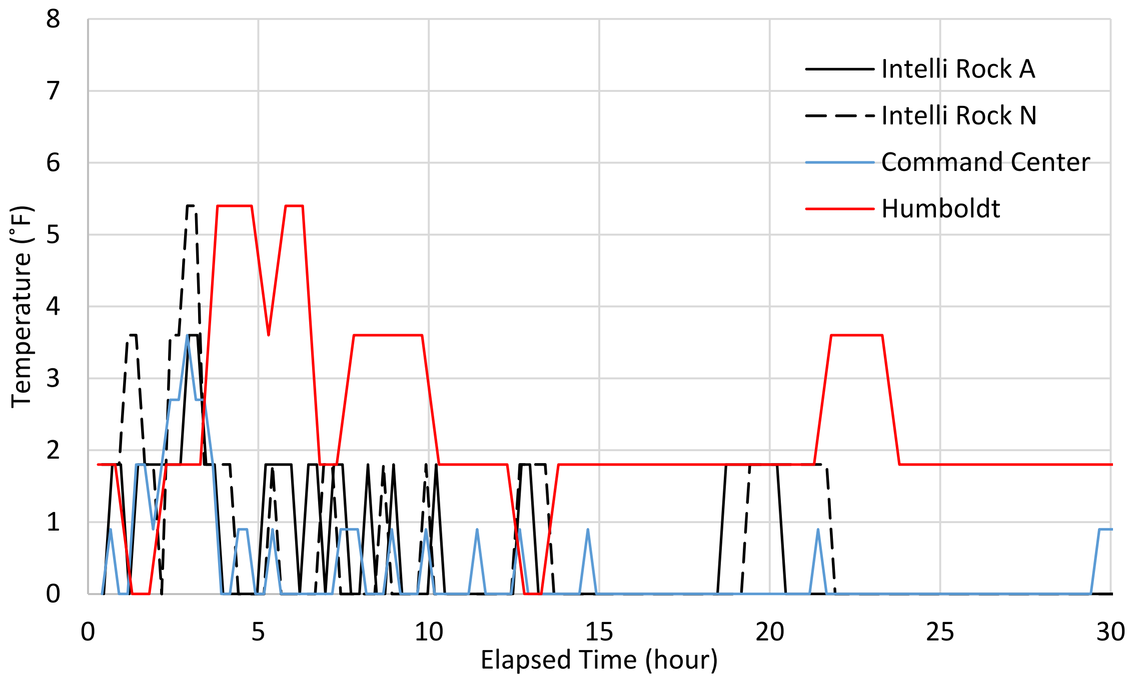


Figure 4-8. Variations of temperature measurements from same temperature sensors cured in 113˚F environment-control chamber.

Figure 4-9 shows the comparison of temperature-time plots of the concrete specimens in the standard curing tank as recorded by the different maturity meters. The temperature of the curing tank is also plotted on the figure. The compressive strength of the 4″×8″ specimens at the various curing times are also shown on this figure. At equilibrium conditions, the temperatures recorded by the Humboldt maturity meter were 2 to 6˚F lower than the tank temperature, while the temperatures recorded by the Intelli-Rock temperature sensors were 2˚F higher than the tank temperature, and the temperature recorded by the Command Center temperature sensors matched the curing tank temperature.

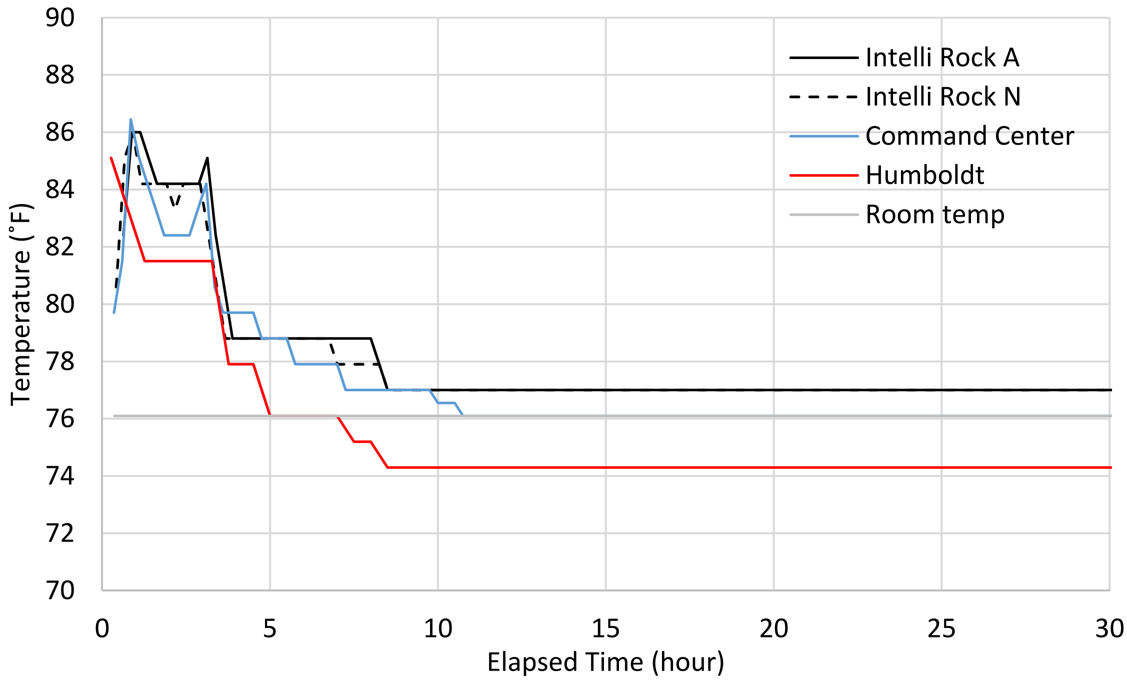


Figure 4-9. Temperature-time plots of 4″×8″ concrete specimens cured in standard curing tank.

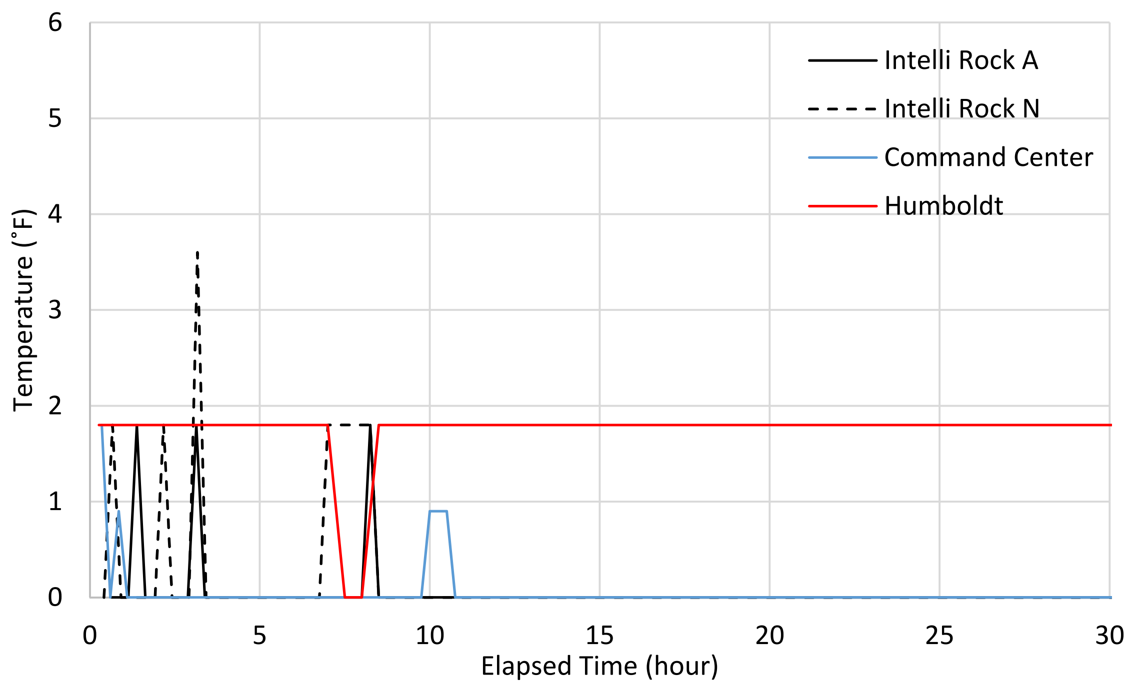


Figure 4-10. Variations of temperature measurements from same temperature sensors cured in 113˚F environment-control chamber.

Figure 4-10 shows variations of temperature measurements from two identical temperature sensors. Similarly, it can be seen that the temperature data from the Humboldt maturity meter once again had greater variations than those from the other sensors.

Overall temperature measurements from Intelli-Rock and Command Center temperature sensors show essentially identical measurement histories. On the other hand, the Humboldt maturity meter show 2 to 5˚F higher temperature measurements at the concrete temperature range of 90 to 120˚F and 2 to 6˚F lower temperature measurements at the range of 85 to 70˚F. In addition, Command Center temperature sensors have the smallest deviation between their temperature measurements at the same condition, whereas the Humboldt maturity meter has the biggest deviation between their temperature measurements.

4.2.2 Comparison of Accuracy of Temperature Reading

The accuracy and response time to the temperature change of the Humboldt, Command Center and Intelli-Rock temperature sensors were evaluated by placing them in an ice water bath as shown in Figure 4-11. The ice water had an exact temperature of 32˚F as measured by a calibrated mercury thermometer as shown in Figure 4-12. The ice water temperature was measured by the different temperature sensors every 5 minutes during a period of 60 minutes. Two replicate tests were performed for a more reliable evaluation of the different temperature sensors.

Figure 4-11. Different temperature sensors placed in ice water.

Figure 4-12. Temperature reading on a mercury thermometer in ice water.

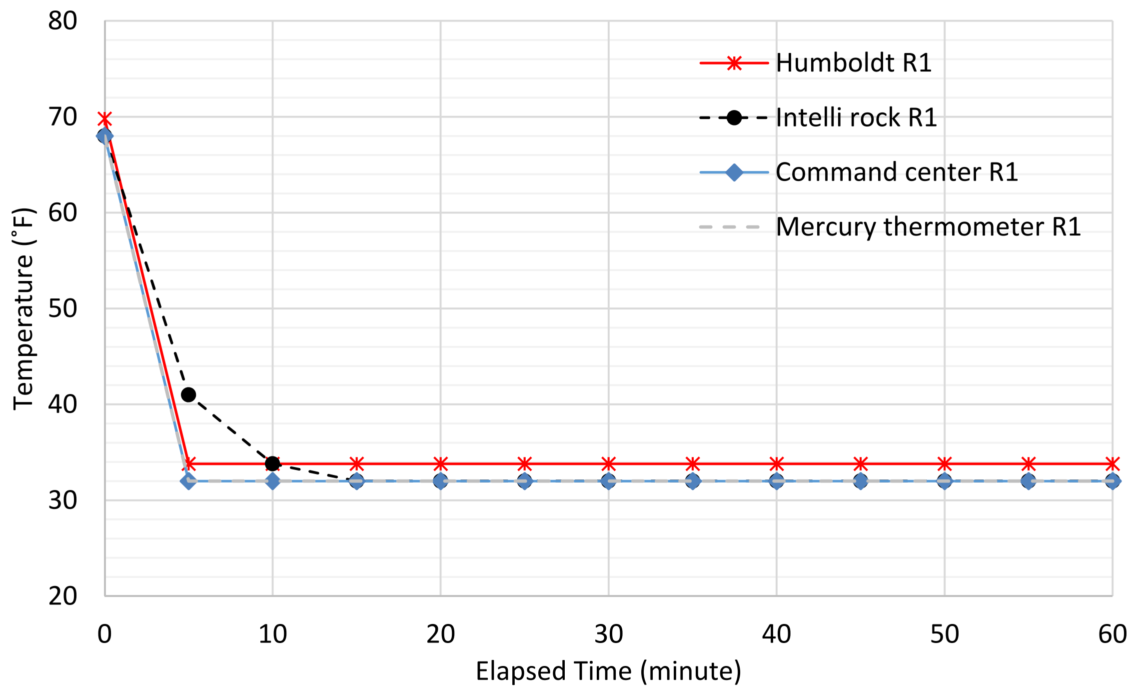


Figure 4-13. Temperature-time plots as recorded by different temperature sensors in ice water (replicate 1).

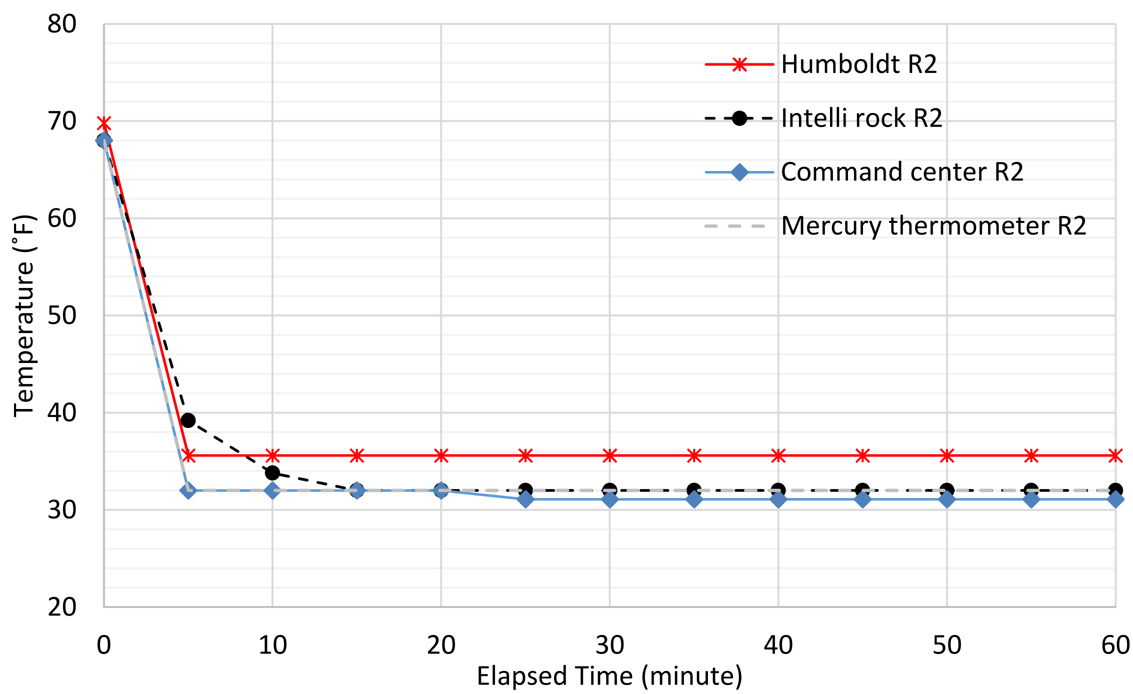


Figure 4-14. Temperature-time plots as recorded by different temperature sensors in ice water (replicate 2).

Figures 4-13 and 4-14 show comparisons of temperature-time plots as recorded by the different temperature sensors in ice water. It can be seen that the two Command Center and the two Intelli-Rock temperature sensors gave readings of 31.1˚F to 32˚F, while the two thermocouple wires from the Humboldt maturity system gave constant readings of 33.8˚F and 35.6˚F in the ice water bath. Also, both Intelli-Rock temperature sensors can be noted to have a delay time of 15 minutes before the constant final reading was obtained. The slower response time of the Intelli-Rock temperature sensors has also been observed in the previous test.

4.2.3 Comparison of Equivalent Ages Generated by COMA Meter and Intelli-Rock Maturity System

As explained earlier, the COMA meter measures equivalent age with the liquid in the glass capillary where the rate of evaporation varies in accordance with the concrete temperature. Figure 4-15 shows the equivalent age reading for the COMA meter.

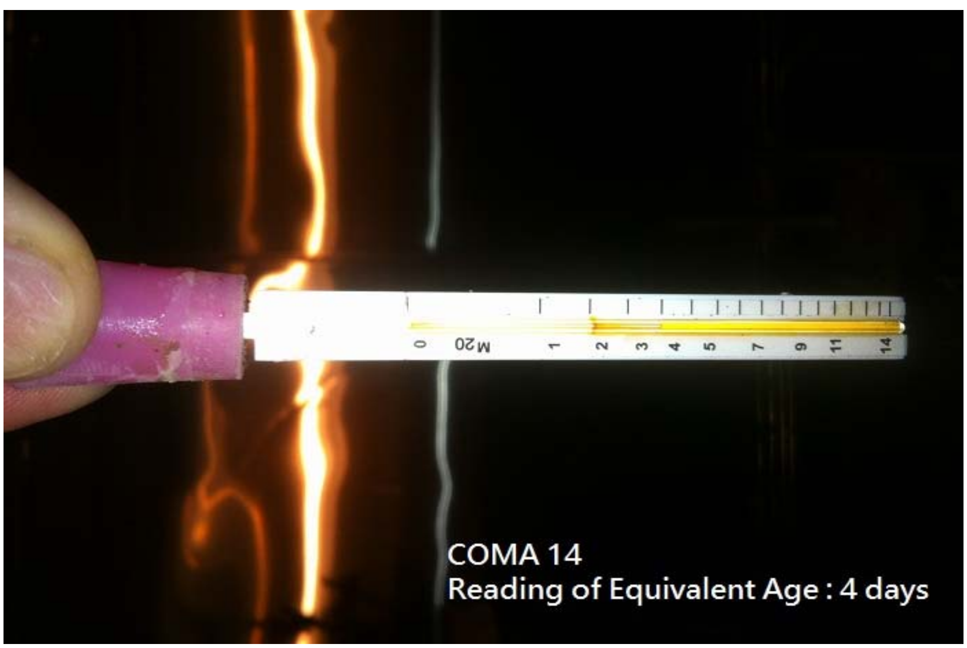


Figure 4-15. Equivalent age reading for COMA meter.

Since measurement of the equivalent age only requires a reading of the scale behind the glass capillary, the COMA meter is considered as the most convenient maturity system.

However, its reading is initially calibrated for the use of a reference temperature of 20˚C and activation energy of 40,000 J/mol, and thus, it may not be used for different reference temperatures and activation energies.

In order to evaluate the accuracy of the COMA meter, the readings of the equivalent age made by the COMA meter were compared to those from the Intelli-rock maturity system under three different curing conditions. A reference temperature of 20˚C and activation energy of 40,000 J/mol were also used for the intelli-rock maturity system. The corresponding computed equivalent ages from the Intelli-Rock maturity system are plotted in Figure 4-16.

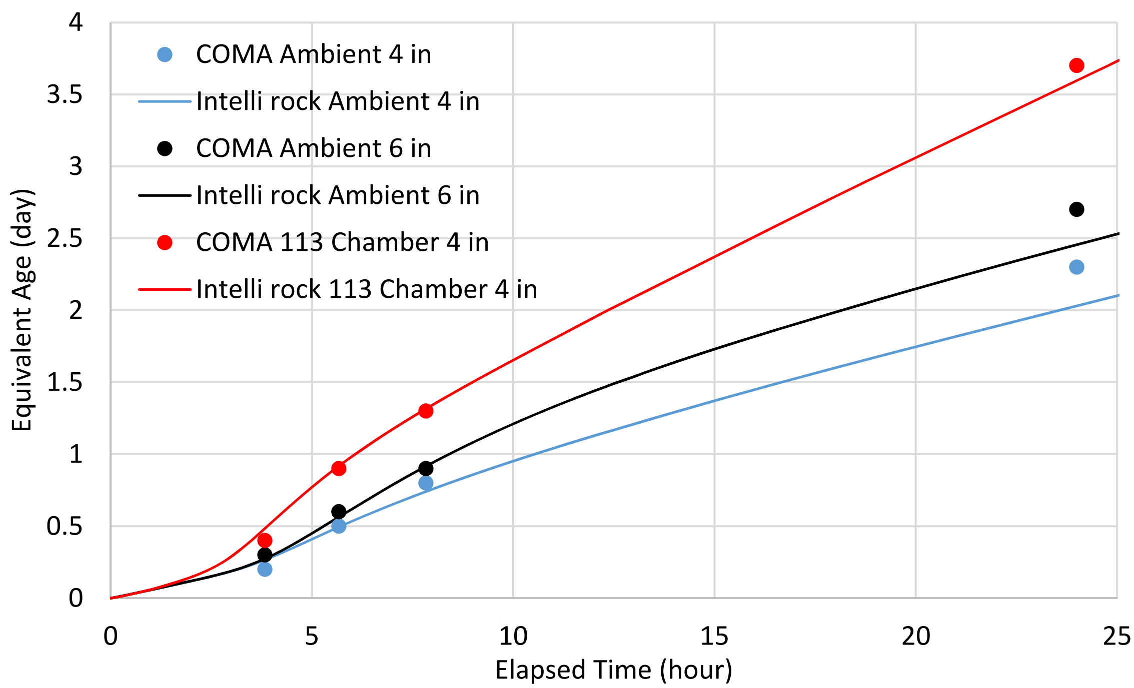


Figure 4-16. Equivalent ages from COMA meter and Intelli-Rock maturity system under three different curing conditions.

As can be observed in Figure 4-15, the readings made by COMA meter underestimated at early age and overestimated at the curing time of one day. Though the COMA meter is easy to use, it has limitations related with accuracy and application.

4.2.4 Effects of Embedded Temperature Sensors on the Strength of Concrete Specimens

An evaluation was made to determine how embedding different temperature sensors in concrete specimens may affect the compressive strength of the concrete specimens. The 4″×8″ concrete specimens, which were embedded with various temperature sensors, were tested for their compressive strengths after curing for 200 hours in the ambient room and 200 hours in the 113˚F curing chamber. Two replicate specimens for each condition were tested.

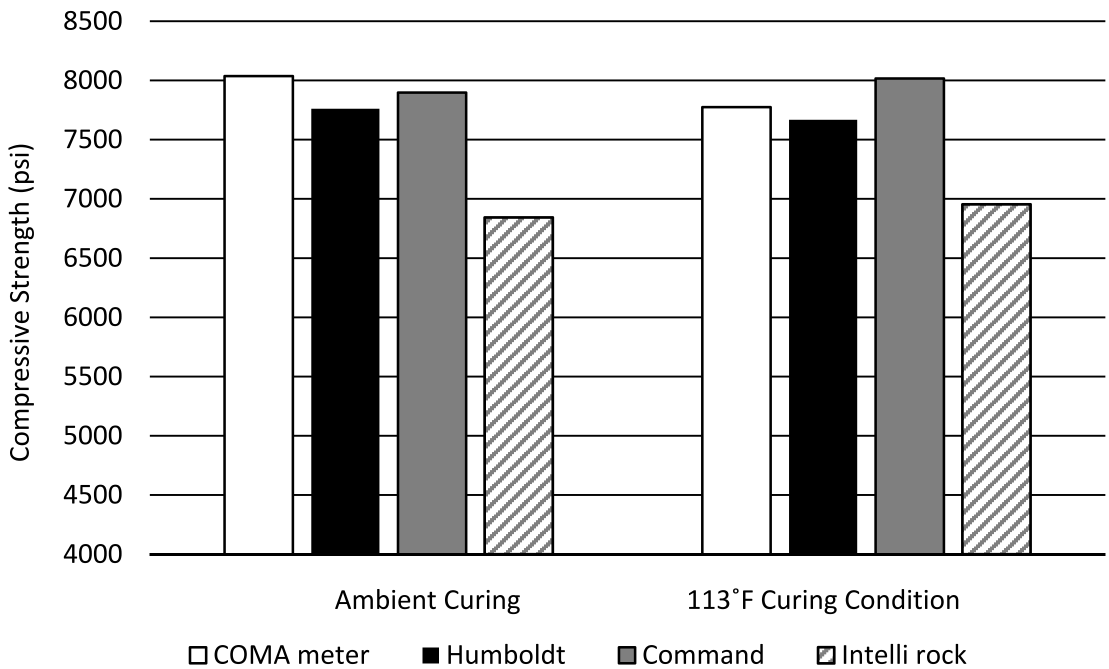


Figure 4-17. Compressive strengths of 4″×8″ concrete specimens with different embedded temperature sensors.

Figure 4-17 presents the comparison of compressive strengths of the concrete specimens with different embedded temperature sensors at the two curing conditions. It can be seen that the specimens containing the Intelli-Rock temperature sensors show approximately 20 % lower strength than the other specimens for both curing conditions. The concrete specimens containing the Command Center temperature sensor and the Humboldt thermocouple wire show similar strength as the concrete specimens without any temperature sensor.

Figure 4-18. A section of broken 4″×8″ specimen containing Intelli-Rock temperature sensor.

The significant effect of the Intelli-Rock temperature sensor on the compressive strength of the concrete specimen is possibly due to the relatively large size of the sensor. Figure 4-18 shows a picture of a broken 4″×8″ specimen containing the Intelli-Rock temperature sensor. It can be seen that the sensor takes up a significant portion of the cross-section of the specimen.

4.2.5 Evaluation of Different Maturity Measuring Systems

Table 4-1 presents a summary of the observed characteristics of the different maturity meters evaluated. The costs of the different temperature sensors are also given in the table. Based on the results of the evaluation, the Command Center maturity system was chosen to be used for the second set of experiments and field studies. This decision was based on the accuracy, resolution, response time and convenience of use of this system.

Table 4-1. Summary of the Observed Characteristics of the Different Maturity Systems Evaluated

	Intelli-Rock	Command Center	Humboldt	COMA Meter
Accuracy in Temperature Reading	No detectable error	No detectable error	Error of 2 - 4˚F	N/A
Frequency of Temperature Reading	Pre-determined by type of temperature sensor (1 to 1440 minute)	Determined by user programming (1 to 225 minutes)	Every 30 minutes for 2 days and every 1 hour for remaining time	N/A
Duration of Temperature Reading	Up to 365 days depending on type of temperature sensor	7 days with 5 minutes frequency, 28 days with 15 minutes frequency	Up to 334 days	Until the equivalent age reaches 14 days
Resolution of Temperature Reading	2˚F	1˚F	2˚F	N/A
Cost of Temperature sensor	$33/each temperature sensor	$28/each temperature sensor	$0.81/foot of thermocouple wire	$28/each
Convenience to Use	Easy to use. Relatively big temperature sensor may have negative effect on the structure strength	Convenient and easy to use.	Easy to use. Sensor needs to be connected to meter continuously	Convenient and easy to use. Gives only equivalent age

4.3 Evaluation of the Effectiveness of Different Specimen Sizes

4.3.1 Comparison of Temperature Histories of 6″×12″ and 4″×8″ Specimens

Temperature sensors from the Humboldt, Command Center and Intelli-Rock temperature sensor were also pre-installed to the middle of 6″×12″ cylinder molds before concrete placement. Only the ambient condition was used for both sizes of specimens to compare their temperature histories. Figures 4-19, 4-20 and 4-21 show the comparisons of temperature histories of two different sizes of specimens recorded by Intelli-Rock temperature sensor, Command Center temperature sensor and Humboldt maturity meter, respectively.

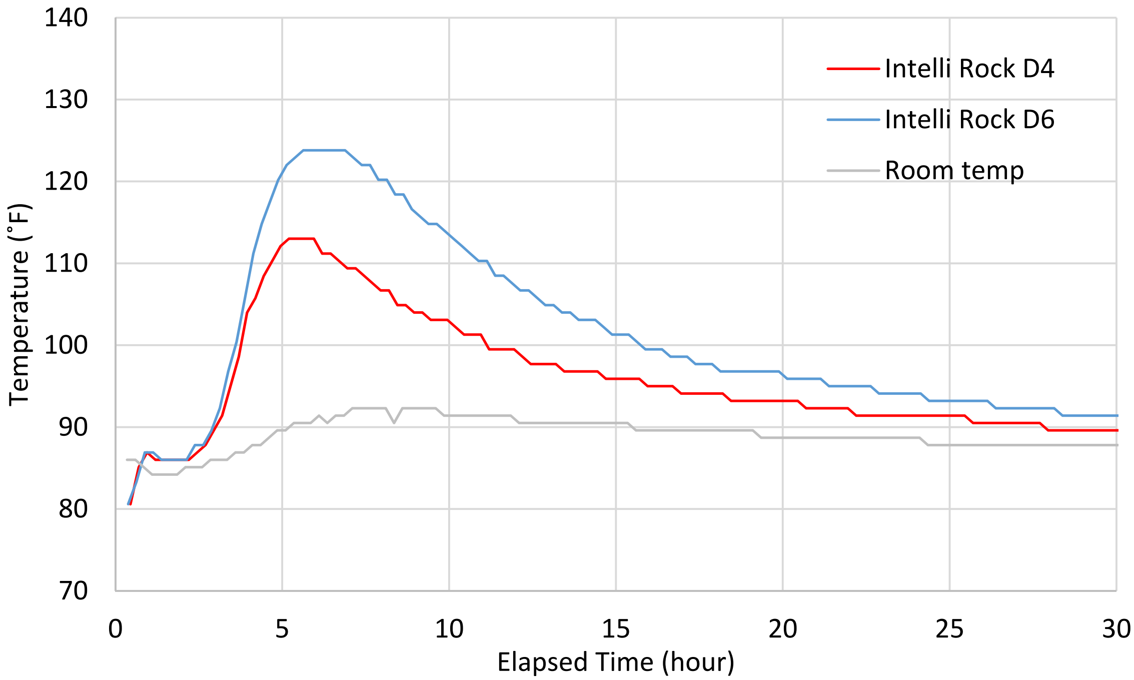


Figure 4-19. Temperature histories of 6″×12″ and 4″×8″ concrete specimens cured under ambient temperature as recorded by Intelli-Rock temperature sensors.

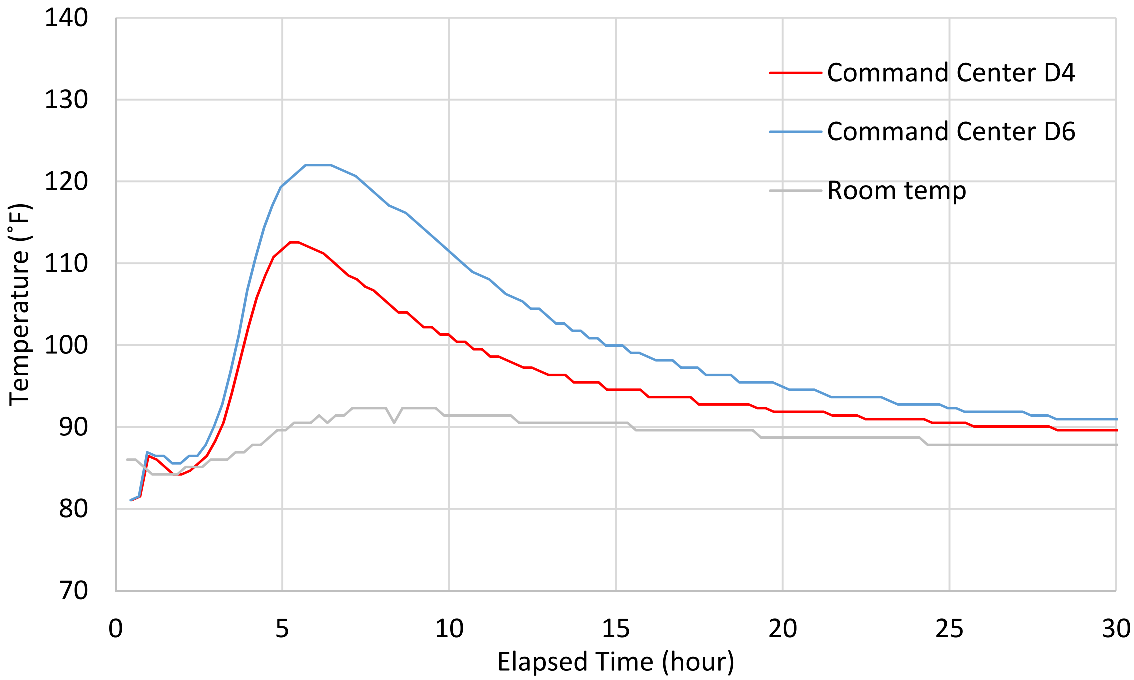


Figure 4-20. Temperature histories of 6″×12″ and 4″×8″ concrete specimens cured under ambient temperature as recorded by Command Center temperature sensors.

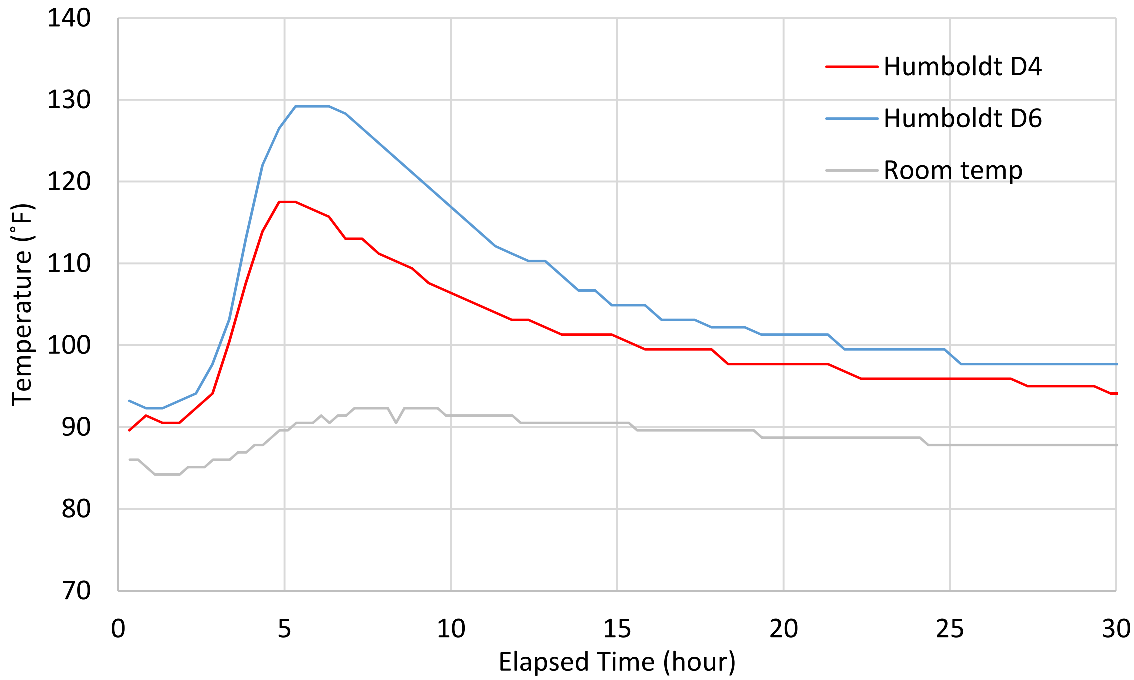


Figure 4-21. Temperature histories of 6″×12″ and 4″×8″ concrete specimens cured under ambient temperature as recorded by Humboldt maturity meter.

In all three figures, it appeared that the temperature histories of 6″×12″ specimens were 0 to 12˚F higher than those of 4″×8″ specimens. On the other hand, 4″×8″ specimens reached the highest temperature approximately 1 hour earlier than the 6″×12″ specimens.

4.3.2 Comparison of Strength Development of 6″×12″ and 4″×8″ Specimens

To generate and compare the maturity-strength curves developed from the 6″×12″ and 4″×8″ specimens, compressive strength tests were performed for both sizes of specimens. The compressive strength of three 4″×8″ specimens were tested at 4, 6, 8, 24, 168, and 336 hours. On the other hand, the compressive strength of one 6″×12″ specimen was tested at 5 hours 40 minutes, 7 hours 40 minutes, and 23 hours 40 minutes. Table 4-2 and Figure 4-22 show the results of the compressive strength tests for both 4″×8″ and 6″×12″ specimens.

Table 4-2. **Compressive Strength Test Results for Both 4″×8″ and 6″×12″ Specimens**

4″×8″ specimens					6″×12″ specimens	
Elapsed Time	1st (psi)	2nd (psi)	3rd (psi)	Average (psi)	Elapsed Time	1st (psi)
4H	287	295	306	296	N/A	N/A
6H	1,496	1,529	1,506	1,510	5H40	1,589
8H	2,549	2,511	2,527	2,529	7H40	2,640
24H	5,736	5,841	5,707	5,762	23H40	5,979
7D	7,903	7,735	N/A	7,819	N/A	N/A
14D	8,012	7,699	N/A	7,856	N/A	N/A

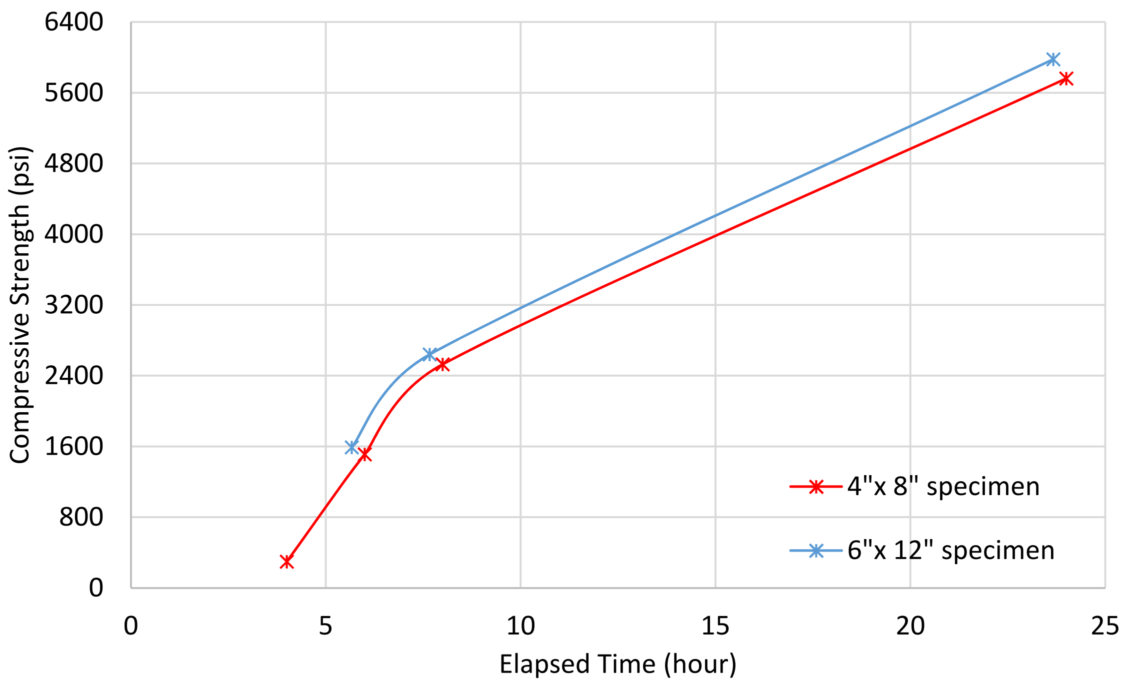


Figure 4-22. Comparisons of compressive strength-time plots for 6″×12″ and 4″×8″ specimens cured under ambient laboratory condition.

In Figure 4-22, it can be observed that the 6″×12″ specimens have higher compressive strengths than those of 4″×8″ specimens at the same curing time. It can be explained that the higher temperature history of the 6″×12″ specimens causes higher rate of hydration of the concrete used and results in higher strength at the same curing time.

4.3.3 Effect of Specimen Size on the Maturity-Strength Relationship

As shown in the previous section, different sizes of specimens produce different temperature histories and different compressive strength for the same curing time. In order to evaluate the effect of different specimen sizes on the maturity-strength relationship, two maturity-strength curves were generated. Nurse-Saul maturity function was used to calculate TTF with datum temperature of 32˚F and a modified exponential modeling function was used to generate the maturity-strength curve. There was no remarkable strength increase observed at the 14-day strength as compared to the 7-day strength, which had a compressive strength of 7,800 psi.

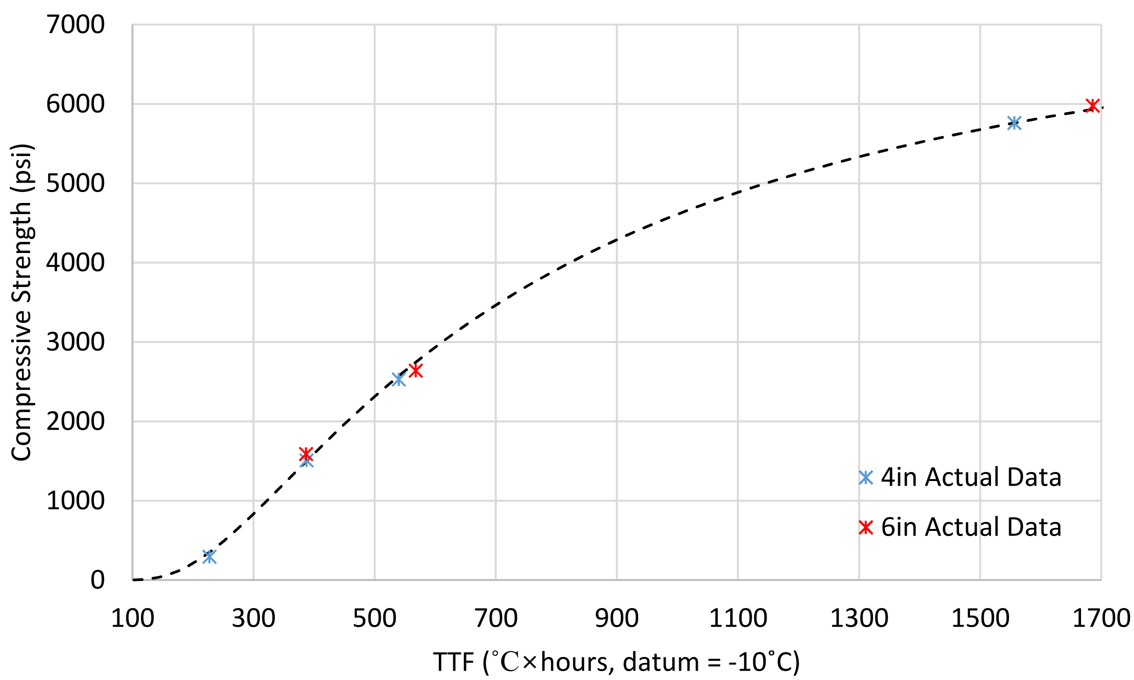


Figure 4-23. Maturity-strength plots for 6″×12″ and 4″×8″ specimens cured under same curing condition.

Figure 4-23 shows the maturity-strength plots for 4″×8″ specimens and 6″×12″ specimens. As shown in Figure 4-23, there were no visible differences detected between the maturity-strength plots for 4″×8″ specimens and maturity-strength plots for 6″×12″ specimens.

Therefore, it can be concluded that the different specimen sizes do not have any effect on the maturity-strength relationship. For the convenience of use of the 4″×8″ specimens, this specimen size was chosen to be used for the second set of experiments and field studies.

CHAPTER 5
SECOND SET OF LABORATORY EXPERIMENT

5.1 Laboratory Experiment Design

5.1.1 Main Objectives

The main objectives of the second set of experiments are to evaluate the possible effects of different placement and curing environments on the predicted strength of concrete from the maturity method and to determine the most appropriate procedure to be used to obtain accurate predicted strength of concrete.

5.1.2 Maturity System

Command Center maturity system was chosen to be used for the second set of experiments because the maturity system was determined to be the most effective system in the first set of experiments. This decision was made based on the accuracy, resolution, response time and convenience of use of this system.

5.1.3 Curing Conditions

The following four different curing temperatures were used for the second set of experiments:

- 73˚F in curing tank (standard curing condition) and in environment-control chamber
- 113˚F in environment-control chamber
- 43˚F in environment-control chamber
- Ambient condition in laboratory

73˚F curing chamber conditions were used as a standard curing temperature. 113˚F and 43˚F curing chamber conditions were designed to simulate extremely hot and cold curing conditions with consideration of the historically highest and lowest temperature records in

Florida of 109˚F and 43˚F respectively (Wikipedia, 2013). An ambient room curing temperature was also used to represent the usual variation of air temperature in the field.

For each curing temperature, with the exception of the standard curing condition, the following two exposure conditions were applied in the second set of experiments.

- Exposed to air
- Covered with Burlene curing blanket

Thus, a total of nine curing conditions, including the standard curing condition, were used for this set of experiments.

5.1.4 Concrete Specimens

Three different mix designs were used for this set of experiments and the following concrete specimens were tested for each mix design.

- Three replicate 4″×8″ cylindrical specimens were tested at each of the five curing times (4, 6, 8, 24 and 168 hours) for specimens cured under the following five conditions:

  a) Standard curing tank
  b) 73˚F and exposed to air
  c) 73˚F and covered with Burlene
  d) Ambient temperature and exposed to air
  e) Ambient temperature and covered with Burlene

- Three replicate 4″×8″ cylindrical specimens were tested at each of the six curing times (3, 4, 6, 8, 24, and 168 hours) for specimens cured under the following two conditions:

  a) 113˚F and exposed to air
  b) 113˚F and covered with Burlene

- Three replicate 4″×8″ cylindrical specimens were tested at each of the six curing times (7, 10, 13, 24, 48, and 168 hours) for specimens cured under the following two conditions:

  a) 43˚F and exposed to air
  b) 43˚F and covered with Burlene

- 18 4″×8″ cylindrical specimens to be instrumented for temperature reading under the following conditions:

  a) Nine curing conditions
  b) Two replicate specimens for each curing condition.

Each batch was divided into 4 small batches due to lack of time for the hardened concrete tests. Also two replicate batches were made for each of the three concrete mix designs.

5.2 Fresh Concrete Properties in the Second Set of Experiments

The fresh concrete properties of the eight replicate batches of Mix #1, #2, and #3 are presented in Tables 5-1, 5-2, and 5-3, respectively. Though the eight replicate batches of each concrete mix design were meant to be identical, there were some variations in their fresh concrete properties as can be observed from the test values given in these three tables.

Table 5-1. Fresh Concrete Properties of Eight Replicate Batches of Mix #1

Mix #1								
Curing condition	Ambient		Hot Curing Chamber		Standard Curing Chamber		Cold Curing Chamber	
Curing Temp (˚F)	71-73		111-114		72-74		44-55	
Curing Humidity (%)	40-55		35-45		45-70		60-90	
Mixture properties								
Replicate Number	1	2	1	2	1	2	1	2
Coarse aggregate Moisture content (%)	6.15	7.55	6.74	6.86	6.57	5.95	5.67	5.94
Slump (in)	9.00	6.25	6.25	8.25	6.75	6.50	7.00	7.25
Mix temperature (˚F)	85	85	85	86	76	77	76	76
Air content (%)	1.90	2.00	2.00	1.90	2.20	2.30	2.10	2.00
Unit weight (pcf)	148.96	148.55	148.96	146.54	146.14	145.74	147.35	147.75
Mixing room temperature (˚F)	83	85	81	82	77	79	75	73
Elapsed time to remove cylinder from mold (hour)	3	3	2	2	3	3	6	6

Table 5-2. Fresh Concrete Properties of Eight Replicate Batches of Mix #2

Mix #2								
Curing condition	Ambient		Hot Curing Chamber		Standard Curing Chamber		Cold Curing Chamber	
Curing Temp (˚F)	71-73		111-114		72-74		44-50	
Curing Humidity (%)	40-55		35-45		45-70		60-90	
Mixture properties								
Replicate Number	1	2	1	2	1	2	1	2
Coarse aggregate Moisture content (%)	5.46	6.00	6.29	6.33	6.53	6.66	7.34	6.16
Slump (in)	6.75	4.25	4.00	4.00	4.00	4.25	4.25	5.50
Mix temperature (˚F)	83F	82F	82F	82F	78F	75F	79F	79F
Air content (%)	5.10	4.10	4.20	4.90	7.20	7.60	7.10	7.30
Unit weight (pcf)	139.70	143.32	143.32	141.72	138.09	137.69	139.30	138.49
Mixing room temperature (˚F)	82F	81F	81F	81F	75F	72F	75F	75F
Elapsed time to remove cylinder from mold (hour)	3	3	2	2	3	3	6	6

Table 5-3. Fresh Concrete Properties of Eight Replicate Batches of Mix #3

Mix #3								
Curing condition	Ambient		Hot Curing Chamber		Standard Curing Chamber		Cold Curing Chamber	
Curing Temp (˚F)	71-73		111-114		72-74		44-50	
Room Humidity (%)	40-55		35-45		45-70		60-90	
Mixture properties								
Replicate Number	1	2	1	2	1	2	1	2
Coarse aggregate Moisture content (%)	5.81	6.64	6.81	7.20	6.03	6.53	7.18	7.23
Slump (in)	8.00	8.25	7.50	6.75	8.25	8.00	8.00	8.00
Mix temperature (˚F)	84F	84F	79F	77F	76F	79F	77F	77F
Air content (%)	2.50	2.80	2.00	2.10	2.70	2.50	2.10	2.40
Unit weight (pcf)	145.25	143.81	146.54	147.35	144.53	145.74	147.35	146.94
Mixing room temperature (˚F)	82F	82F	76F	72F	68F	75F	75F	73F
Elapsed time to remove cylinder from mold (hour)	3	3	2	2	3	3	6	6

One possible reason for the variations in air content from one replicate batch to another is the change in mixing temperature, especially in Mix #2. Figure 5-1 shows a plot of air content versus mixing room temperature for Mix #2. It can be observed that air content generally increased with decreasing room temperature.

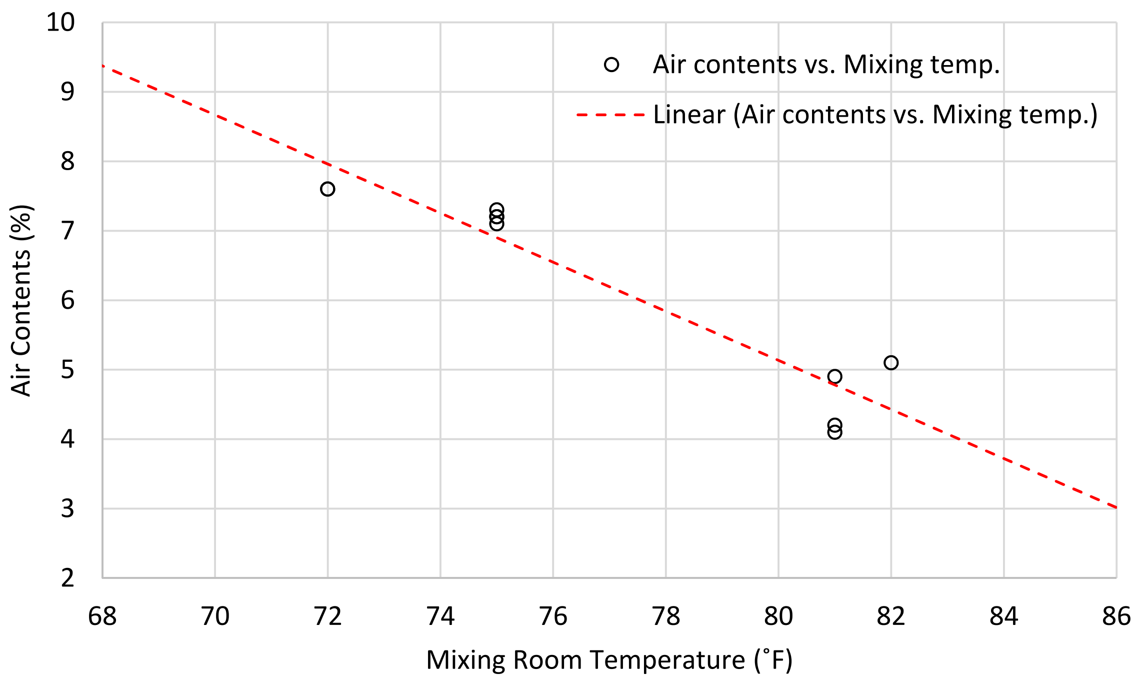


Figure 5-1. Air content versus mixing room temperature for Mix #2.

Another source of variation in fresh concrete properties is the variation in moisture content of the aggregates, which may not be accurately accounted for during batching of materials for the concrete mixtures. An underestimation of the actual moisture content of the aggregates may result in too much mixing water added, which can cause a higher slump and higher water- to-cement ratio of the concrete. Adding too much water may also cause a reduction in unit weight and air content of the fresh concrete (Wilson and Kosmatka, 2011).

5.3 Evaluation of Maturity Functions with Test Result

5.3.1 Introduction

Both Nurse-Saul and Arrhenius maturity functions were originated from the same concept that for concrete to reach the same strength under different curing temperatures, it must have the same equivalent age (Wade et al., 2006). Since its nonlinear age conversion factor represents strength development of concrete well, the Arrhenius maturity function has been reported to give more accurate predictions of concrete strength. However, some studies have reported that, for certain mix designs and curing conditions, the Nurse-Saul maturity function gives better prediction than the Arrhenius maturity function, and thus, some researchers have recommended that both maturity functions be evaluated with regards to their accuracy in predicting strength of concrete in practice (Wade et al., 2006). This chapter presents the results of an in-depth evaluation of different maturity functions for prediction of early strength of concrete for application in slab replacement.

5.3.2 Parametric Study on Nurse-Saul Maturity Function

For use of the Nurse-Saul maturity function, different datum temperatures cause a change in age conversion factor and a change in the calculated TTF. Thus, using an appropriate datum temperature is very important for accurate prediction of concrete strength in the Nurse-Saul maturity method. Many researchers proposed to use different datum temperatures (Wade, 2005), and most of them are in the range of 11 ~ -10˚C. In this parametric evaluation, three different datum temperatures, namely 5˚C (Tank and Carino, 1991), 0˚C (ASTM C 1074, 2004) and -10˚C (Mohsen et al., 2004), were applied to the test results from the second set of experiments to develop maturity-strength relationships under different curing temperatures.

Since the differences in fresh concrete properties could affect the maturity-strength relationship, batches of concrete that had the same or very similar fresh concrete properties were selected for use in the parametric study. Table 5-4 shows the selected batches for each mix design.

Table 5-4. Selected Concrete Batches for the Parametric Study

Mix Design	Mix #1		
Curing Condition	Med	Hot	Cold
Mixture Identification	Ambient R2	113˚F R1	45˚F R1
Slump	6.25	6.25	7.00
Mix temperature	85˚F	85˚F	76˚F
Air content	2.00 %	2.00 %	2.10 %
Unit weight	148.55	148.55	147.35
Mix Design	**Mix #2**		
Curing Condition	Med	Hot	N/A
Mixture Identification	Ambient R2	113˚F R1	
Slump	4.25	4.00	
Mix temperature	82˚F	82˚F	
Air content	4.10 %	4.20 %	
Unit weight	143.32	143.32	
Mix Design	**Mix #3**		
Curing Condition	Med	Hot	Cold
Mixture Identification	Ambient R1	113˚F R2	45˚F R2
Slump	8.00	7.50	8.00
Mix temperature	84F	77F	77F
Air content	2.50 %	2.10 %	2.40 %
Unit weight	145.25	147.35	146.94

Figures 5-2 through 5-4 show various Nurse-Saul maturity-strength relationships developed with the data from the specimens cured under different curing temperatures for Mix #1. It can be observed that the datum temperature of 5˚C gives the best match between the maturity-strength relationships developed from the specimens cured under three different curing temperatures. However, more than 25 % of differences in the values of TTF were observed between the specimens cured under three different temperatures at the critical strength of 2,200 psi for both exposed curing and Burlene covering conditions

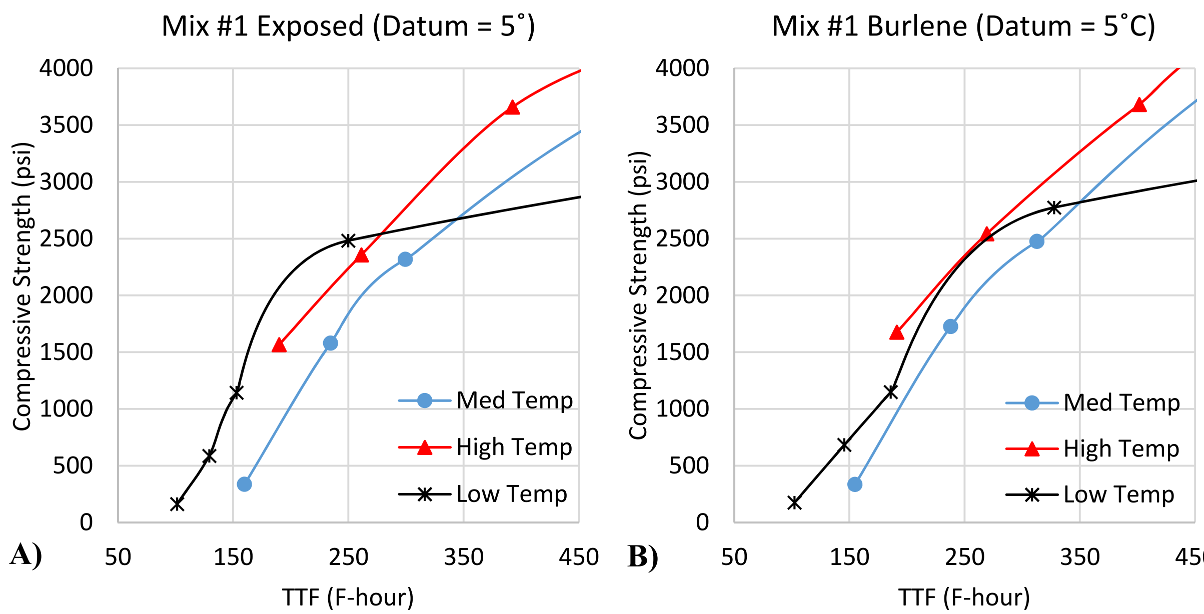


Figure 5-2. Nurse-Saul maturity-strength relationships with datum temperature of 5˚C for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

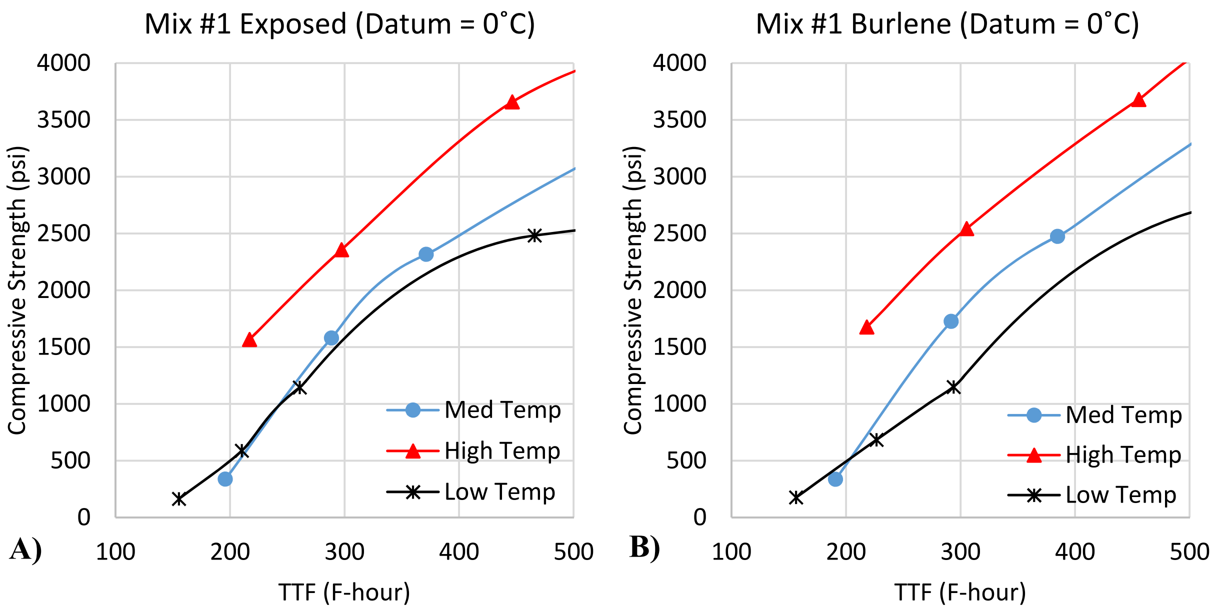


Figure 5-3. Nurse-Saul maturity-strength relationships with datum temperature of 0˚C for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

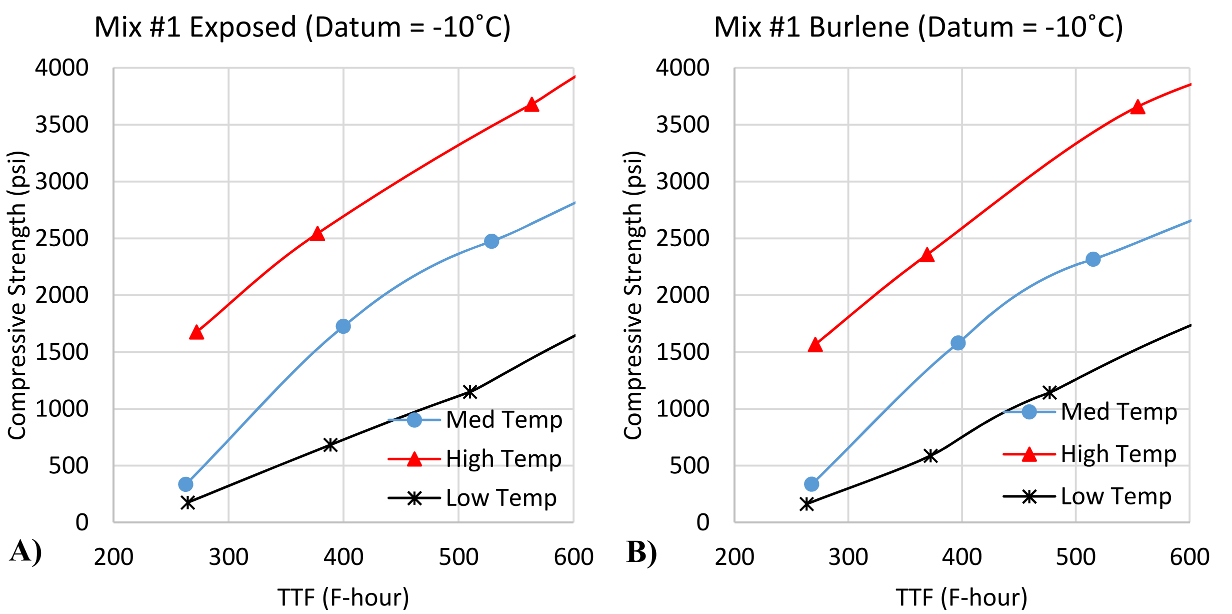


Figure 5-4. Nurse-Saul maturity-strength relationships with datum temperature of -10˚C for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

Figures 5-5 through 5-7 show various Nurse-Saul maturity-strength relationships developed from the specimens cured under two different curing temperatures for Mix #2. Similarly, it can be observed that the datum temperature of 5˚C gives the best matching between the maturity-strength relationships developed from the specimens cured under two different curing temperatures. However, more than 15 % of differences in the values of TTF were observed between the specimens cured under two different curing temperatures at the critical strength of 2,200 psi for both exposed curing and Burlene covering conditions.

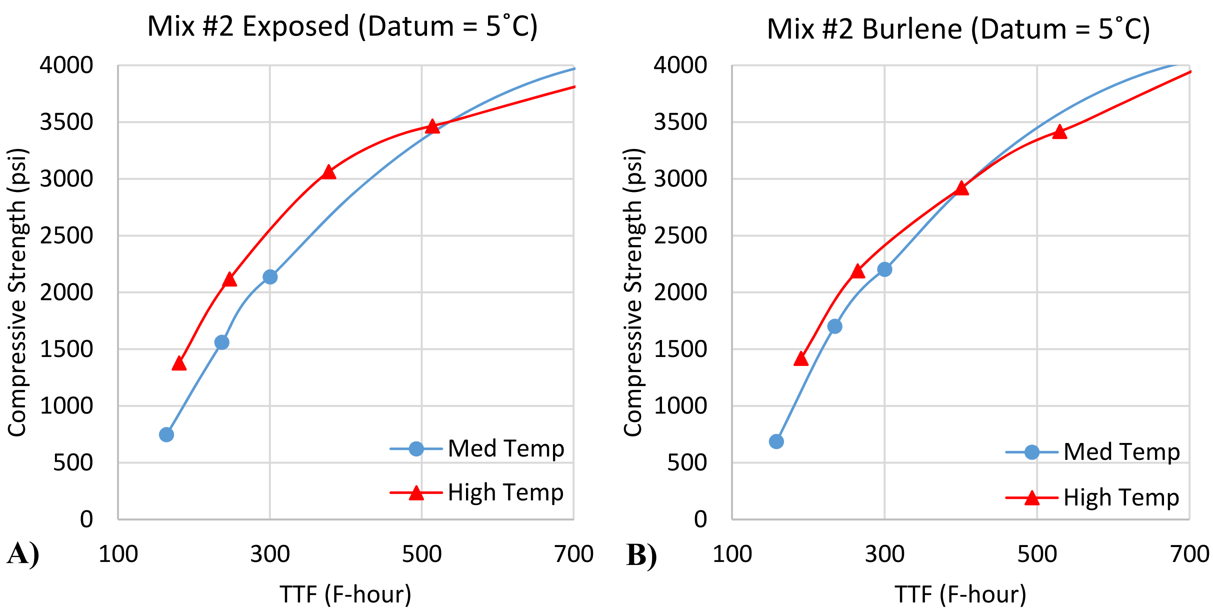


Figure 5-5. Nurse-Saul maturity-strength relationships with datum temperature of 5˚C for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

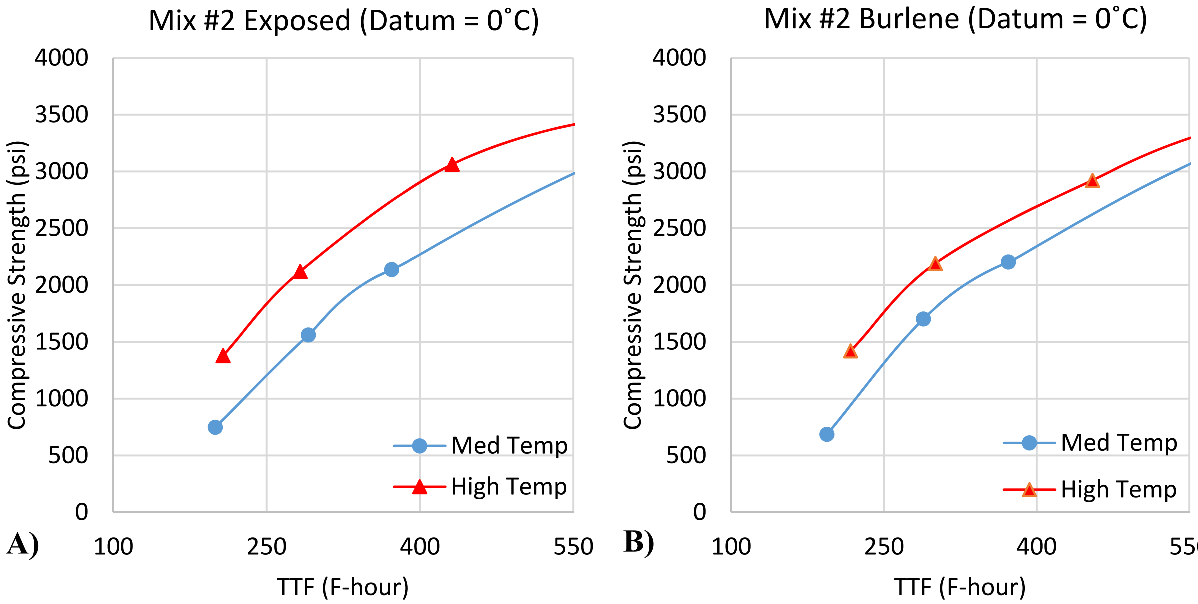


Figure 5-6. Nurse-Saul maturity-strength relationships with datum temperature of 0˚C for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

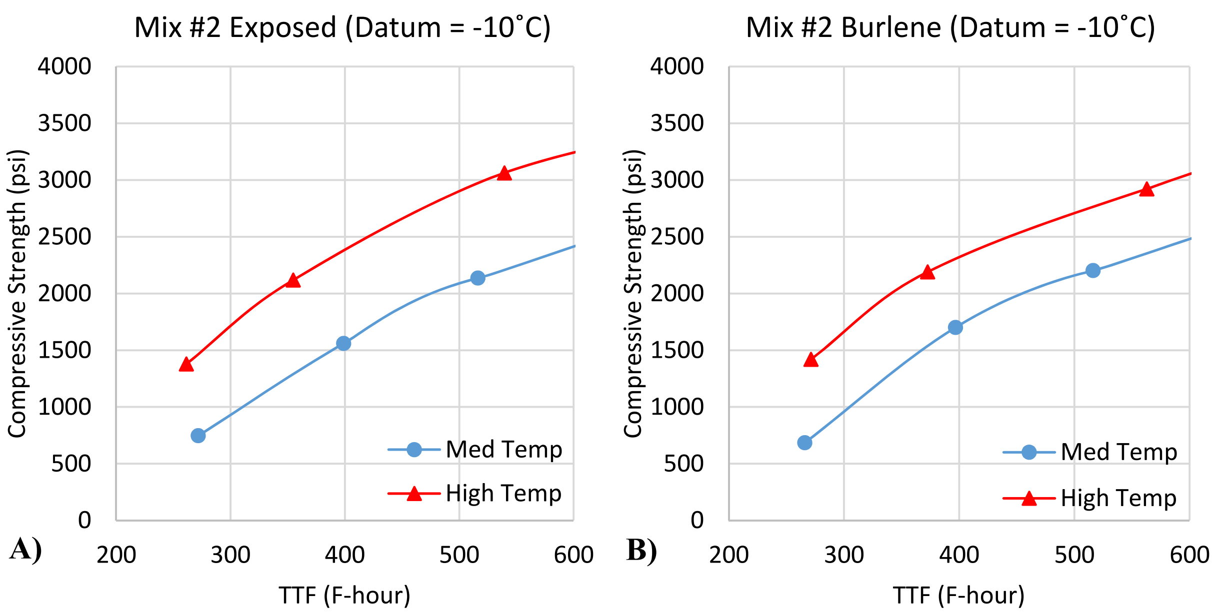


Figure 5-7. Nurse-Saul maturity-strength relationships with datum temperature of -10˚C for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

Figures 5-8 through 5-10 show various Nurse-Saul maturity-strength relationships developed from the specimens cured under three different curing temperatures for Mix #3. It can be observed that the datum temperature of 0˚C gives the best matching between the maturity-strength relationships developed from the specimens cured under three different curing temperatures. However, more than 30 % of differences in the calculation of TTF were also observed between the specimens under three different curing temperatures at the critical strength of 2,200 psi for both exposed curing and Burlene covering conditions.

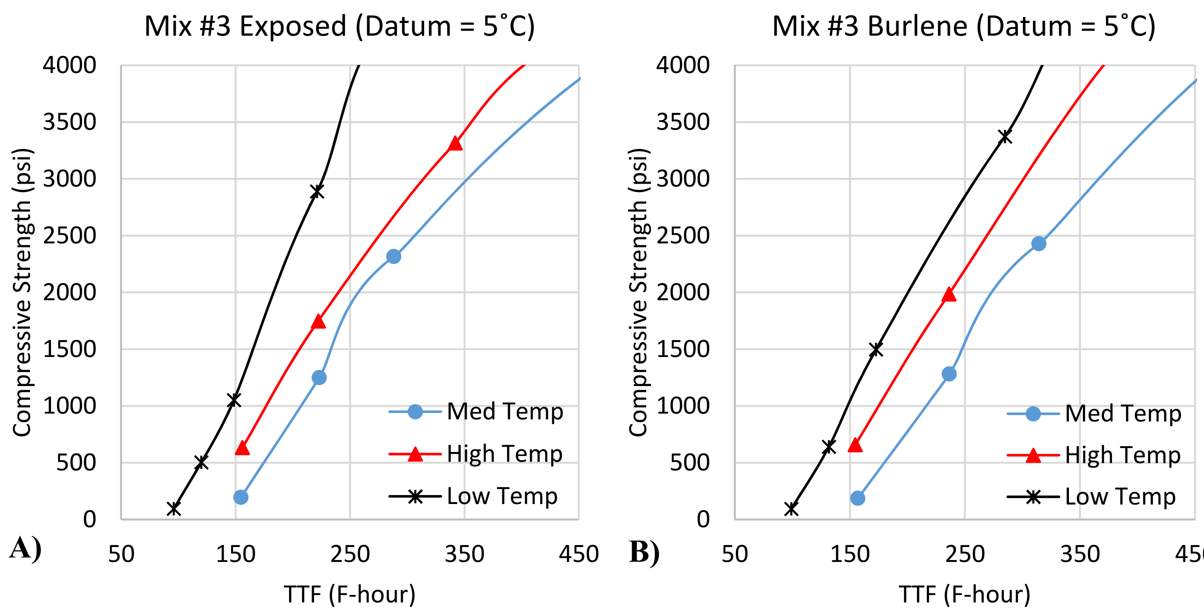


Figure 5-8. Nurse-Saul maturity-strength relationships with datum temperature of 5˚C for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

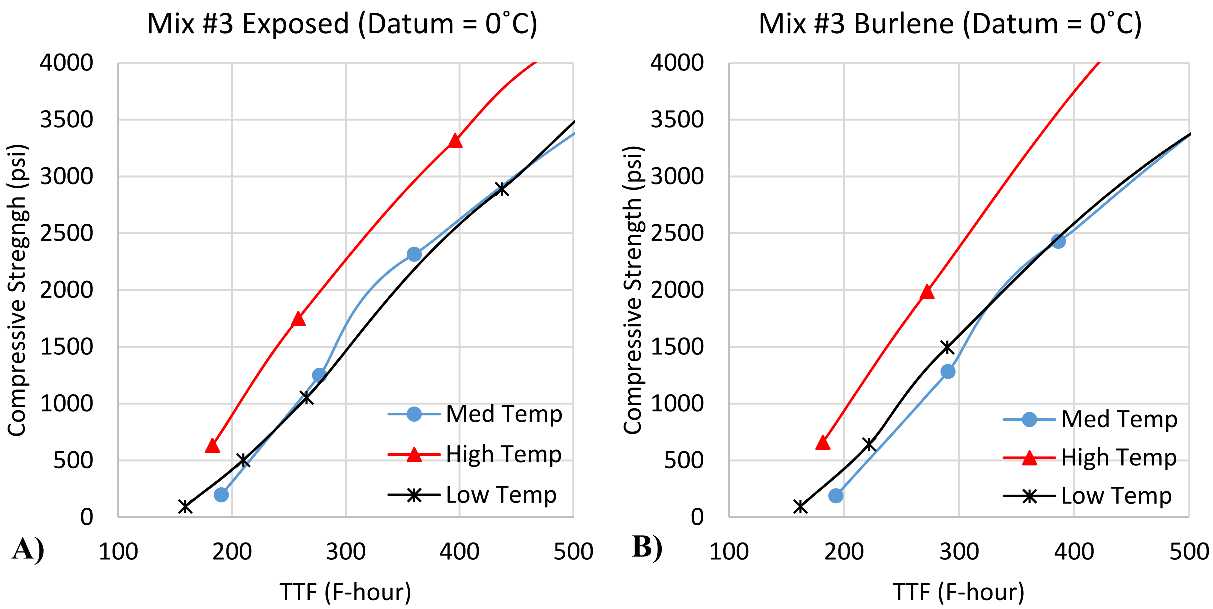


Figure 5-9. Nurse-Saul maturity-strength relationships with datum temperature of 0˚C for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

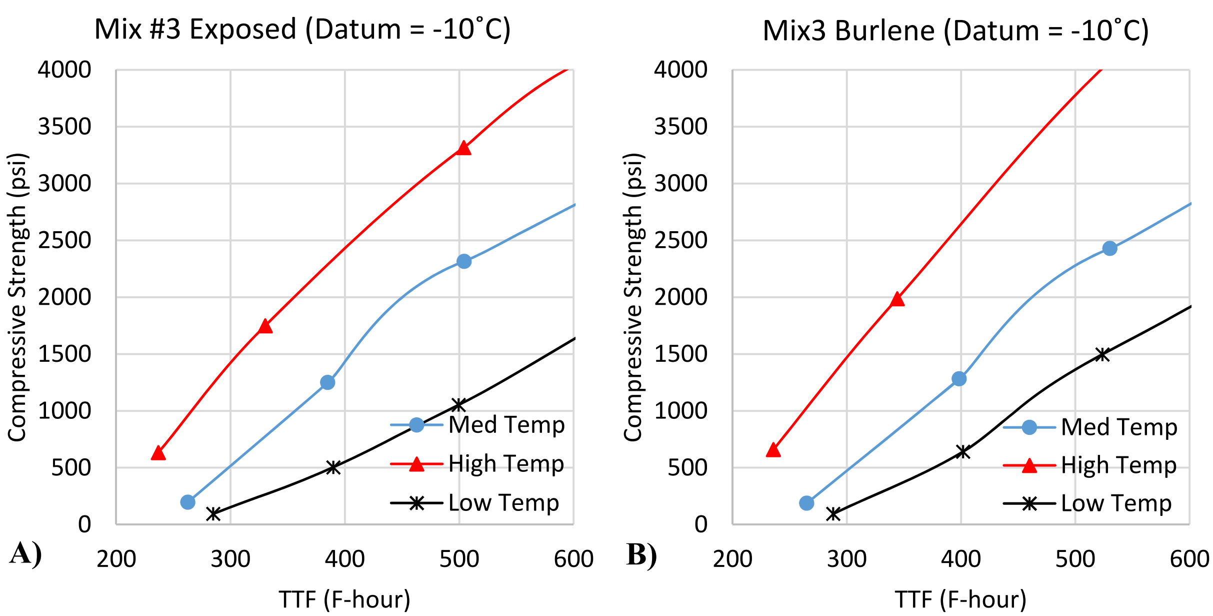


Figure 5-10. Nurse-Saul maturity-strength relationships with datum temperature of -10˚C for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

For the three mix designs and datum temperatures, significant differences between the Nurse-Saul maturity-strength relationships developed with the concrete cured under the three different curing temperatures. Thus, the use of the maturity-strength relationship generated by Nurse-Saul maturity function for prediction of strength of concrete at early age under various curing conditions could result in substantial errors.

5.3.3 Parametric Study on Arrhenius Maturity Function

Similar to the Nurse-Saul maturity function, a change in activation energy directly affects the calculation of equivalent age, and thus, using an appropriate activation energy is very important for accurate prediction of concrete strength with the Arrhenius maturity method.

Many researchers have proposed and used various activation energies in their research (Freiesleben-Hansen and Pedersen, 1977; Carino and Malhotra, 1991; Tank and Carino, 1991). Samuel reported that an activation energy of 33,500 J/mol showed accurate strength prediction for warm-weather concrete curing, and an activation energy of 40,000 J/mol showed accurate strength prediction for cold-weather concrete curing. ASTM C 1074 suggests using an activation energy in the range of 40,000 to 45,000 J/mol for concrete made with Type I cement when no chemical admixture is used. Also, Freiesleben and Pedersen suggested an equation for calculating appropriate activation energy depending on the temperature of the concrete as follows:

$$T_a \geq 20^{\circ}C\ (68^{\circ}F): E = 33{,}500\ J/mol$$

$$T_a \leq 20^{\circ}C\ (68^{\circ}F): E = 33{,}500 + 1{,}470(20 - T_a)\ J/mol \qquad (5\text{-}1)$$

Where, T_a = Average concrete temperature during time interval, ΔT, (˚C),

For this parametric analysis, three activation energies, namely (1) 33,500 J/mol (Freiesleben-Hansen et al., 1977), (2) 40,000 J/mol, and (3) 45,000 J/mol (Wade et al., 2006 and

ASTM C 1074, 2004) were used and applied to the test results of the second set of experiments to develop maturity-strength relationship under different curing conditions. In order to compare the maturity-strength relationships generated by both maturity functions, the same batches of concretes used for the parametric analysis of Nurse-Saul maturity function were also used.

Figures 5-11 through 5-13 show various Arrhenius maturity-strength relationships developed from the specimens cured under three different curing temperatures for Mix #1. For both exposed curing and Burlene covering conditions, the use of activation energy of 33,500 J/mol gives the best matching between the maturity-strength relationships generated from the specimens cured under three different curing temperatures. Also, the differences between the calculated equivalent ages at the critical strength of 2,200 psi were less than 6 % for both exposed curing and Burlene covering conditions.

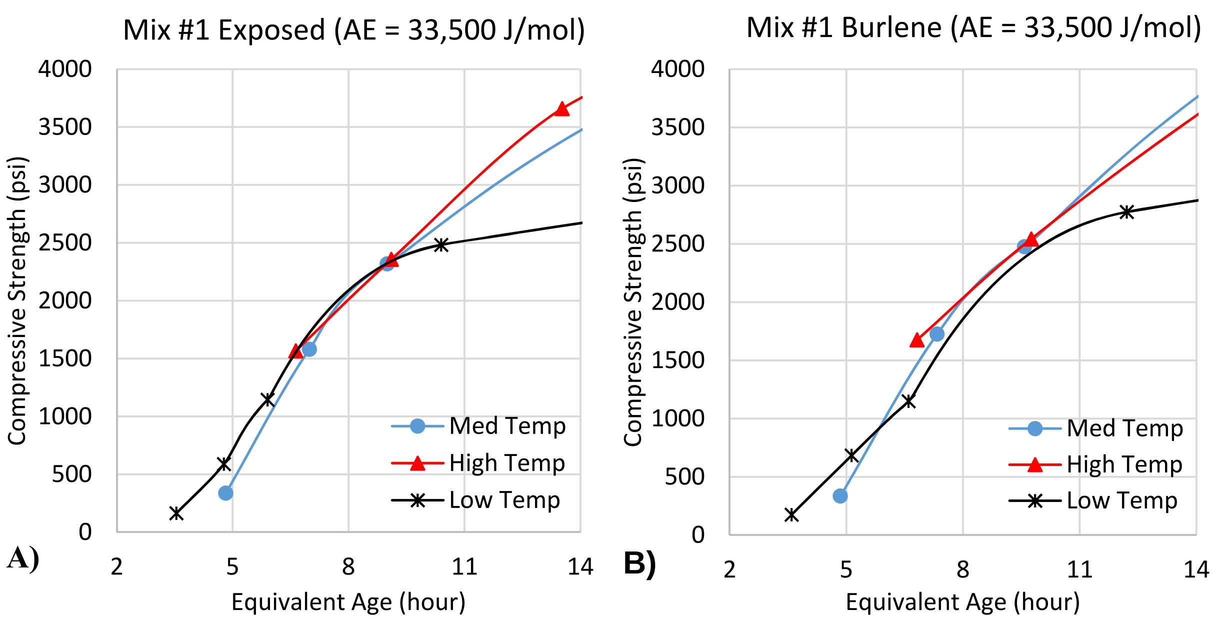


Figure 5-11. Arrhenius maturity-strength relationships with activation energy of 33,500 J/mol for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

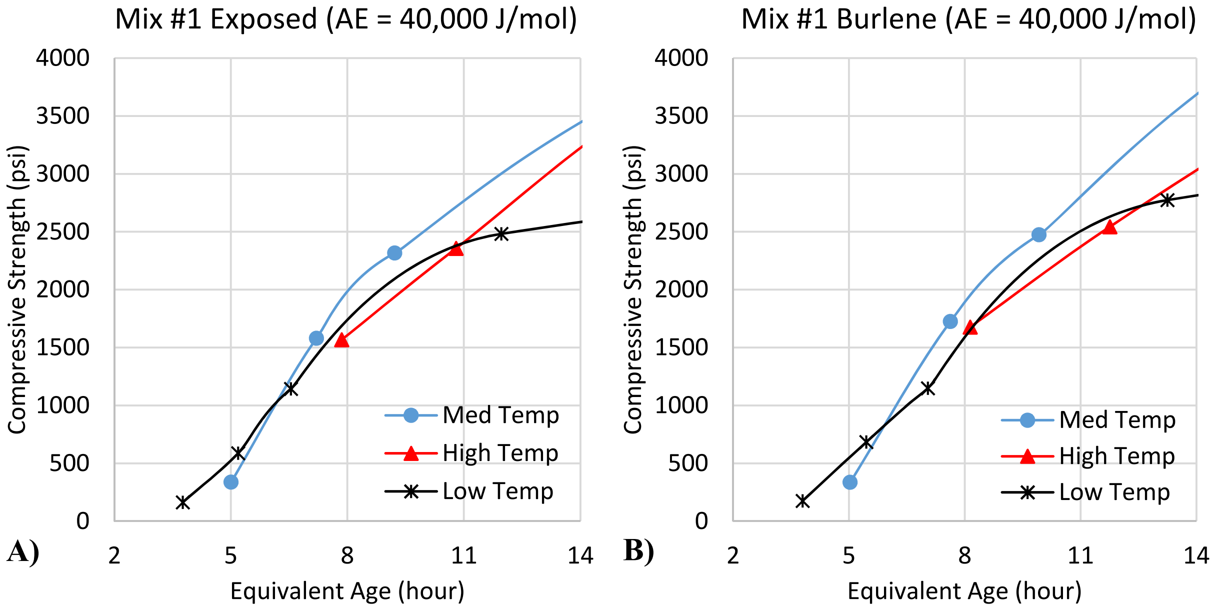


Figure 5-12. Arrhenius maturity-strength relationships with activation energy of 40,000 J/mol for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

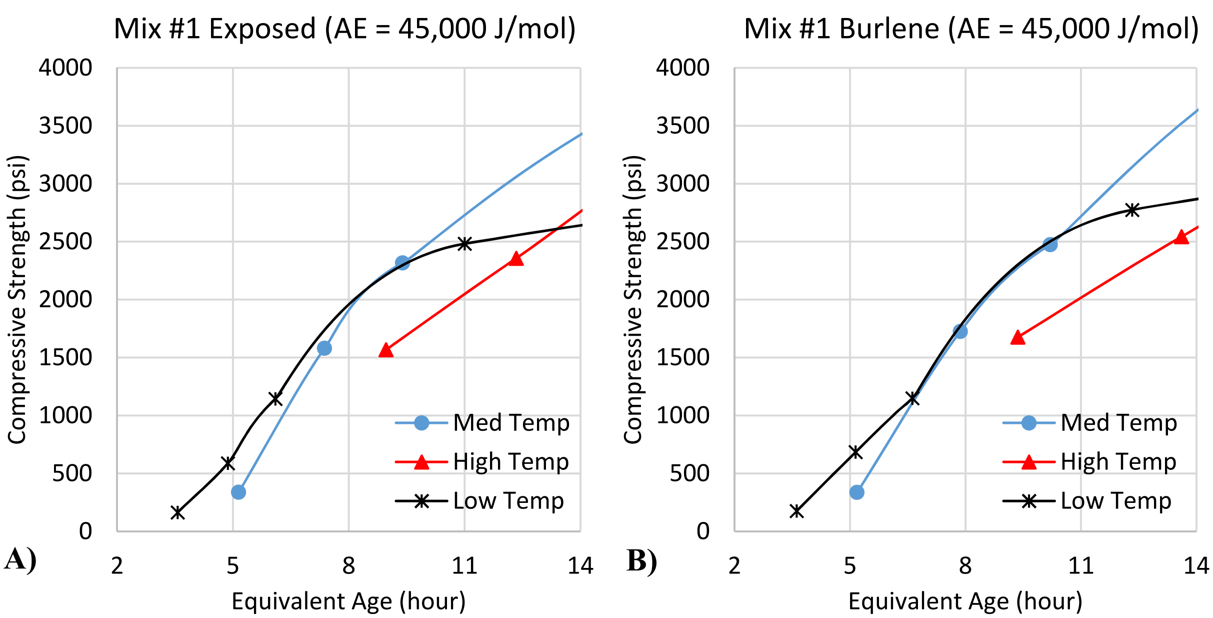


Figure 5-13. Arrhenius maturity-strength relationships with activation energy of 45,000 J/mol for Mix #1. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

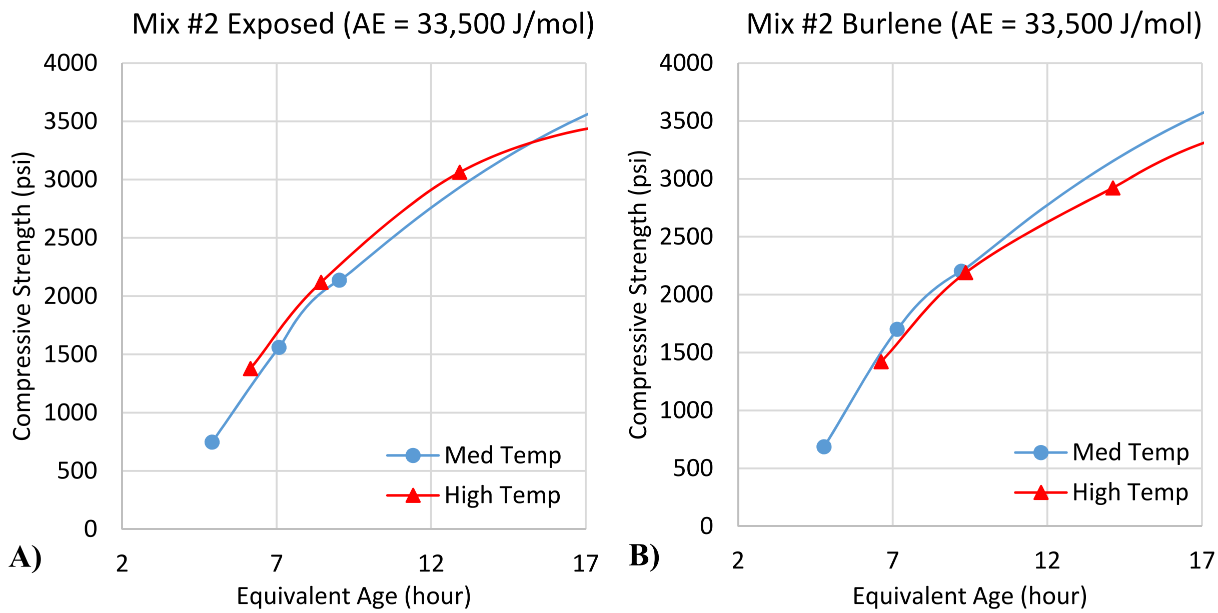


Figure 5-14. Arrhenius maturity-strength relationships with activation energy of 33,500 J/mol for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

Figures 5-14 through 5-16 show various Arrhenius maturity-strength relationships developed from the specimens cured under two different curing temperatures for Mix #2. Similarly, for both exposed curing and Burlene covering conditions, the use of activation energy of 33,500 J/mol gives the best matching between the maturity-strength relationships generated from the specimens cured under two different curing temperatures. Also, the differences between the calculated equivalent ages at the critical strength of 2,200 psi were less than 7 % for both exposed curing and Burlene covering conditions.

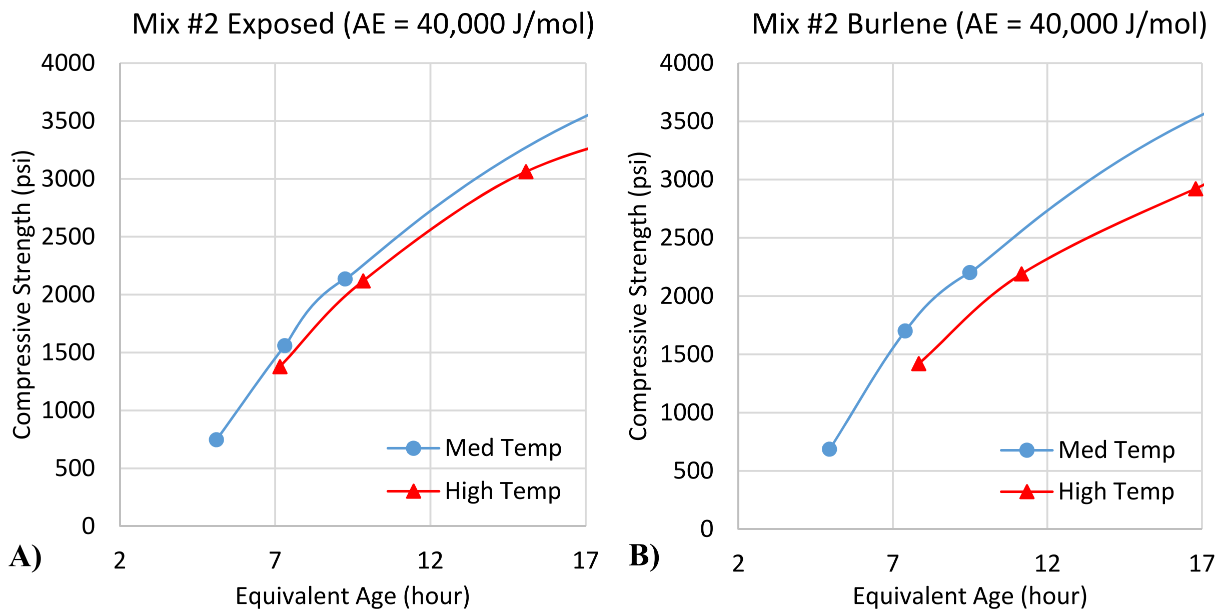


Figure 5-15. Arrhenius maturity-strength relationships with activation energy of 40,000 J/mol for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

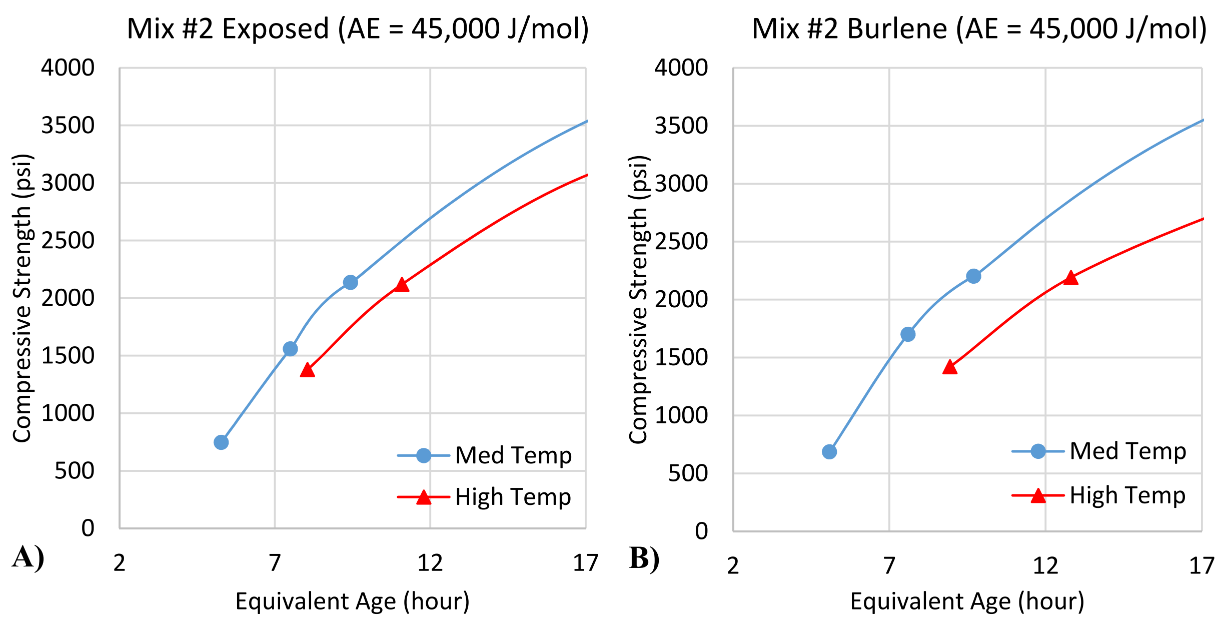


Figure 5-16. Arrhenius maturity-strength relationships with activation energy of 45,000 J/mol for Mix #2. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

Figures 5-17 through 5-19 show various Arrhenius maturity-strength relationships developed from the specimens cured under three different curing temperatures for Mix #3. Similarly, for both exposed curing and Burlene covering conditions, the use of activation energy of 33,500 J/mol gives the best matching between the maturity-strength relationships generated from the specimens cured under three different curing temperatures. Also, the differences between the calculated equivalent ages at the critical strength of 2,200 psi were less than 3 % for both exposed curing and Burlene covering conditions.

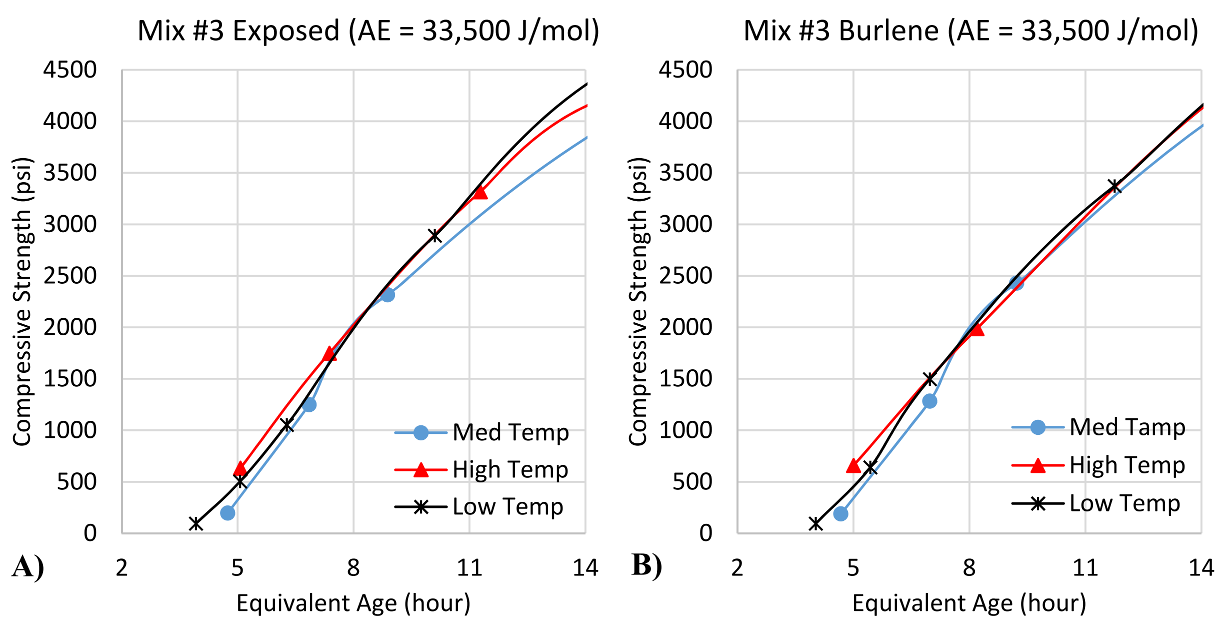


Figure 5-17. Arrhenius maturity-strength relationships with activation energy of 33,500 J/mol for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

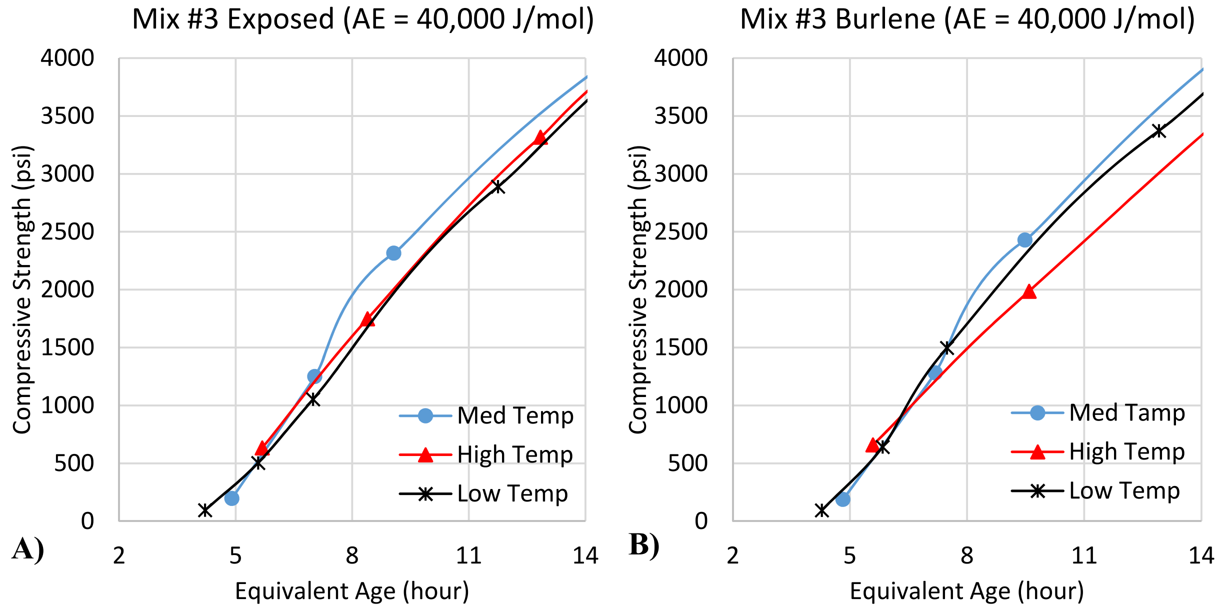


Figure 5-18. Arrhenius maturity-strength relationships with activation energy of 40,000 J/mol for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

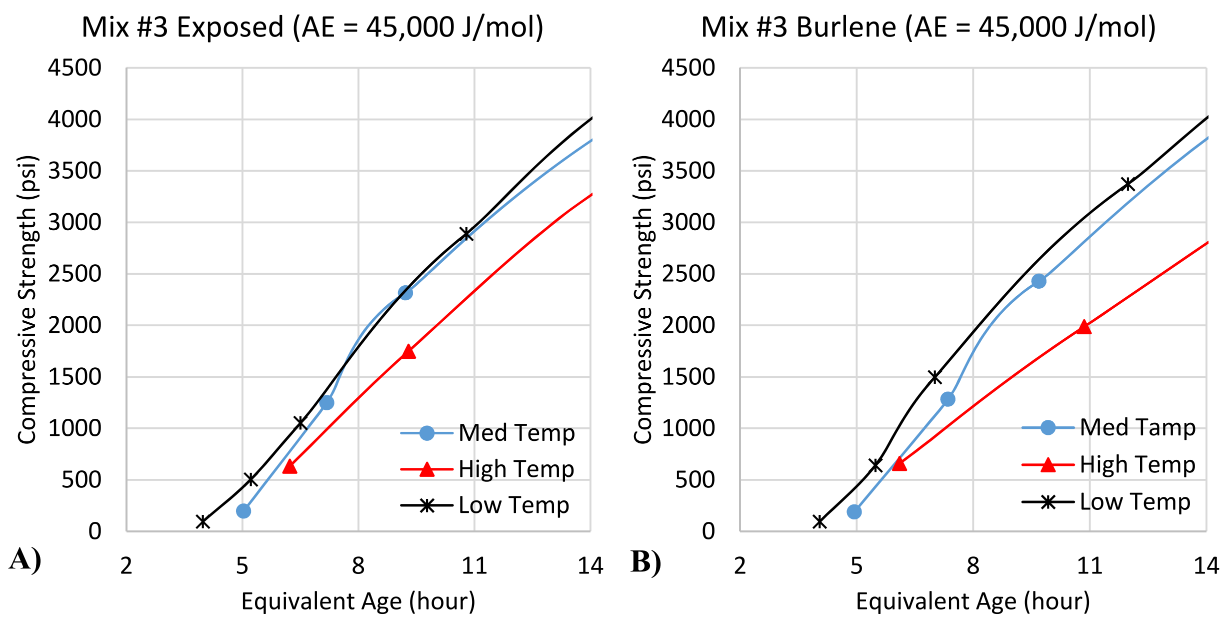


Figure 5-19. Arrhenius maturity-strength relationships with activation energy of 45,000 J/mol for Mix #3. A) Specimens cured under exposed curing condition, B) Specimens cured with Burlene covering.

As shown in both parametric studies for both Nurse-Saul and Arrhenius maturity method, the maturity-strength relationships developed by Arrhenius maturity function with activation energy of 33,500 J/mol gave the best strength prediction under different curing temperatures and curing conditions with errors of less than 7 %, 6 % and 3 % for Mix #1, Mix #2, and Mix #3, respectively. Therefore, the Arrhenius maturity function with activation energy of 33,500 J/mol was used for the calculation of maturity indices for the further experiments and field studies

5.4 Evaluation of Functions for Modeling Maturity-Strength Relationship

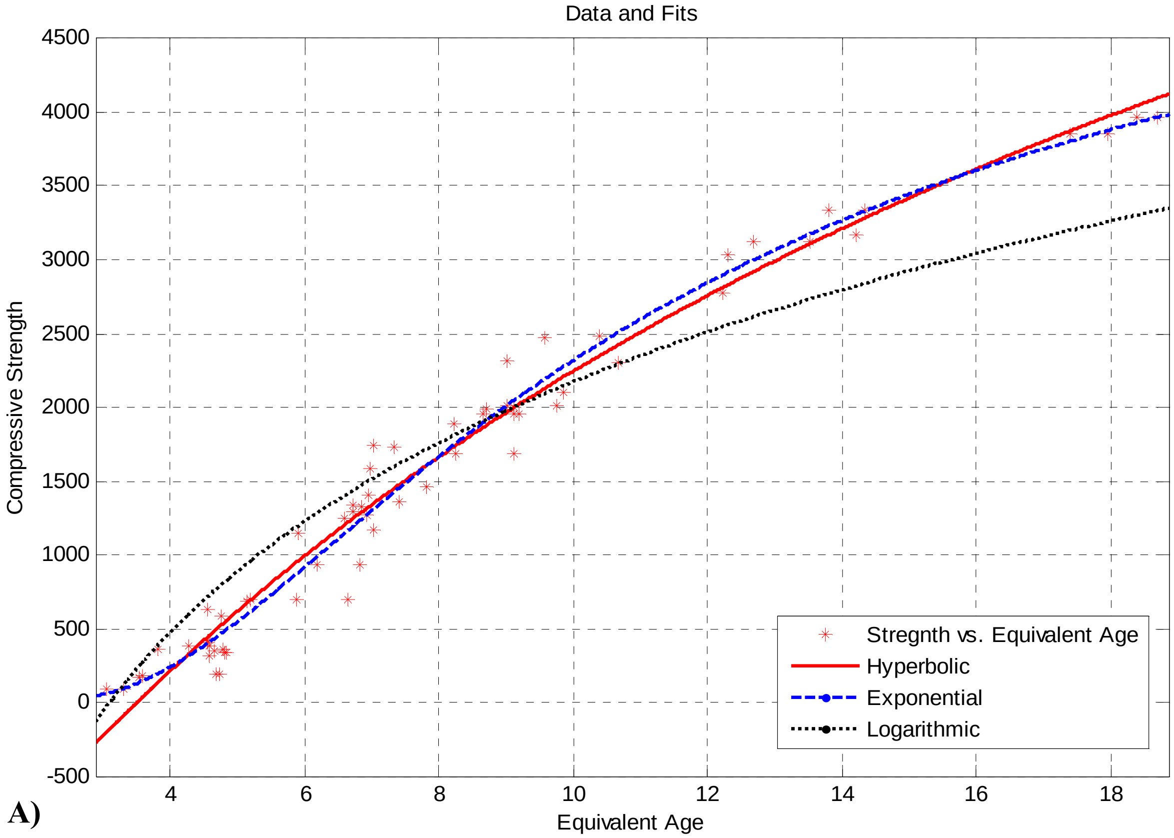
In 1991, Carino conducted a study of comparisons between the three types (hyperbolic, logarithmic, and exponential) of functions for modeling the maturity-strength relationship of concrete. He concluded that in the case of his strength and maturity data, the logarithmic function did not fit the maturity-strength data well while the other two functions showed a good fit to the maturity-strength data.

Similar comparisons for the three different modeling functions were made in this study to evaluate their suitability for modeling the maturity-strength relationship of concrete by using the data from the test results of Mix #1. Regression analyses were performed to relate the compressive strengths to the corresponding equivalent ages of the concrete using these three functions. Since the strength-equivalent age relationship works well only at early ages of the concrete, only the strength data at equivalent ages of less than 20 hours were used in these regression analyses. The regression analyses were performed using MATLAB® program. The best fit line for each function was determined by the program by minimizing the sum of squared error (SSE). The results of these regression analyses are shown in Table 5-5.

Table 5-5. Results of Regression Analysis Relating Compressive Strengths to Equivalent Age of Mix #1 Using Three Different Modeling Functions

Model		
Hyperbolic model	Exponential model	Logarithmic model
$f(x) = a\times(b\times(x-c)/(1+b\times(x-c)))$	$f(x) = a\times\exp(-(b/x)^c)$	$f(x) = a+b\times\log(x)$
$a = 1.067\times10^4$	a = 5,987	a = -2,100
b = 0.04104	b = 9.619	b = 1,855
c = 3.506	c = 1.335	
Goodness of fit:		
Hyperbolic model	Exponential model	Logarithmic model
SSE: 2.111×10^6	SSE: 1.759×10^6	SSE: 7.355×10^6
R-square: 0.9726	R-square: 0.9772	R-square: 0.9045
Adjusted R-square: 0.9717	Adjusted R-square: 0.9764	Adjusted R-square: 0.9029
RMSE: 186	RMSE: 169.8	RMSE: 344.4

As can be seen from Table 5-5, the exponential and hyperbolic models gave better fit to the data from Mix #1 with R-square values of 0.9772 and 0.9726, respectively. The logarithmic model gave a poorer fit with the smallest adjusted R-square value of 0.9045 and the highest root mean squared error (RMSE) value of 344.4.



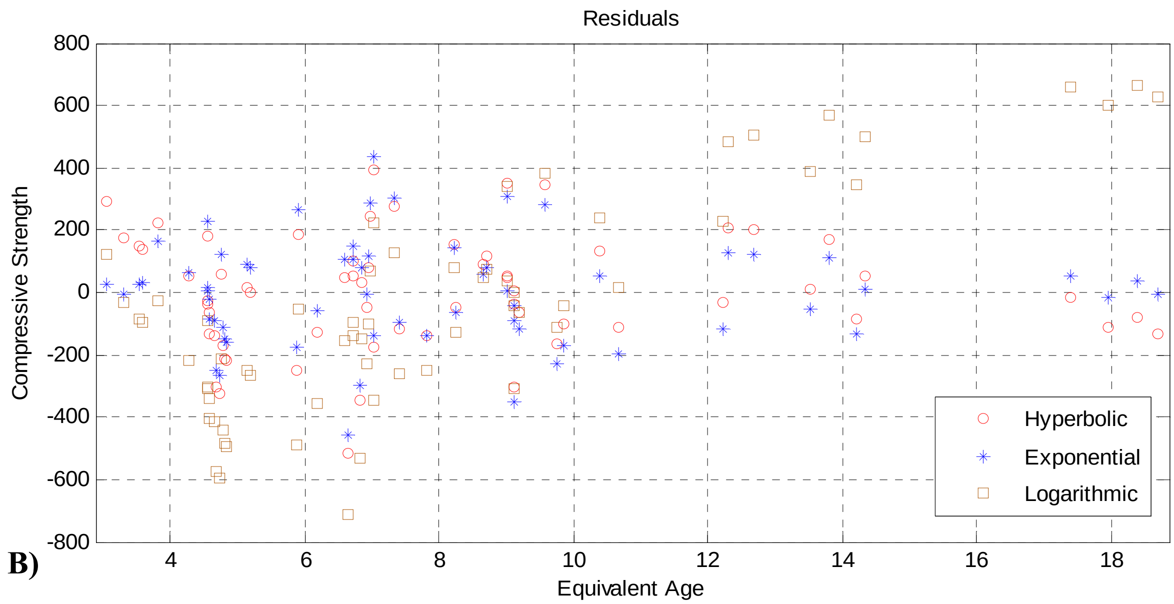


Figure 5-20. Results of regression analyses performed using MATLAB® program. A) Comparison of maturity-strength curves generated by three different modeling functions for Mix #1, B) Comparison of residuals of the generated maturity-strength curves.

Figure 5-20 shows the comparison of these three functions in modeling the strength-equivalent age relationship for the entire Mix #1 data. It can be seen that the exponential and the hyperbolic models give better fit to the data than the logarithmic model which is the same as the findings from Carino's study performed in 1991.

5.5 Evaluation of Curing Environments

5.5.1 Comparison of Maturity-Strength Plots of Mix #1

Figure 5-21 shows the comparison of the maturity-strength plots for Mix #1 cured without Burlene covering at three different curing temperatures and cured under standard condition.

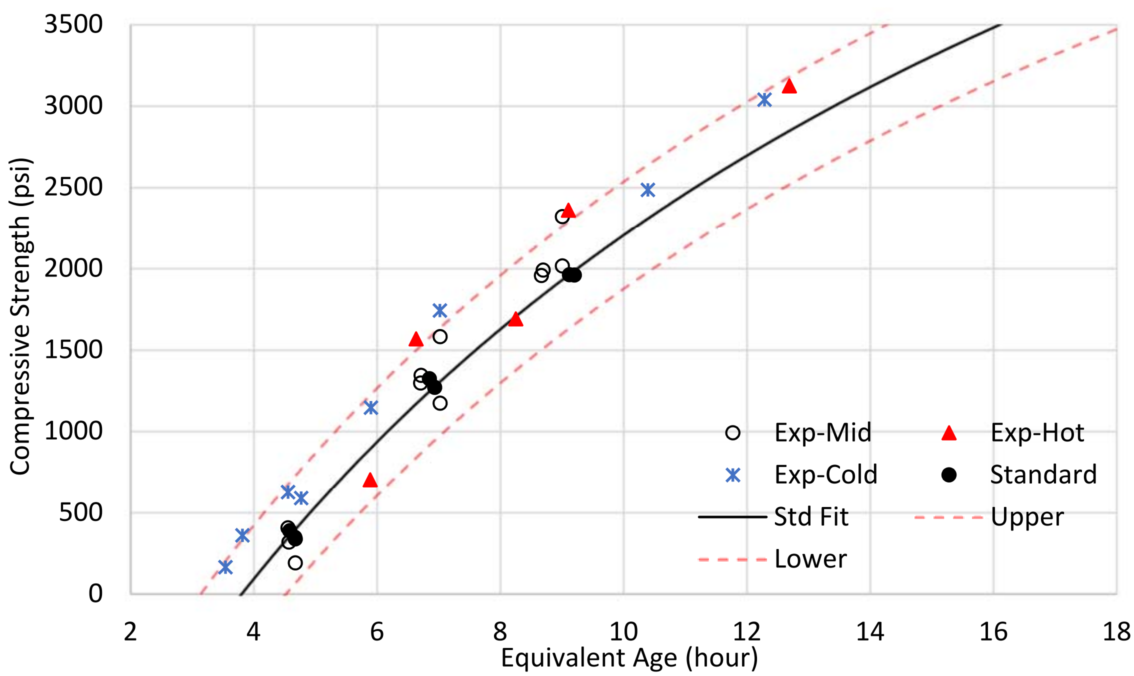


Figure 5-21. Strength versus equivalent age plots for Mix #1 cured without Burlene covering at three different temperatures and standard condition.

The strength–equivalent age plots for the concrete cured under the standard condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the standard condition is shown as a solid black line, along with two other thinner dashed red lines showing the upper and lower bounds for ±330 psi (±15 % of

2,200 psi) of this prediction line. It can be seen that out of 32 maturity-strength points plotted, 5 points (or 15.6 %) fall slightly above the upper bound and no points fall below the lower bound of this prediction line.

Figure 5-22 shows the comparison of the maturity-strength plots for Mix #1 cured with Burlene covering at three different curing temperatures and cured under standard condition. Similarly, the strength–equivalent age plots for the concrete cured under standard condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the standard condition is shown as a solid line, along with two other thinner dashed lines showing the upper and lower bounds for ±330 psi (±15 % of 2,200 psi) of this prediction line. It can be seen that out of 32 maturity-strength points plotted, 3 points (or 9.4 %) fall slightly above the upper bound and no points fall below the lower bound of this prediction line.

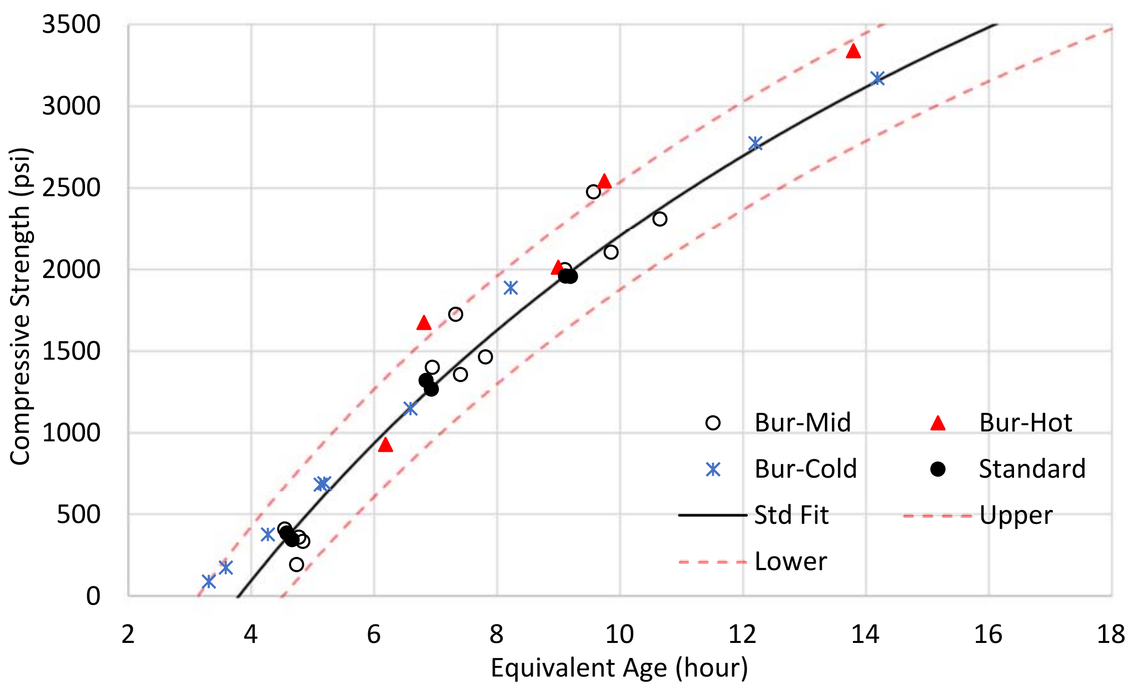


Figure 5-22. Strength versus equivalent age plots for Mix #1 cured with Burlene covering at three different temperatures and standard condition.

Among the eight points which fall above the upper bound, six points were from two separate batches (Replicate 1 of Mix #1 cured in hot curing chamber, and Replicate 2 of Mix #1 cured in ambient condition) that had lower slump and air content than batches for standard curing condition. The slump of these two batches of concrete was 6.25 inches, as compared with 6.5 to 6.75 inches, and the air content of these two batches of concrete was 2.0 %, as compared with 2.2 to 2.3 % for the standard batches. The lower slump of the fresh concrete might be due to a lower water content, which would result in a lower water-to-cement ratio and thus resulting in a higher strength of the concrete. Also, as it has already been shown by previous research results, for every 1 % increase in total volume of air, a 5 % decrease in compressive strength can be expected (Mindess et al., 2003). Lower air content of fresh concrete results in higher strength of the concrete. For the other batches of concrete, which had similar fresh concrete properties, the different curing conditions did not have any significant effects on the strength-equivalent age plots at an early age.

5.5.2 Comparison of Maturity-Strength Plots of Mix #2

As mentioned previously, some of the concrete batches of Mix #2 had air content exceeding the specified limit of 6 % due to high-mixture temperature and water-to-cement ratio (Wilson and Kosmatka, 2011). Figure 5-23 shows the comparison of the maturity-strength plots for batches containing an appropriate amount of air to batches containing inappropriate amount of air exceeding the specified limit. Concrete batches for hot and ambient curing temperatures contained appropriate amount of air while batches for standard and low curing temperatures contained inappropriate amount of air.

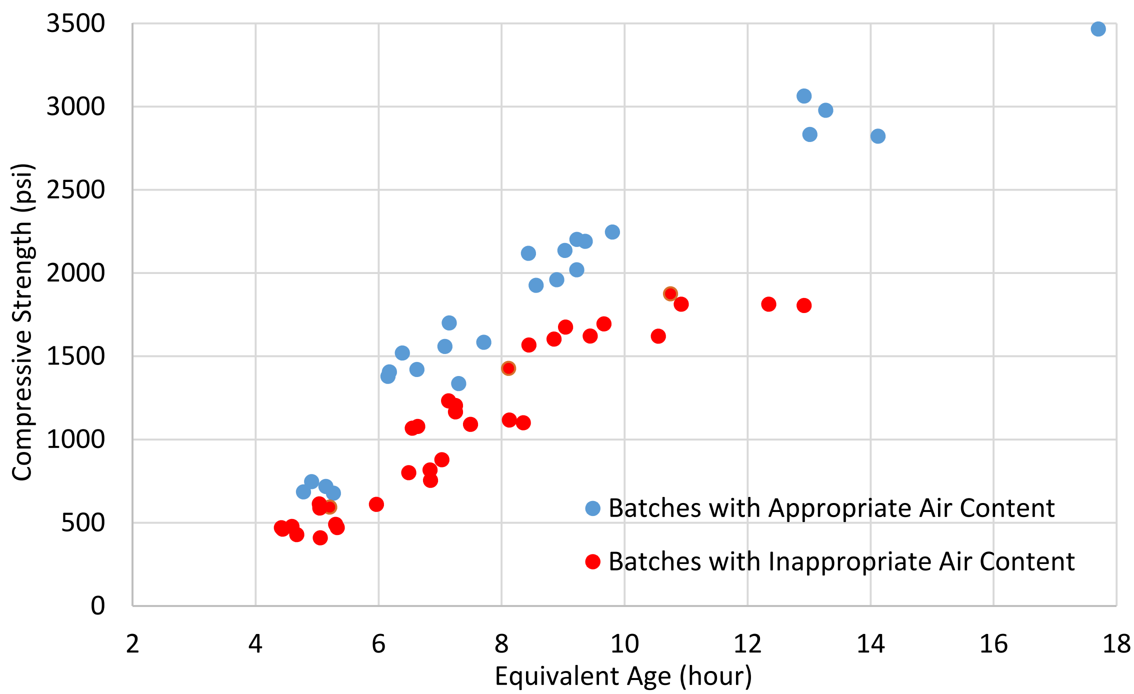


Figure 5-23. Strength versus equivalent age plots for Mix #2 containing appropriate and inappropriate amount of air

As shown in Figure 5-23, significant strength loss occurred on the batches containing inappropriate amount of air. The data points for the four batches of concrete with exceedingly high air content were thus excluded, and the remaining maturity-strength plots are shown in Figure 5-24. Since the data from the standard curing condition had been removed (due to high air content), the data from the concrete cured with Burlene covering at ambient temperature, which seemed to be identical to those from the standard curing condition, were selected as the data for standard curing condition. The plots for the "modified standard" curing condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the "modified standard" condition is shown as a solid line, along with two other thinner dashed lines showing the upper and lower bounds for ±330 psi (±15 % of 2,200 psi) of this prediction line. It can be seen that all of the 19 maturity-strength points lie between the upper and lower bounds.

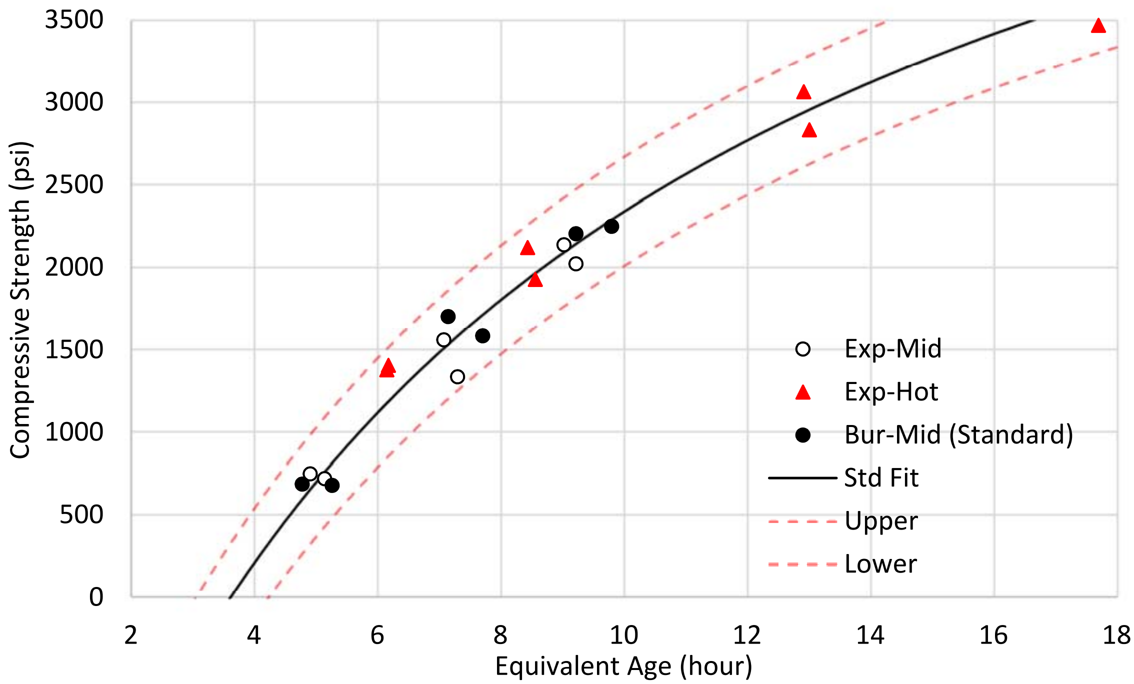


Figure 5-24. Strength versus equivalent age plots for Mix #2 cured without Burlene covering at two different temperatures and modified standard condition.

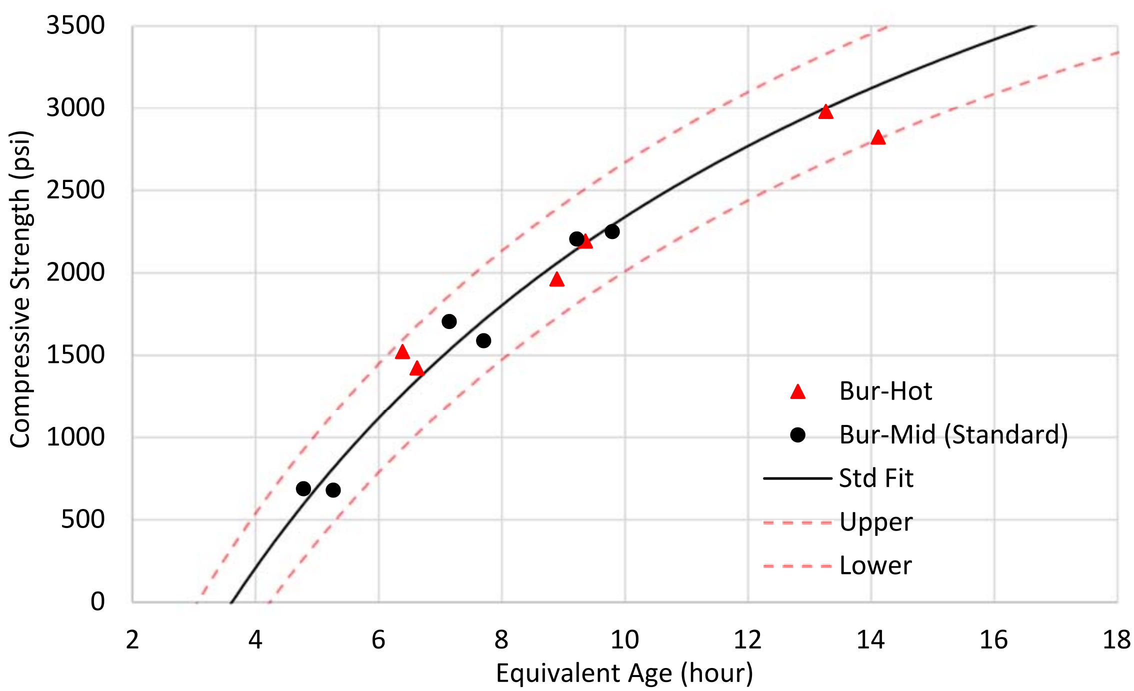


Figure 5-25. Strength versus equivalent age plots for Mix #2 cured with Burlene covering at two different temperatures and modified standard condition.

For the batches of Mix #2 cured with Burlene covering, two of these batches had air content exceeding 6 % and these two batches were those cured at 43˚F. Similarly, the data from these two batches of concrete were excluded from Figure 5-25, which shows the comparison of the maturity-strength plots for Mix #2 cured with Burlene covering at two different curing temperatures.

Similarly, since the data from the standard curing condition had been excluded (due to high air content), the data from the concrete cured with Burlene covering and at ambient condition were selected as the data for the standard curing condition. The plots for the "modified standard" curing condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the "modified standard" condition is shown as a solid line, along with two other thinner dashed lines showing the upper and lower bounds for ±330 psi (±15 % of 2,200 psi) of this prediction line. It can be seen that all of the 12 maturity-strength points lie between the upper and lower bounds.

5.5.3 Comparison of Maturity-Strength Plots of Mix #3

Figure 5-26 shows the comparison of the maturity-strength plots for Mix #3 cured without Burlene covering at three different curing temperatures and cured under the standard condition. The strength–equivalent age plots for the concrete cured under the standard condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the standard condition is shown as a solid line, along with two other thinner dashed lines showing the upper and lower bounds for ±330 psi (±15 % of 2,200 psi) of this prediction line. It can be seen that all of the 33 maturity-strength points lie between the upper and lower bounds.

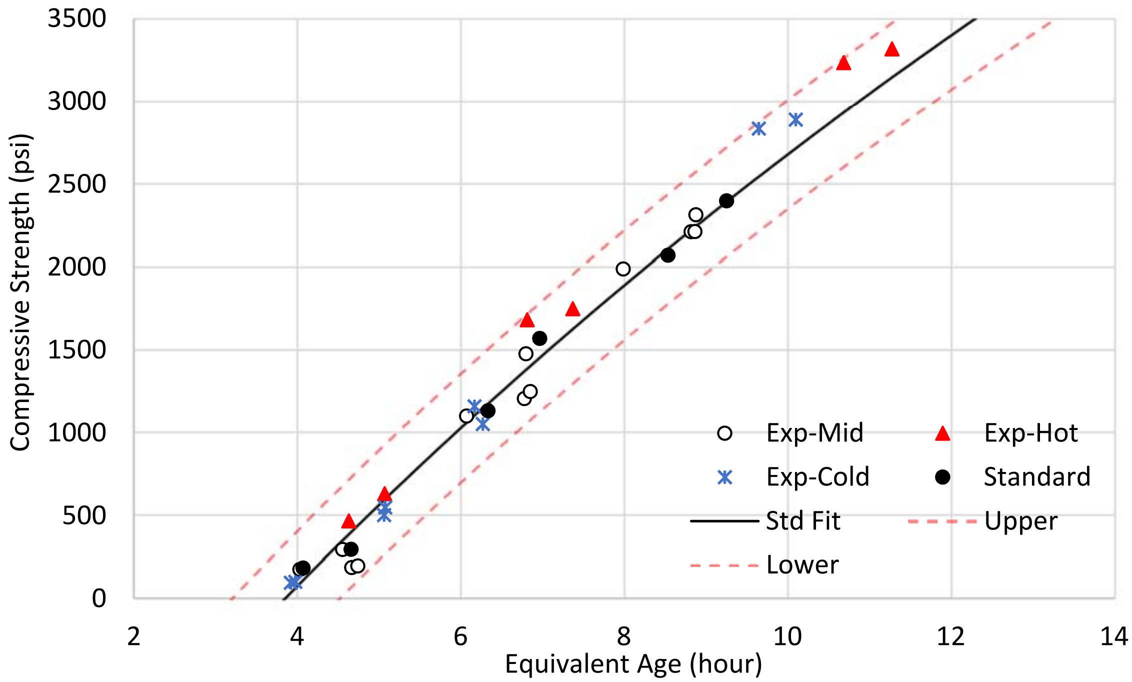


Figure 5-26. Strength versus equivalent age plots for Mix #3 cured without Burlene covering at three different temperatures and standard condition.

Figure 5-27 shows the comparison of the maturity-strength plots for Mix #3 cured with Burlene covering at three different curing temperatures that cured under the standard condition.

Similarly, the strength–equivalent age plots for the concrete cured under standard curing condition are shown by the solid circular black dots on the figure. A best-fit hyperbolic line for the strength-equivalent age relationship for the standard condition is shown as a solid line, along with two other thinner dashed red lines showing the upper and lower bounds for ±330 psi (±15 % of 2,200 psi) of this prediction line. It can be seen that all of the 34 maturity-strength points lie between the upper and lower bounds.

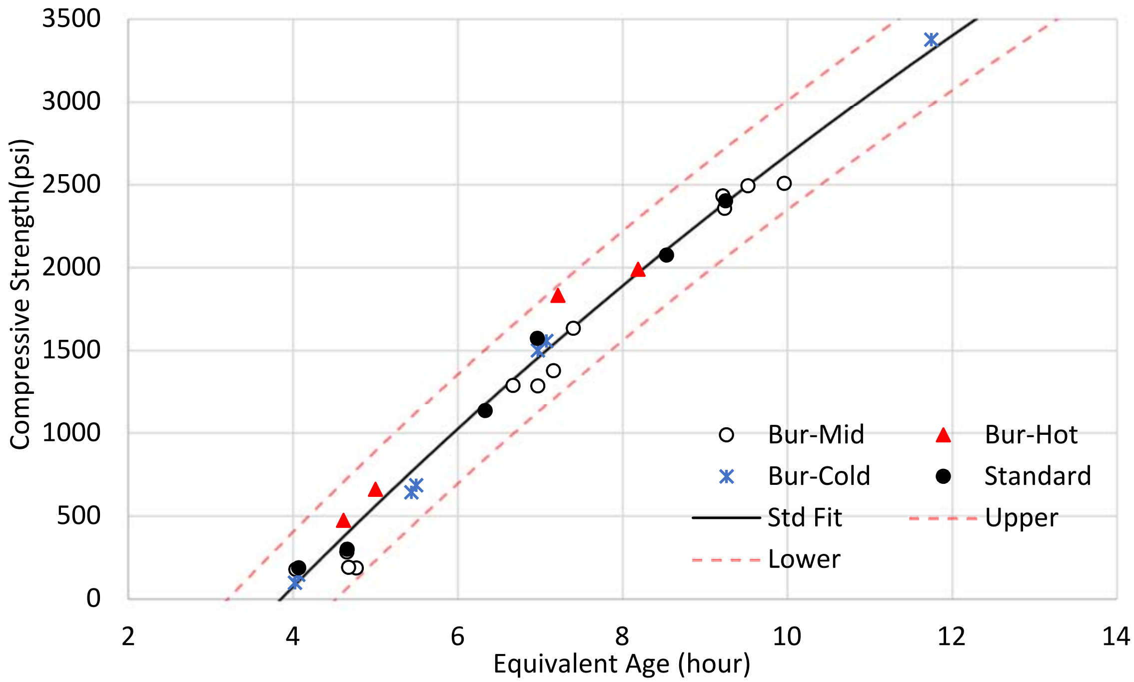


Figure 5-27. Strength versus equivalent age plots for Mix #3 cured with Burlene covering at three different temperatures and standard condition.

5.6 Evaluation of Effect of Fresh Concrete Properties

The previous section shows that while the Arrhenius maturity method was effective in predicting the strength of the concrete at early age, the variation in fresh concrete properties such as air content and slump could cause errors in strength prediction. This section presents the effects of variation of fresh concrete properties on the maturity-strength characteristics of the concrete according to the data from the second set of experiments of the laboratory study.

5.6.1 Compressive Strength Prediction

The effects of fresh concrete properties on the maturity-strength characteristics are evaluated by comparing the predicted strength of the concrete at a typical equivalent age for each mix design. The equivalent ages of 8, 9, and 8 hours were selected for the strength prediction because the compressive strength reached 2,000 psi for Mix #1, Mix #2, and Mix #3 at the equivalent ages of 8, 9, and 8 hours, respectively. Compressive strengths at the chosen equivalent ages were calculated by interpolation of separately developed hyperbolic trend lines for each curing condition. Tables 5-6, 5-7, and 5-8 show the developed hyperbolic trend lines and predicted compressive strengths for Mix #1, Mix #2, and Mix #3, respectively.

Table 5-6. Hyperbolic Trend Lines and Predicted Strengths Calculated by MATLAB® Program for Mix #1

Hyperbolic Trend Line $f(x) = a\times(b\times(x-c)/(1+b\times(x-c))$							
Curing Condition	a	b	c	Sum of Squared Error	R-square	RMSE	Predicted Strength
Amb 1 Exp	5,754	0.1242	4.558	9.61×10^4	0.9948	219.2	1,723
Amb 1 Cur	6,917	0.08405	4.459	1.03×10^4	0.9996	71.67	1,586
Amb 2 Exp	6,463	0.1185	4.244	3,222	0.9999	40.14	1,991
Amb 2 Cur	7,807	0.09462	4.399	1.62×10^4	0.9995	90.09	1,984
113F 1 Exp	6,972	0.1156	4.291	9.03×10^4	0.9957	173.5	2,092
113F 1 Cur	8,533	0.0738	3.7	3.59×10^4	0.9989	109.4	2,056
113F 2 Exp	5,993	0.1415	5.081	7.36×10^4	0.9964	156.6	1,752
113F 2 Cur	7,639	0.07908	4.431	1.56×10^4	0.9995	72.17	1,681
43F 1 Exp	6,391	0.08752	3.38	1.95×10^4	0.999	98.62	1,840
43F 1 Cur	6,989	0.0702	3.425	4.07×10^4	0.9982	142.7	1,699
43F 2 Exp	6,204	0.09855	3.107	5.08×10^4	0.9972	130.1	2,018
43F 2 Cur	7,293	0.06927	3.358	3.76×10^4	0.9983	111.9	1,774
Standard 1	7,366	0.07586	3.962	2.70×10^4	0.999	116.1	1,727
Standard 2	8,385	0.06085	4.017	5,236	0.9999	51.17	1,636
73F 1 Exp	6,558	0.09453	4.12	3.73×10^4	0.9983	136.6	1,760
73F 1 Cur	7,979	0.06419	3.721	4,334	0.9999	46.55	1,719
73F 2 Exp	6,838	0.09708	4.195	4.63×10^4	0.9982	152.1	1,845
73F 2 Cur	8,666	0.05308	3.949	1,545	1	27.8	1,534

Table 5-7. Hyperbolic Trend Lines and Predicted Strengths Calculated by MATLAB® Program for Mix #2

Hyperbolic Trend Line $f(x) = a\times(b\times(x-c)/(1+b\times(x-c))$							
Curing Condition	a	b	c	Sum of Squared Error	R-square	RMSE	Predicted Strength
Amb 1 Exp	6,041	0.08419	3.607	1.69×10^{4}	0.9989	91.94	1,886
Amb 1 Cur	6,735	0.08211	3.896	3.53×10^{3}	0.9998	42	1,989
Amb 2 Exp	6,494	0.08297	3.291	3,539	0.9998	42.06	2,087
Amb 2 Cur	7,506	0.06668	3.088	2.08×10^{4}	0.9991	101.9	2,122
113F 1 Exp	5,215	0.1519	3.827	2.60×10^{4}	0.9975	93.07	2,295
113F 1 Cur	7,392	0.05411	2.132	3.14×10^{4}	0.9987	102.3	2,003
113F 2 Exp	5,288	0.1141	3.145	1.53×10^{4}	0.9986	71.42	2,118
113F 2 Cur	7,220	0.05322	1.252	1.73×10^{5}	0.9921	240.3	2,108
43F 1 Exp	5,465	0.0626	3.68	2.74×10^{4}	0.9972	95.55	1,365
43F 1 Cur	6,127	0.04254	3.111	1.79×10^{4}	0.9983	77.23	1,227
43F 2 Exp	5,351	0.05403	3.248	2.28×10^{4}	0.9976	87.2	1,269
43F 2 Cur	5,962	0.0397	3.002	3.60×10^{4}	0.9965	109.5	1,147
Standard 1	6,282	0.04488	2.301	2.96×10^{4}	0.9982	121.7	1,452
Standard 2	6,022	0.04807	2.242	4.48×10^{4}	0.9971	149.6	1,477
73F 1 Exp	5,955	0.06198	3.032	8,687	0.9994	65.9	1,608
73F 1 Cur	6,197	0.05749	3.215	7,389	0.9995	60.78	1,547
73F 2 Exp	5,630	0.05879	2.635	3.33×10^{4}	0.9976	129	1,533
73F 2 Cur	5,733	0.06062	3.026	4,159	0.9997	45.6	1,524

Table 5-8. Hyperbolic Trend Lines and Predicted Strengths Calculated by MATLAB® Program for Mix #3

Hyperbolic Trend Line f(x) = a×(b×(x-c)/(1+b×(x-c))							
Curing Condition	a	b	c	Sum of Squared Error	R-square	RMSE	Predicted Strength
Amb 1 Exp	6,570	0.1376	4.699	2.48×10^5	0.9903	352.2	1,828
Amb 1 Cur	7,954	0.0959	4.705	2.93×10^5	0.9921	382.5	1,910
Amb 2 Exp	6,816	0.1223	4.632	2.05×10^5	0.9925	319.9	1,989
Amb 2 Cur	8,077	0.09477	4.789	3.02×10^5	0.9919	388.8	1,884
113F 1 Exp	6,902	0.1371	4.189	4.68×10^4	0.9984	124.9	2,369
113F 1 Cur	8,300	0.09944	4.188	2.71×10^5	0.9938	300.3	2,281
113F 2 Exp	6,957	0.1351	4.462	8.80×10^4	0.9969	171.2	2,250
113F 2 Cur	8,380	0.09301	4.335	2.35×10^5	0.9944	280.1	2,130
43F 1 Exp	7,729	0.1144	4.148	2.52×10^5	0.9923	290	2,364
43F 1 Cur	8,561	0.08446	4.238	2.81×10^5	0.9926	306.2	2,064
43F 2 Exp	8,271	0.09431	4.153	3.23×10^5	0.9911	328.1	2,202
43F 2 Cur	8,780	0.07597	4.288	3.14×10^5	0.9918	323.7	1,931
Standard 1	7,454	0.07808	3.811	1.40×10^4	0.9995	83.55	1,837
Standard 2	7,780	0.08632	4.146	5,982	0.9998	54.69	1,942
73F 1 Exp	6,502	0.1112	3.931	6.22×10^4	0.9974	176.4	2,026
73F 1 Cur	7,775	0.07419	3.761	2.22×10^4	0.9993	105.2	1,860
73F 2 Exp	6,957	0.1068	4.211	2.47×10^4	0.9991	111.2	2,004
73F 2 Cur	7,735	0.09853	4.378	7.99×10^4	0.9975	199.9	2,034

5.6.2 Effect of Variation of Slump on Maturity-Strength Plots

Figure 5-28 shows plots of predicted compressive strength at an equivalent age of 8 hours versus the slump of the fresh concrete for Mix #1. It can be observed that the compressive strength generally decreases with increasing slump. As the slump increases by 2 inches, the compressive strength can decrease by as much as 300 psi.

Figure 5-29 shows plots of compressive strength at an equivalent age of 9 hours versus the slump of the fresh concrete for Mix #2. Since Mix #2 had four batches of concrete with exceedingly high air content (as noted in Section 5.2), the effect of slump might be over-shadowed by the effects of air content, and thus was not clearly observed. However, the linear trend line for data from valid batches shows a clear trend that follows the general trend as well.

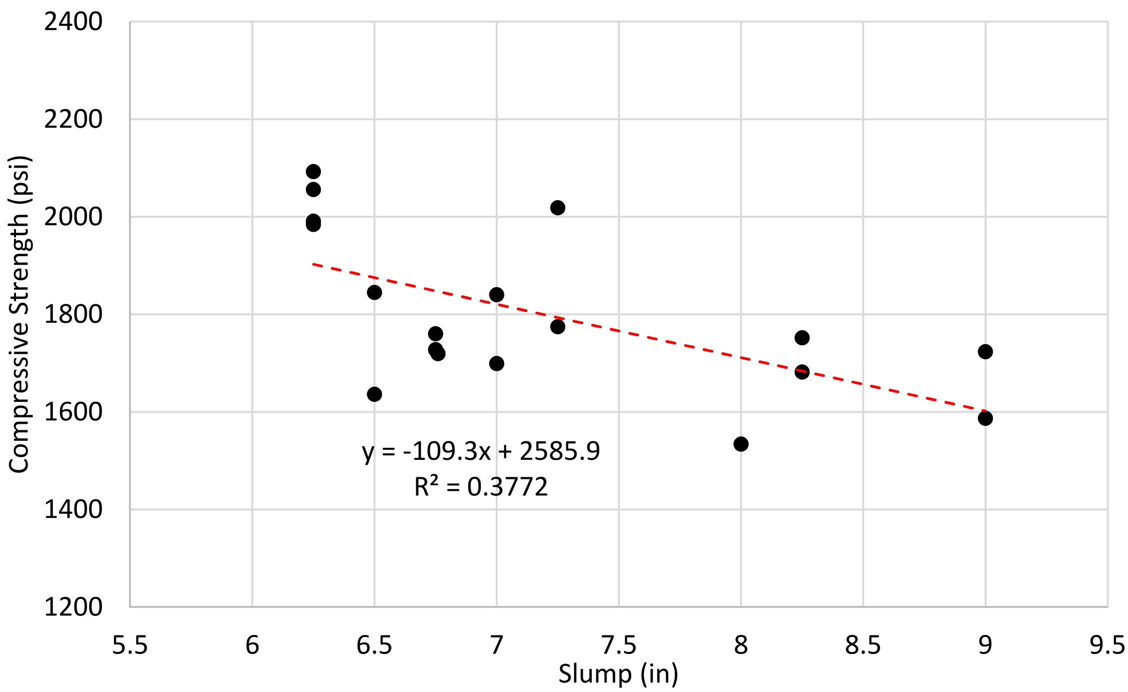


Figure 5-28. Plots of compressive strength at equivalent age of 8 hours versus slump of fresh concrete for Mix #1.

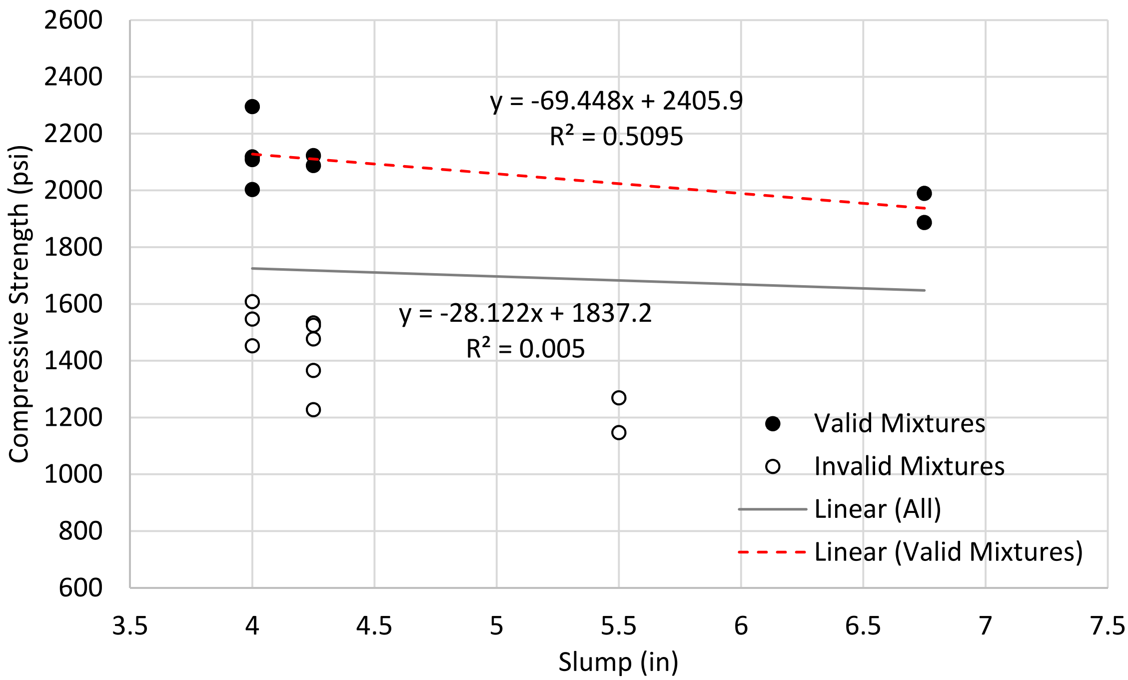


Figure 5-29. Plots of compressive strength at equivalent age of 9 hours versus slump of fresh concrete for Mix #2.

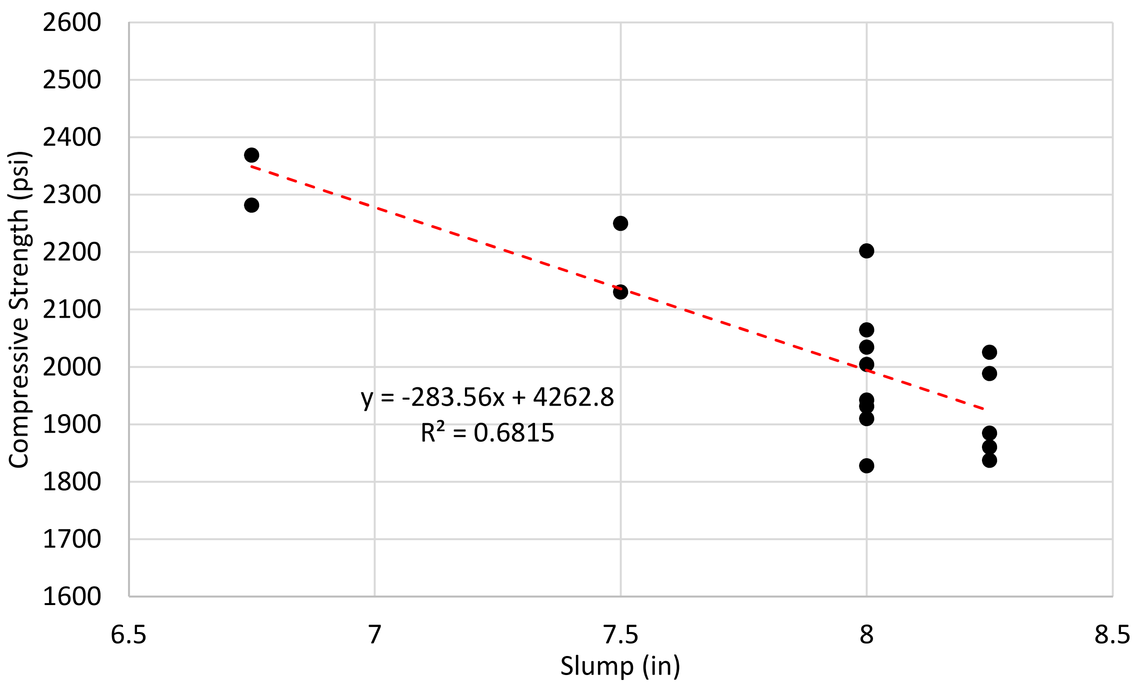


Figure 5-30. Plots of compressive strength at equivalent age of 8 hours versus slump of fresh concrete for Mix #3.

Figure 5-30 shows plots of predicted compressive strength at an equivalent age of 8 hours versus the slump of the fresh concrete for Mix #3. Similarly, it can be seen that the compressive strength generally decreases with increasing slump. As the slump increases by 2 inches, the compressive strength can decrease by as much as 500 psi.

5.6.3 Effect of Air Content on Maturity-Strength Plots

Figure 5-31 shows plots of compressive strength at an equivalent age of 8 hours versus the air content of the fresh concrete for Mix #1. It can be observed that the compressive strength generally decreases as the air content increases for all mixes. The effect of air content of fresh concrete on compressive strength of concrete has been reported by other researchers. It has been reported that for every 1 % increase in total volume of air, a 5 % decrease in compressive strength can be expected (Mindess et al., 2003).

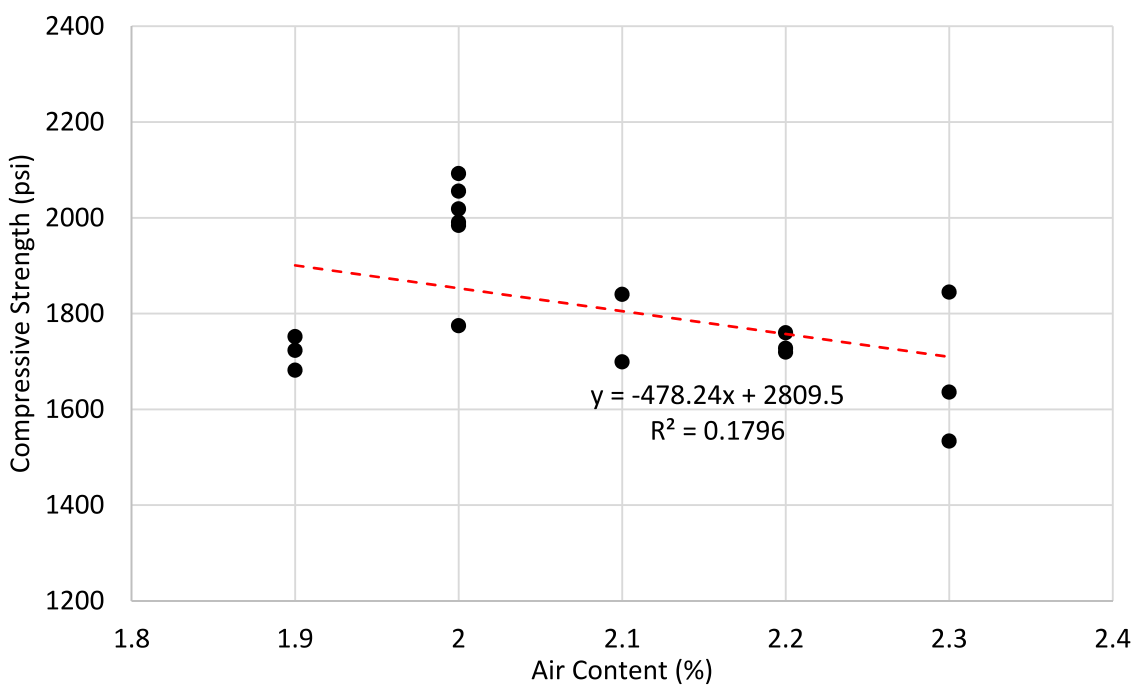


Figure 5-31. Plots of compressive strength at equivalent age of 8 hours versus air content of fresh concrete for Mix #1.

Figure 5-32 shows plots of compressive strength at an equivalent age of 9 hours versus the air content of the fresh concrete for Mixes #2. Similarly, it can be observed that the compressive strength generally decreases as the air content increases for all mixes. The trend of plots for valid batches also follows a similar general trend as well.

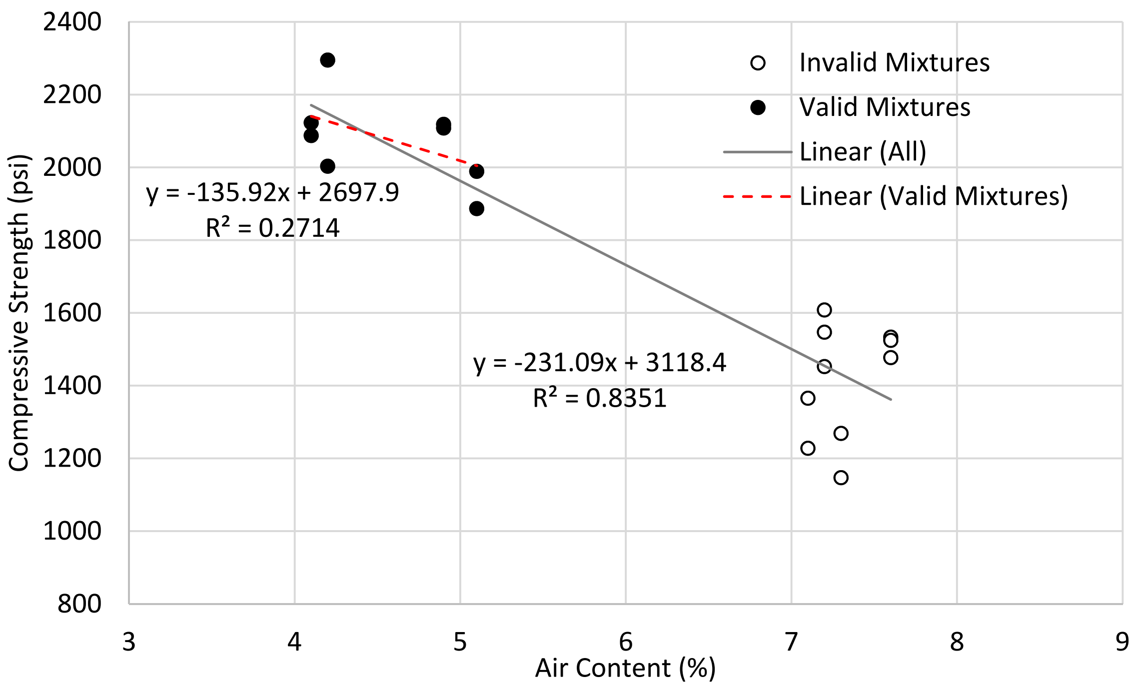


Figure 5-32. Plots of compressive strength at equivalent age of 9 hours versus air content of fresh concrete for Mix #2.

Figure 5-33 shows plots of compressive strength at an equivalent age of 8 hours versus the air content of the fresh concrete for Mixes #3. Similarly, it can be observed that the compressive strength generally decreases as the air content increases for all mixes.

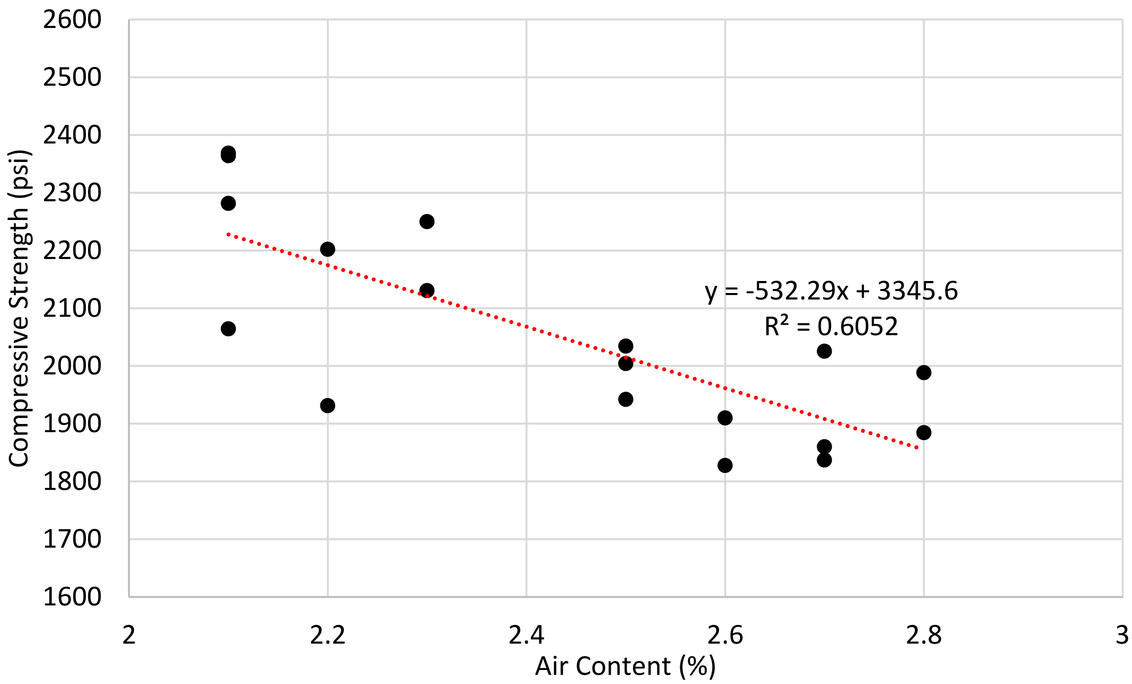


Figure 5-33. Plots of compressive strength at equivalent age of 8 hours versus air content of fresh concrete for Mix #3.

5.6.4 Effect of Unit Weight on Maturity-Strength Plots

Figure 5-34 shows plots of compressive strength at an equivalent age of 8 hours versus the unit weight of the fresh concrete for Mix #1. It can be observed that the compressive strength generally decreases as the unit weight of the concrete decreases. A decrease in unit weight of concrete can be caused by an increase in air content or water content, which will generally reduce the strength of the concrete.

Figure 5-35 shows plots of compressive strength at an equivalent age of 9 hours versus the unit weight of the fresh concrete for Mix #2. Similarly, it can be observed that the compressive strength generally decreases as the unit weight decreases for all mixes. The trend of plots for valid batches also follows a similar general trend as well.

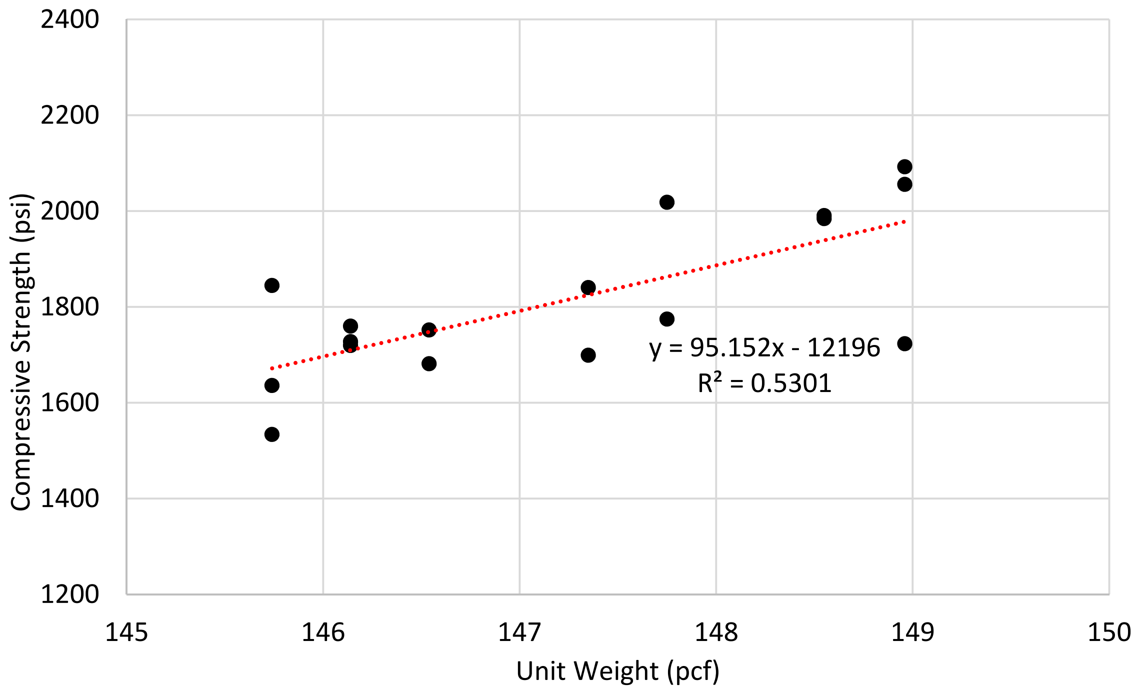


Figure 5-34. Plots of compressive strength at equivalent age of 8 hours versus unit weight of fresh concrete for Mix #1.

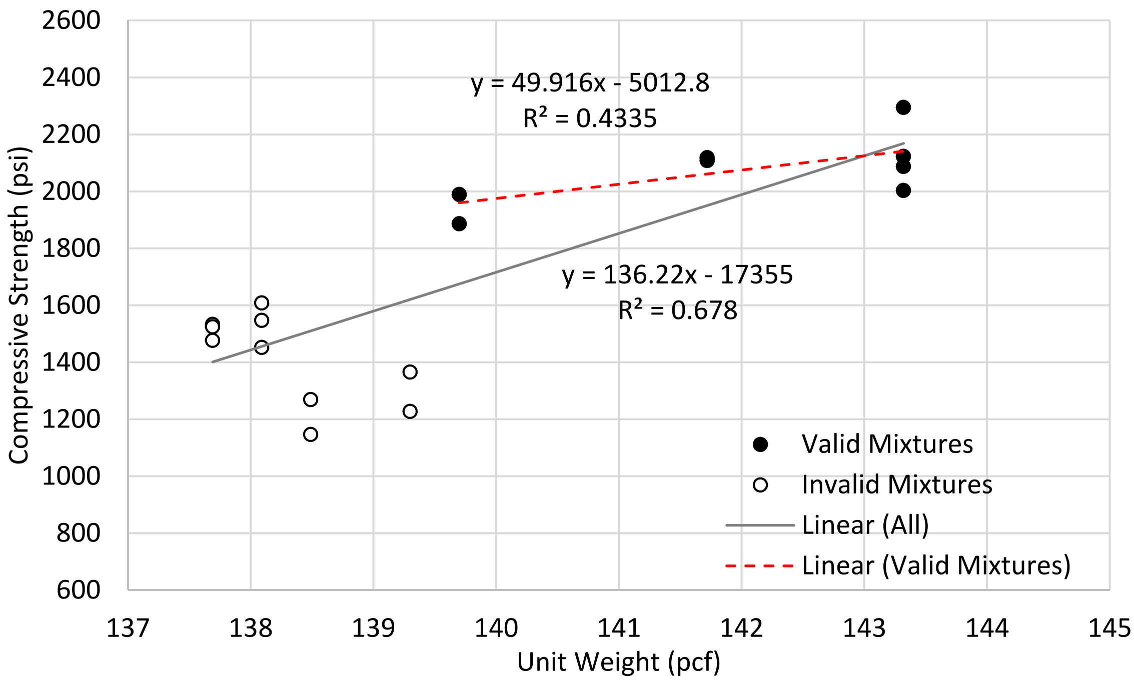


Figure 5-35. Plots of compressive strength at equivalent age of 9 hours versus unit weight of fresh concrete for Mix #2.

Figure 5-36 shows plots of compressive strength at an equivalent age of 8 hours versus the unit weight of the fresh concrete for Mix #3. Similarly, it can be observed that the compressive strength generally decreases as the unit weight decreases for all mixes.

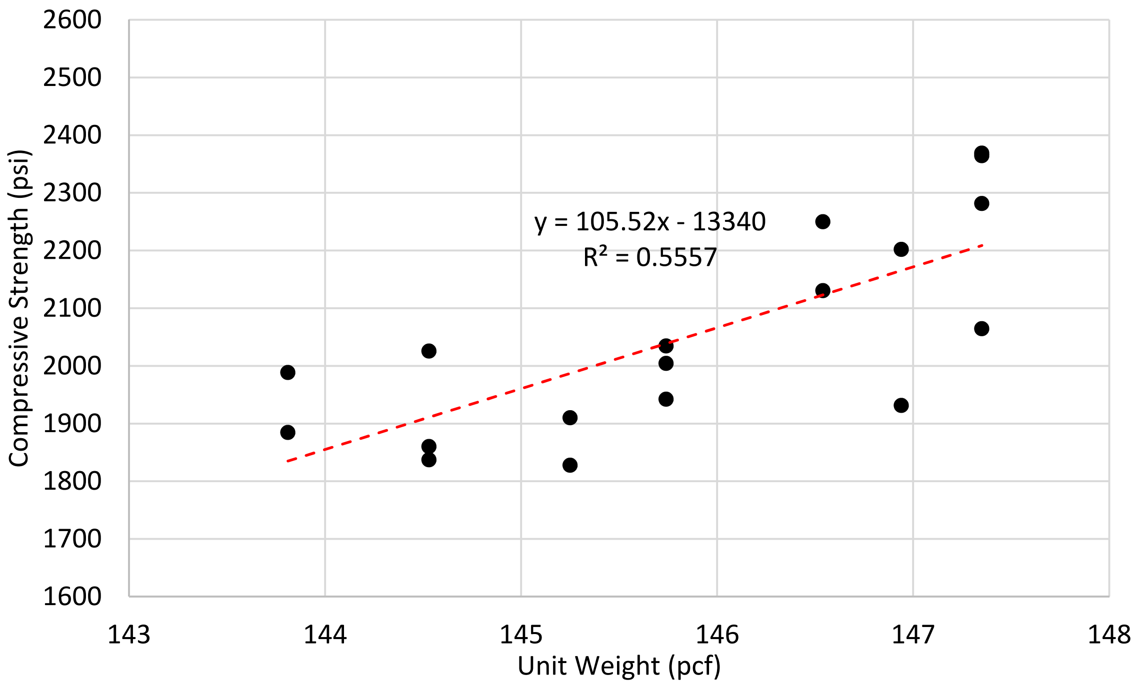


Figure 5-36. Plots of compressive strength at equivalent age of 8 hours versus unit weight of fresh concrete for Mix #3.

5.7 Recommended Testing Protocols for Generating Maturity-Strength Curves

Based on the test results, observations, and experience gained from the second set of experiments, the following testing protocol for the use of maturity method to estimate compressive strength of concrete at early age for slab replacement application is recommended.

5.7.1 Preparation of Concrete in the Laboratory

The laboratory concrete mixtures which are to be used to develop maturity-strength curves have to be produced using the same mix design and the same time frame to resemble the concrete to be used in an actual project.

Table 5-9. Recommended Time Frame for the Laboratory Concrete

Activity	Time (minutes)	Simulating activities for Ready-Mix Concrete
Mix without Accelerator	5	Concrete Mix in batch plant
Slow or Intermittent Mix	15-30 (depends on the distance from batch plant to project site)	Delivery time from batch plant to the project site
Mix with Accelerator	5	Adding Accelerator at the project site
Producing specimens	Less than 10	Pouring and finishing time of actual slab

Table 5-9 shows the recommended time frame determined by an actual slab replacement project. The delivery time may vary according to the location of the batch plant and the project site. Thus it is recommended to accurately estimate the delivery time before producing the concrete mixture in the laboratory. The concrete can also be sampled from the concrete used in the slab replacement project site if the same concrete mix is going to be used in the project to be monitored.

5.7.2 Testing of Fresh Concrete

In order to check the similarity of the laboratory produced concrete to the concrete used in an actual project, slump and air content need to be measured and recorded. The fresh concrete properties of the laboratory produced concrete have to be determined before adding accelerator to simulate the testing of the concrete used at the actual project. When the fresh concrete properties for laboratory produced concrete are within the tolerance as specified by Section 346 of the Florida Department of Transportation Standard Specification for Road and Bridge Construction, the concrete can then be used to generate maturity-strength curves that can be used to predict early-age strength of the in-place concrete.

5.7.3 Instrumenting the Concrete Specimens

Two of the concrete specimens are to be instrumented with temperature sensors to record temperature at a frequency of once every 10 minutes. To prevent the temperature sensors from being moved during pouring and vibrating of concrete, they should be fixed at the middle of the cylinder molds with low temperature conductivity wires so that accurate temperature recording can be achieved.

5.7.4 Curing of the Concrete Specimens

All the concrete specimens are to be cured in cylindrical molds. The cylindrical molds are to be covered during the entire time and stored together in the same location. These specimens should not be placed into a water curing tank for curing. The concrete specimens are to be taken out of the cylinder molds right before the time when they are tested for compressive strength. This is done to reduce damage to the concrete specimens at early age.

5.7.5 Testing of Concrete Specimens

A minimum of twelve 4″×8″ cylindrical specimens are tested for compressive strength at four different testing times around the estimated time when the concrete is expected to have a compressive strength of 2,200 psi. These four curing times can be 3, 5, 7 and 9 hours, but can be adjusted depending on the type of concrete mix and the curing temperature used. Three replicate specimens are to be tested per curing time.

5.7.6 Development of Maturity-Strength Relationship for the Concrete

The temperature history of the concrete specimens as recorded by the sensors in the two concrete specimens are to be downloaded to a computer and used to compute the equivalent ages of the concrete at the various times when the concrete specimens are tested. Since the concrete temperature of the high early age concrete during the curing time should not drop below 73˚F, an activation energy of 33,500 J/mol can be used for the calculation of equivalent age.

The compressive strength versus equivalent age data for the tested concrete are to be plotted to develop a relationship between compressive strength and equivalent age of the concrete. Both modified hyperbolic and exponential modeling functions can be used for developing the maturity-strength curve. From the developed maturity-strength curve, the equivalent age of the concrete when compressive strength will be 2,200 psi can be determined.

CHAPTER 6
FIELD STUDY

6.1 Testing Plan for Field Study

6.1.1 Overview

The main purpose of the field study is to evaluate the effectiveness and reliability of the proposed maturity method for prediction of concrete strength at early age for slab replacement application. The proposed testing protocol was applied to multiple actual slab replacement projects in Florida. The field developed maturity-strength curve was compared to the laboratory developed maturity-strength curve for validation of the strength prediction. In addition, recorded temperature histories at the different locations of the actual concrete slab were used to calculate the equivalent age and to predict strengths of the in-place concrete at different locations in the slab. Figure 6-1 shows the exact locations and dates of the field studies performed in the Jacksonville area.

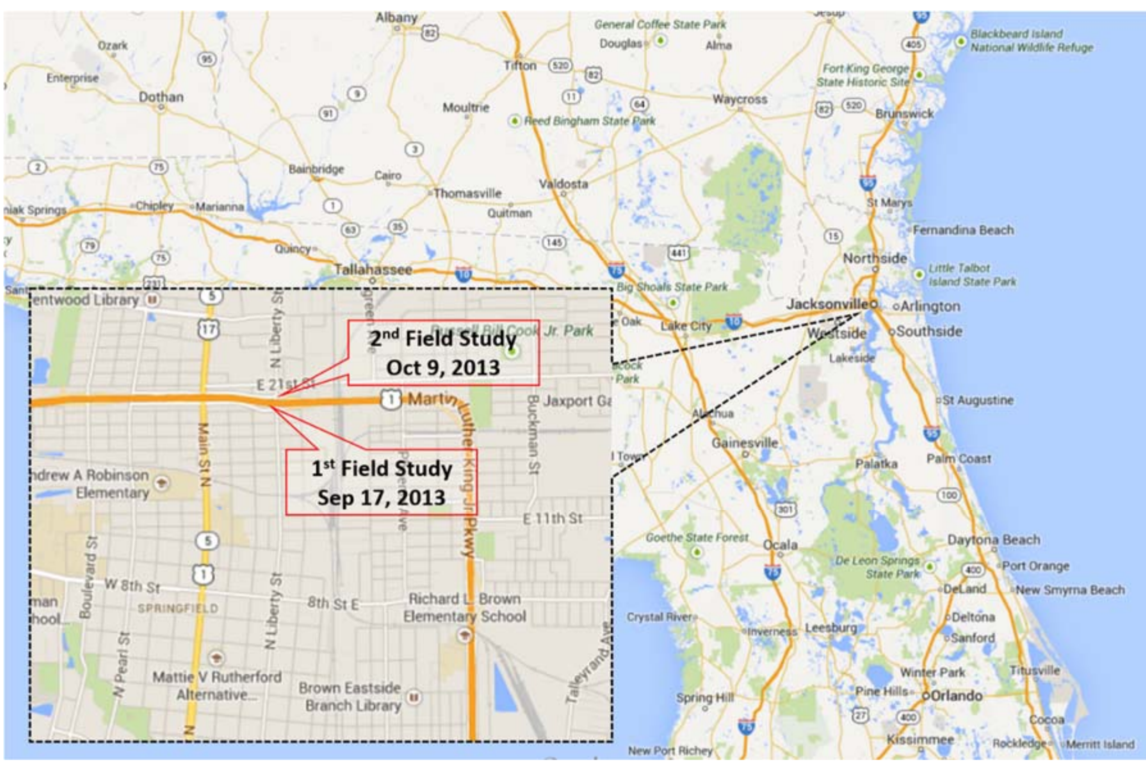


Figure 6-1. Locations and dates of the field studies performed.

Table 6-1 shows the mix design of the concrete used for the replaced concrete slab for the field studies and laboratory produced concrete.

Table 6-1. Mix Design Used for Both First and Second Field Studies

Name	Product Name	Quantity/yd³ of Concrete	Specification
Cement	Type I/II Cement	850 lb	AASHTO M85 - Type I/II
Coarse Aggregate	#57 Stone	1,600 lb	
Fine Aggregate	Silica Sand	1,101 lb	
Air Ent. Admixture	Darex AEA	7.5 oz	AASHTO M 154 - AEA
Type D Admixture	WRDA 60	17.0 oz	AASHTO M 194 - Type D
Type F Admixture	Adva 120	29.8 oz	AASHTO M 194 - Type F
Type E Admixture	Daracel	448.0 oz	AASHTO M 194 - Type E
Water	Water	31.2 ga	

6.1.2 Temperature Measurements from the Instrumented Slabs

For each field study, 4 temperature sensors were installed after preparation of the base material and before concrete was poured. Figure 6-2 shows the installations of temperature sensors at the center, corner, longitudinal edge, and transverse edge of the slab and Figure 6-3 shows a close-up picture of the installed temperature sensors at the corner and the transverse edge of the slab. For accurate temperature measurement, plastic spikes that have relatively low heat conductivity were used to fix the temperature sensors. The temperature data from the temperature sensors were downloaded to a laptop computer on the following day and used to predict compressive strength with the previously developed maturity-strength curve. Comparison was made between the predicted strength of the actual slab at the four different locations and the measured strength of the field cured specimens on the replacement slab, namely the “protection specimens”, in order to evaluate the reliability of protection specimens which are assumed to present the strength of the concrete in the actual slab. The temperature sensors were programmed to record the concrete temperature every 10 minutes.

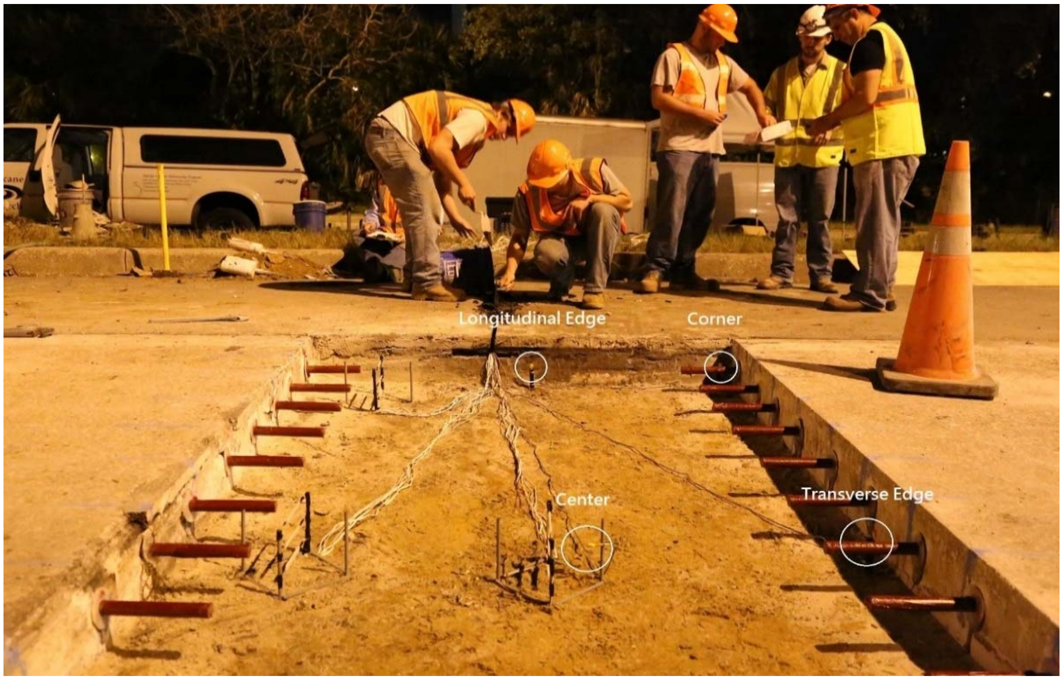


Figure 6-2. Installed temperature sensors at four different locations in the slab.

Figure 6-3. Installed temperature sensors at the corner and edge of the slab.

6.2 The First Field Study

6.2.1 Overview

The first field study was performed on Sepembar 17, 2013, at US-1 Alt S Exit to Liberty St., Jacksonville, as shown in Figure 6-1. Two different batches of the ready-mix concrete were used at the project site.

The ready-mix concrete used for the monitored concrete slab, which was the fifth replacement slab placed on that night, was used to produce specimens at the project site and cured in the insulated curing box as shown in Figure 6-4. This concrete is referred to as the "project concrete" here. The temperature history of the specimens was recorded, and the compressive strength was tested at multiple curing times to develop a field-generated maturity-strength curve. Also, the temperature histories of the monitored slab at four different locations were recorded to evaluate the strength differences at different locations of the concrete slab. Figure 6-5 shows a drawing of the exact locations of the four temperature sensors.

The other ready-mix concrete for the last replaced concrete slab, namely "protection concrete", was used to produce the protection specimens which were used for evaluating the strength of the in-place concrete. The protection specimens were cured on the replaced concrete slab with curing blanket (Burlene) covering. The temperature history of the protection specimens was also recorded to calculate their equivalent age to develop maturity-strength relationships using the actual strengths of the protection concrete specimens tested by the contractor.

Figure 6-4. Curing of the specimens produced from the slab concrete.

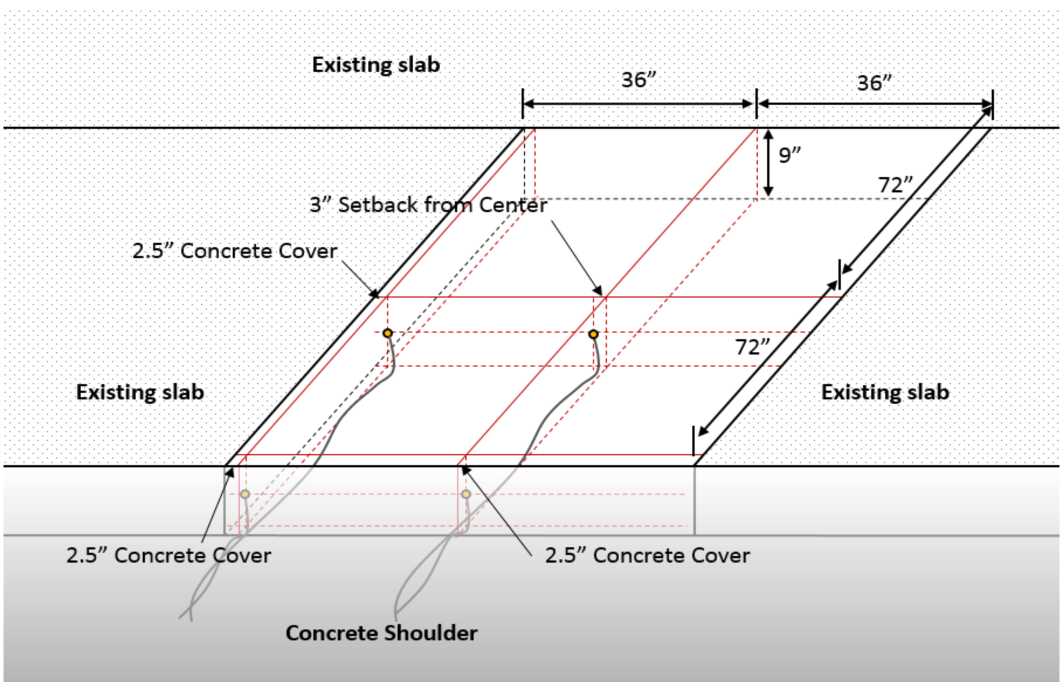


Figure 6-5. Drawing showing the exact locations of the installed temperature sensors.

The laboratory produced concrete, namely “laboratory concrete”, was used to produce specimens in the laboratory. These laboratory specimens were cured under ambient laboratory temperature without stripping the cylinder molds as recommended in the proposed testing protocol. The temperature history of the specimens was recorded and the compressive strength was determined at multiple curing times to generate the laboratory-generated maturity-strength. The generated maturity-strength curves and maturity-strength plots were compared to each other to validate the accuracy of the maturity-strength prediction under different curing conditions. In addition, the predicted strength at four different locations of the monitored replaced concrete slab was compared to the measured strength of the protection specimens.

6.2.2 Development of Maturity-Strength Curves

In order to validate the strength prediction of the maturity method with application of the proposed testing protocol, multiple maturity-strength relationships were generated under different curing conditions and compared to each other. The time for placing concrete at the project site and the time for producing specimens in the laboratory were proposed to be the starting point of the curing time because temperature history could be recorded from those points. However, the prior elapsed time after addition of accelerator but before concrete placement is also very important and should be included in the maturity method. Thus, all elapsed times for preparation activities of the concrete were recorded to calibrate the generated maturity-strength curve.

6.2.2.1 Laboratory-generated maturity-strength curve

To develop the maturity-strength relationship for the replacement slab concrete in the laboratory, twelve 4″×8″ cylindrical specimens for testing compressive strength and two 4″×8″ cylindrical specimens for recording temperature history were produced with the same concrete mix design used in the field studies (Table 6-1). All specimens were cured in the 73 to 80˚F ambient curing room without stripping the cylinder molds. Compressive strength tests for the twelve specimens were performed at curing times of 2 hours 50 minutes, 5 hours 3 minutes, 6 hours 52 minutes, and 8 hours 42 minutes. The temperature sensors in two temperature-recording specimens were programmed to record the concrete temperature every 10 minutes and the Arrhenius maturity function was used with an activation energy of 33,500 J/mol to calculate equivalent age. The activation energy is applicable when the concrete temperature does not drop below 73˚F during curing of the concrete.

6.2.2.2 Field-generated maturity-strength curve

To develop a field generated maturity-strength curve for the first field study, ten 4″×8″ cylindrical specimens for testing compressive strength and two 4″×8″ cylindrical specimens for recording temperature history had been produced from the project concrete at the project site.

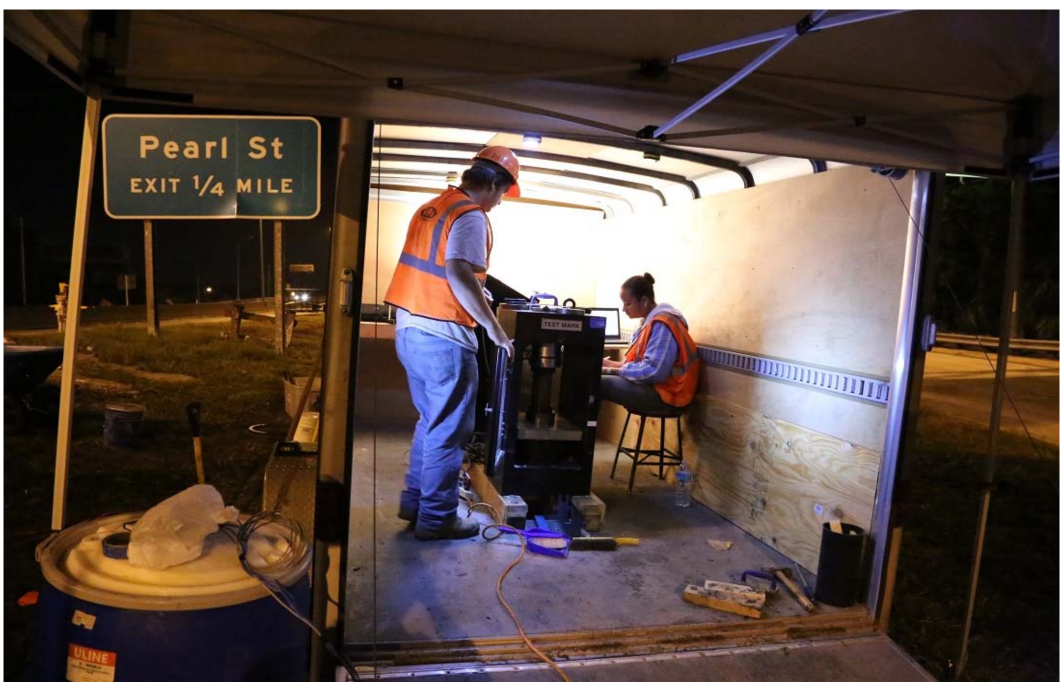


Figure 6-6. Compressive strength test on project concrete specimens.

As shown in Figure 6-4, all the field-produced specimens were cured in the insulated curing box. Compressive strength of these specimens were measured at five different curing times of 1 hour 30 minutes, 1 hour 57 minutes, 2 hours 53 minutes, 4 hours 4 minute, and 6 hours by using a portable compressive strength tester as shown in Figure 6-6. Similarly, temperature sensors in the two temperature specimens were programmed to record the concrete temperature every 10 minutes and the Arrhenius maturity function with an activation energy of 33,500 J/mol was applied to calculate the equivalent ages at the various curing times.

6.2.2.3 Maturity-strength plots of protection specimens

For the first field study, an additional maturity-strength relationship was made by recording the temperature history of the protection specimens. Two 4″×8″ cylindrical specimens for recording temperature history were made from the protection concrete and placed near the protection specimens made by the contractor. The protection specimens were cured by placing them on the newly placed concrete slab with curing blanket (Burlene) covering. Since the contractor measured the compressive strength of the protection specimens at only two different curing times, namely 3 hours 47 minutes and 3 hours 55 minutes, the maturity-strength curve could not be generated, but only two maturity-strength points were determined. Similarly, temperature sensors in two temperature-monitoring specimens were programmed to record the concrete temperature every 10 minutes and the Arrhenius maturity function with an activation energy of 33,500 J/mol was applied to calculate the equivalent age.

6.2.3 Validation of Maturity-Strength Prediction

Three different maturity-strength relationships (slab concrete maturity-strength curve, laboratory concrete maturity-strength curve, and maturity-strength plots of protection specimens) were compared to one another to validate the accuracy of the maturity-strength prediction. As explained previously, all maturity-strength relationships were developed under different curing conditions. Thus, if the three maturity-strength relationships are similar to one another, it can validate the postulation that different curing conditions do not alter the maturity-strength prediction and the maturity method could give a reliable early-age strength prediction for concrete used in slab replacement projects.

Two 4″×8″ cylindrical specimens were used to record temperature histories for each batch of concrete and the average temperature values from the temperature histories were used to calculate equivalent ages. Figure 6-7 shows the recorded temperature histories for the three batches of concrete used in the first field study.

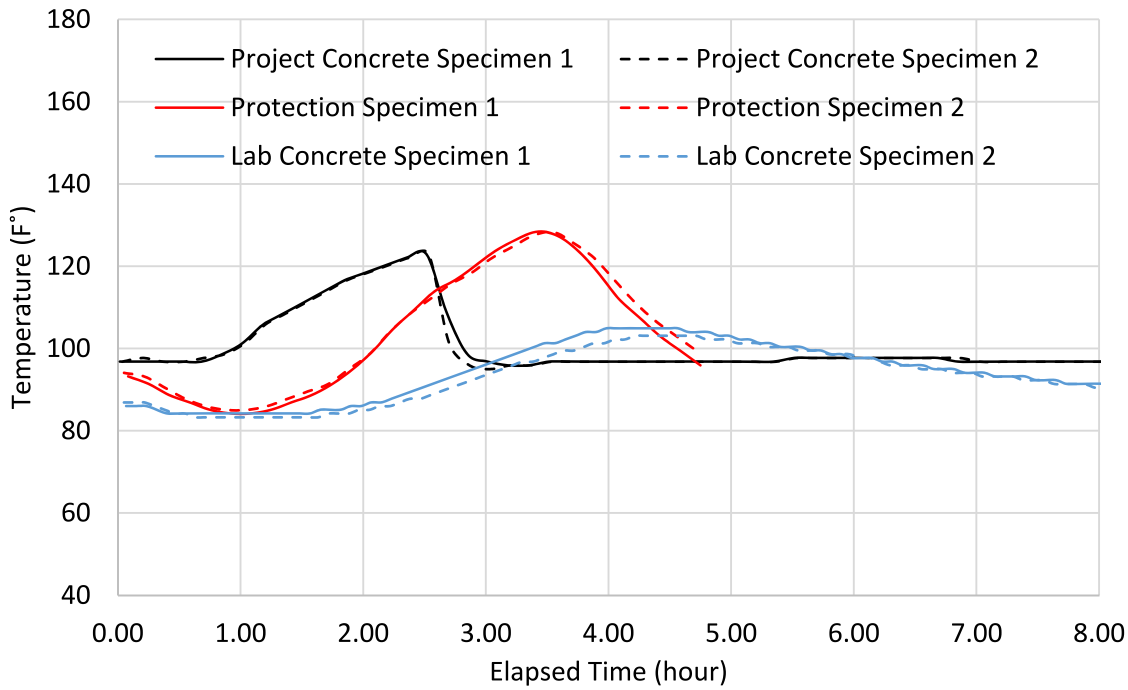


Figure 6-7. Recorded temperature histories for the specimens produced by different batches of concrete.

Table 6-2 shows the strength test results and calculated equivalent ages for the specimens produced from the three different batches of concrete and curing conditions. The specimens produced from the project concrete were cured in the insulated curing tank without temperature control and the specimens produced from the protection concrete were cured on the replacement slab with curing blanket covering. Lastly, the concrete specimens produced from the laboratory concrete were cured under ambient laboratory temperature without stripping cylinder molds.

Since the curing conditions were different, the concrete specimens produced by the same mix design had totally different strength and equivalent ages at the similar elapsed curing time. The time of concrete placement was used as the starting point of the curing time in the calculation of the equivalent ages.

Table 6-2. Compressive Strength Test Results and Corresponding Equivalent Ages for the Three Batches of Concrete

Specimens Produced by the Project Concrete			
Elapsed Curing Time	Compressive Strength (psi)	Equivalent Age	Curing Condition
1 hour 30 minutes	249	2 hours 58 minutes	Cured in the ~~water filled~~ curing box without temperature control
1 hour 57 minutes	687	4 hours 12 minutes	
2 hours 53 minutes	1,934	6 hours 35 minutes	
4 hours 4 minutes	2,420	8 hours 40 minutes	
6 hours	3,526	12 hours 8 minutes	
11 hours 32 minutes	6,203	22 hours 7 minutes	
Specimens Produced by the Protection Concrete			
Elapsed Curing Time	Compressive Strength (psi)	Equivalent Age	Curing Condition
3 hours 47 minutes	2,210	8 hours 7 minutes	Cured on the replacement slab with curing blanket covering
3 hours 55 minutes	2,300	8 hours 20 minutes	
Specimens Produced by the Laboratory Concrete			
Elapsed Curing Time	Compressive Strength (psi)	Equivalent Age	Curing Condition
2 hours 50 minutes	295	3 hours 46 minutes	Cured under ambient laboratory temperature without stripping of their cylinder molds
5 hours 3 minutes	2,168	8 hours 4 minutes	
6 hours 52 minutes	3,224	11 hours 35 minutes	
8 hours 42 minutes	3,854	14 hours 28 minutes	

Table 6-3 shows the best-fit regression equations for the generated maturity-strength relationships. Since the specimens produced from the protection concrete do not have enough strength data for generating maturity-strength curve, only two maturity-strength curves for the other two batches of concrete were generated. MATLAB® program was used to calculate the best-fit maturity-strength curves with a modified exponential function which was recommended by ASTM C 1074. The maturity-strength curves were determined by the program by minimizing the sum of squared errors (SSE). As can be seen from Table 6-3, both maturity-strength curves had a good correlation between the actual strength and the calculated equivalent age with R-square values higher than 0.99.

Table 6-3. Results of Regression Analyses for Two Maturity-Strength Relationships with Modified Exponential Function

Project Concrete Maturity-Strength Curve	Laboratory Concrete Maturity-Strength Curve
$f(x) = a \times \exp(-(b/x)^{c})$	$f(x) = a \times \exp(-(b/x)^{c})$
a = 7,046	a = 6,097
b = 8.848	b = 8.436
c = 1.097	c = 1.449
SSE: 4,092	SSE: 102.2
R-square: 0.9942	R-square: 1
Adjusted R-square: 0.9883	Adjusted R-square: 1
RMSE: 143	RMSE: 10.1

Figure 6-8 shows the comparison of the developed maturity-strength curves and plots for the three different batches of concrete. It can be seen that the maturity-strength curve generated by the project concrete has approximately 7 % higher strength at the critical strength range of 2,000 to 2,500 psi than the other two batches of concrete. On the other hand, the other two batches of concrete, namely the protection concrete and laboratory concrete, have identical maturity-strength plots at the critical strength range of 2,000 to 2,500 psi.

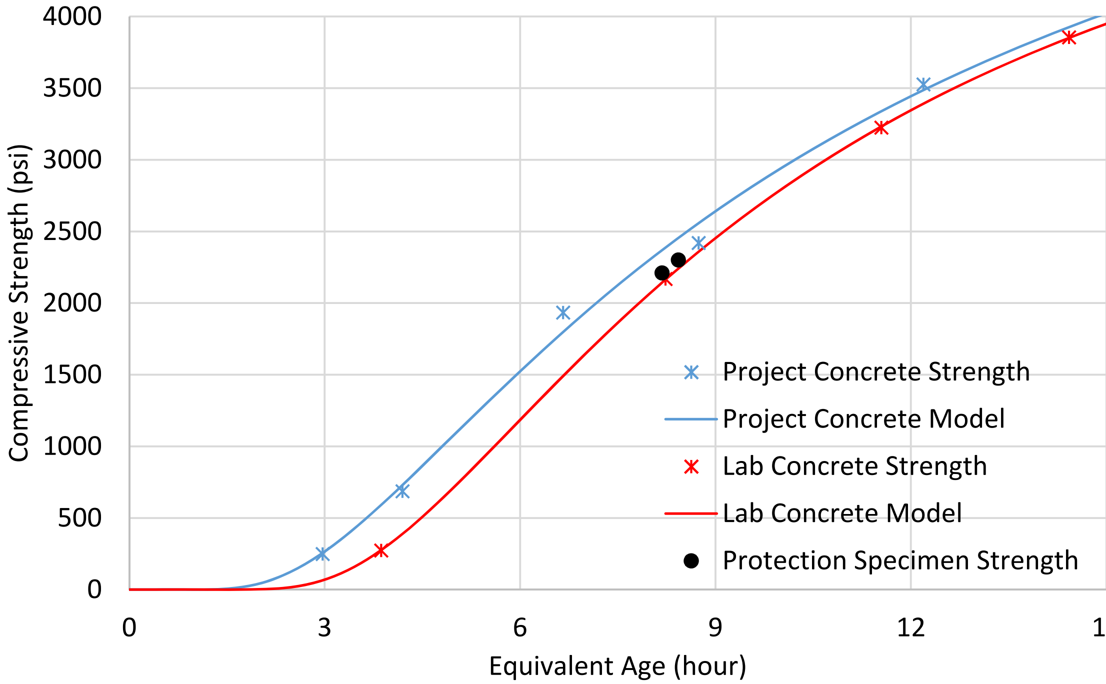


Figure 6-8. Developed maturity-strength curves from different batches of concrete before waiting time adjustment.

Table 6-4 shows the recorded times for the preparation of concrete batches at the project site and laboratory. As shown in Table 6-4, the project concrete had waited for more than 20 minutes after addition of accelerator before it was placed in the concrete slab due to the sudden heavy rain at the project site. This longer waiting time allowed more time for hydration of cement before its temperature history was recorded and it possibly could explain the different strength prediction of the maturity-strength curve generated from the project concrete. On the other hand, the preparation of the protection concrete and the preparation of the laboratory concrete had the same time frame. As a result, strength predictions for the protection specimens made from the laboratory-generated maturity-strength curve were very accurate with errors of only 3.0 % and 2.6 %.

Table 6-4. Recorded Times for Preparation of Concrete in the First Field Test

Activity	Project Concrete (Sep. 17, 2013)		Protection Concrete (Sep. 17, 2013)		Activity	Laboratory Concrete (Sep. 26, 2013)	
	Time	Elapsed Time (minute)	Time	Elapsed Time (minute)		Time	Elapsed Time (minute)
Mix Start	10:46 pm	0	11:45 pm	0	Mix Start	1:11 pm	0
Depart from Batch Plant	11:00 pm	14	11:57 pm	12	Slow Mix Start	1:16am	5
Arrive at Project Site	11:15 pm	29	00:08 am	23	Add Accelerator	1:41 am	30
Add Accelerator	11:20 pm	34	00:13 am	28	Producing Specimens	1:50 am	39
Start of Concrete Placement	11:43 pm	57	00:23 am	38			

6.2.4 Comparisons of the Strength Predictions at Different Locations of Concrete Slab

Currently, 4″×8″ cylindrical specimens cured under identical curing condition of the in-place concrete slab are used to estimate strength of the concrete slab in the slab replacement project. However, it is known that different shape and volume of concrete structures can have different effects on the rate of strength development of the concrete. Thus, it cannot be assumed that strength of the protection specimens will accurately represent the actual strength of the in-place concrete.

In this section, the strength of the in-place concrete at different locations in the slab and the strength of the protection specimens were compared to each other to evaluate their strength differences. Due to the delay in the placement of the project concrete, the preparation time difference was added to the curing time for the protection concrete.

Figure 6-9 shows comparison of the temperature-time plots for the in-place concrete at different locations in the slab and for the protection specimens. It can be seen that the in-place concrete at different locations in the slab and the protection specimens have totally different trends of temperature histories, and these differences would indicate different rates of strength development.

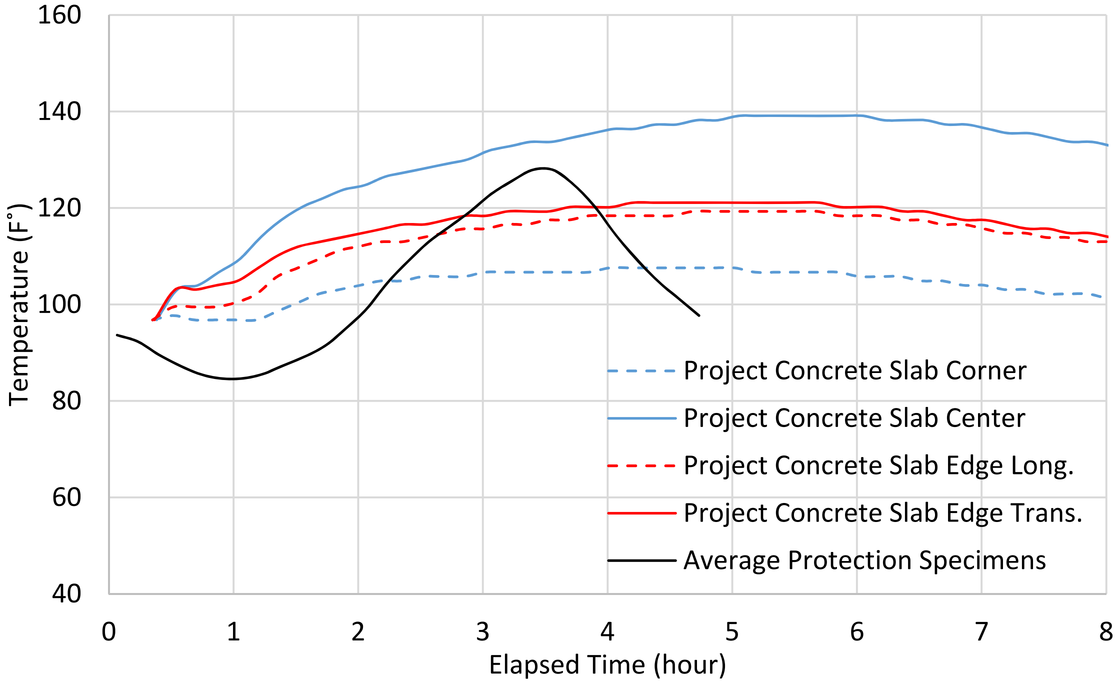


Figure 6-9. Comparison of the temperature-time plots for the concrete at different locations of the slab and the protection specimens.

Figure 6-10 shows the comparison of the predicted strength-time plots for the in-place concrete at different locations in the slab and the protection specimens. Strength predictions for both the in-place concrete and the protection specimens were made from the previously generated maturity-strength curve from the laboratory concrete. Similarly, the curing time adjustments were made in the prediction of strength for the in-place concrete at different locations of the slab. As can be observed in Figure 6-10, the strength of the protection specimens was slightly lower than the lowest strength of the in-place concrete at early age. However, at later than the curing time of around 3 hours, the strength of the protection specimens shows slightly higher strength than the lowest strength of the in-place concrete (at the slab corner). Thus, the replaced concrete slab may be open to traffic when the strength of the concrete at the slab corner may still be less than the required strength value.

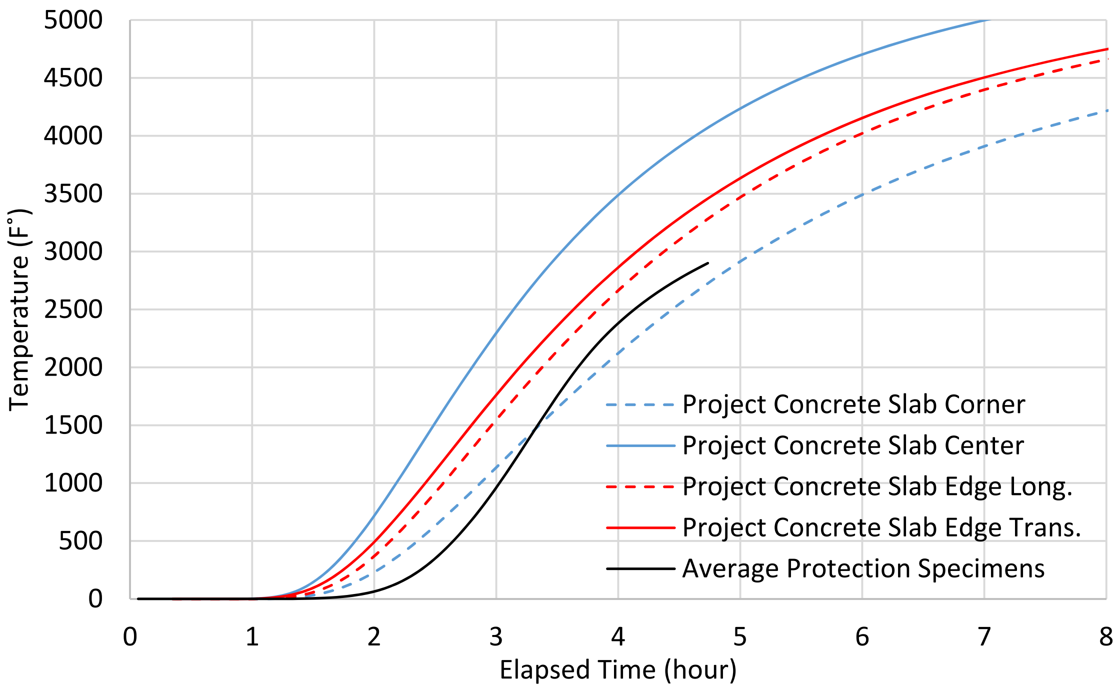


Figure 6-10. Comparison of the predicted strength-time plots for the concrete at different locations of the slab and the protection specimens.

6.2.5 Performance of the Replaced Concrete Slabs in the First Field Study

The project site for the first field study was visited again on January 20, 2014, approximately four months after concrete placement to observe the condition of the replacement slabs. Figure 6-11 shows a picture of the replaced slab, and Figure 6-12 shows a picture of the replaced slab and its neighboring slabs. It can be observed that the replaced slab was in excellent condition with no sign of distress.

Figure 6-11. Picture of the replaced concrete slab in the first field study taken on 1/20/14.

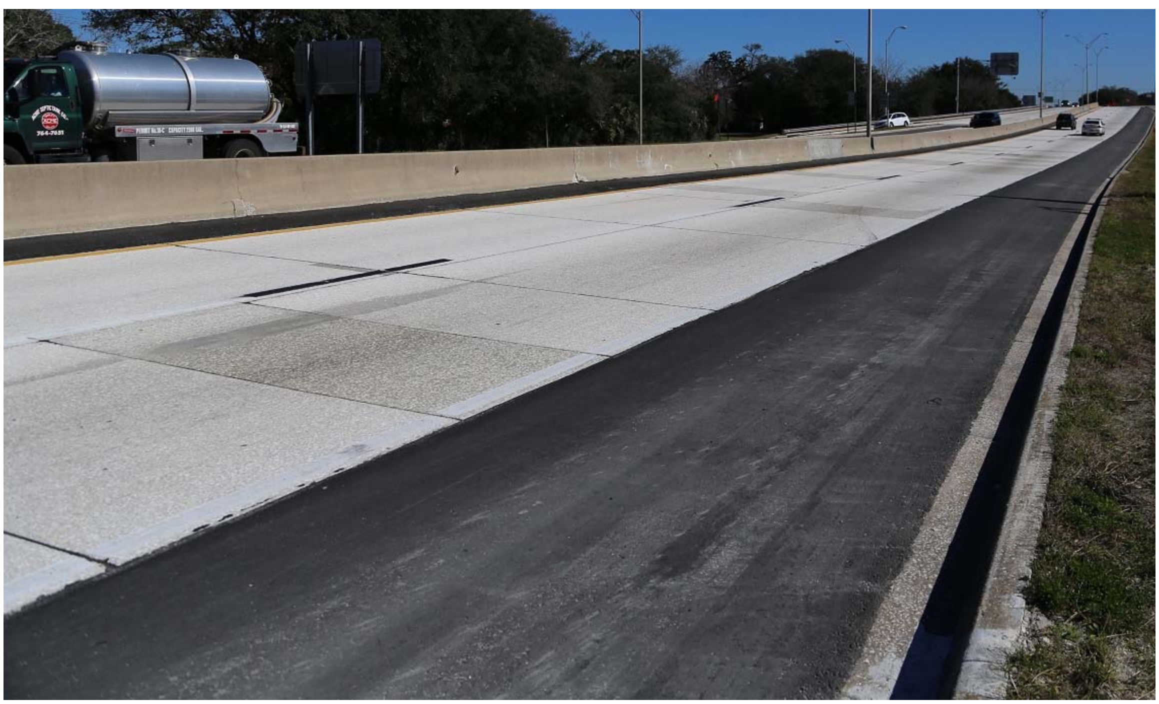


Figure 6-12. Picture of the replaced slab and neighboring slabs in the first field study taken on 1/20/14.

6.3 The Second Field Study

6.3.1 Overview

The second field study was performed on Oct. 9 at US-1 Alt S Exit to Pearl St., Jacksonville as shown in Figure 6-1. As planned, a batch of the ready-mix concrete used for the last concrete slab was used to produce specimens at the project site and cured by placing them on the replaced concrete slab with curing blanket (Burlene) covering to resemble the curing condition of the protection specimens. The temperature history of the specimens was recorded and the compressive strength was determined at multiple curing times to develop the field-generated maturity-strength curve for the second field study. Also, the temperature histories of the in-place concrete at four different locations and the protection specimens were recorded to evaluate the strength differences between the in-place concrete at different locations of the slab and the protection specimens.

Since the batches of concrete used for both the first and second field studies were produced with the same mix design at the same batch plant, the laboratory-generated maturity-strength curve used in the first field study was applied to the second field study as well. Both field and laboratory-generated maturity-strength curves were compared to each other to validate the accuracy of maturity-strength prediction under different curing conditions. In addition, the predicted strength at four different locations of the project concrete slab were compared to the strength of the protection specimens.

6.3.2 Development of Maturity-Strength Curve

To develop a field-generated maturity-strength curve for the second field study, eight 4″×8″ cylindrical specimens for testing compressive strength and two 4″×8″ cylindrical specimens for recording temperature history were produced from the concrete taken at the project site. All field-produced specimens were cured on the newly placed last concrete slab with curing blanket (Burlene) covering. Compressive strengths of these specimens were measured at four different curing times of 2 hours 34 minutes, 3 hours 42 minutes, 5 hours 12 minutes, and 7 hours 29 minutes by using a portable compressive strength tester as shown in Figure 6-6. The temperature sensors in two temperature-monitoring specimens were programmed to record the concrete temperature every 5 minutes and the Arrhenius maturity function with an activation energy of 33,500 J/mol was used to calculate the equivalent ages at the various curing times. Similar to the first field study, the time to start placing concrete on the replacement slab was used as the starting point of the curing time.

6.3.3 Validation of Maturity-Strength Prediction

The field-generated maturity-strength for the second field study was compared to the laboratory maturity-strength used in the first field study to validate the accuracy of the maturity-strength prediction. Since both maturity-strength curves were developed under different curing conditions, if the maturity-strength curves in both cases were very close to one another, it could validate the postulation that different curing conditions would not cause any significant changes on the maturity-strength prediction at early age and the maturity method could give a reliable early-age strength prediction for concrete used in slab replacement projects.

Figure 6-13 shows the recorded temperature histories for the batches used in the second field study. Two 4″×8″ cylindrical specimens were used to record the temperature histories for each batch of concrete and the average value of the temperature histories was used to calculate the corresponding equivalent age.

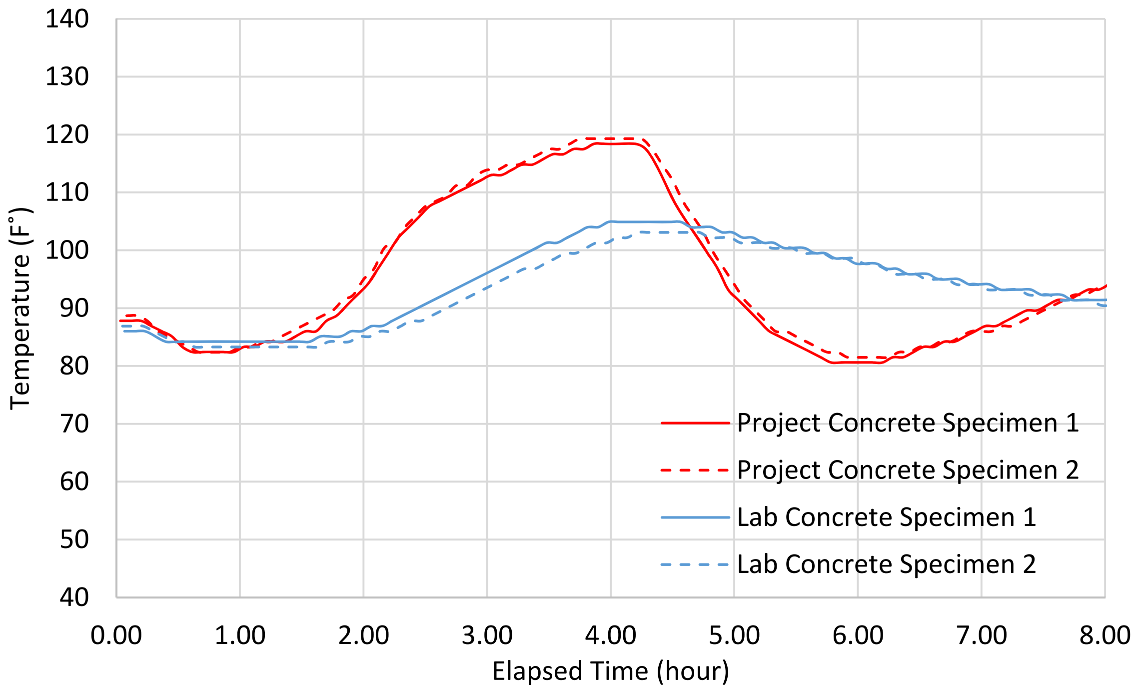


Figure 6-13. Recorded temperature histories for the specimens produced by different batches of concrete.

Table 6-5 shows the strength test results and calculated equivalent ages for the specimens produced from the project concrete and the laboratory concrete. The specimens produced from the project concrete were cured on the replacement slab with curing blanket covering and the concrete specimens produced from laboratory concrete were cured under ambient laboratory temperature without stripping cylinder molds. As shown in Table 6-5, concrete specimens made from the two different batches of concrete had different strength and equivalent ages at the similar elapsed curing time due to the different curing conditions. Similarly, the time of placement for both batches of concrete was used as the starting point of curing time in the calculation of the equivalent ages.

Table 6-5. Compressive Strength Test Results and Corresponding Equivalent Ages for Two Batches of Concrete

Project Concrete			
Elapsed Curing Time	Compressive Strength (psi)	Equivalent Age	Curing Condition
2 hours 34 minutes	481	3 hours 55 minutes	Cured on the replacement slab with curing blanket covering
3 hours 42 minutes	1,599	6 hours 53 minutes	
5 hours 12 minutes	2,963	10 hours 24 minutes	
7 hours 29 minutes	3,911	13 hours 25 minutes	
Laboratory Concrete			
Elapsed Curing Time	Compressive Strength (psi)	Equivalent Age	Curing Condition
2 hours 50 minutes	295	3 hours 46 minutes	Cured under ambient laboratory temperature without stripping of their cylinder molds
5 hours 3 minutes	2,168	8 hours 4 minutes	
6 hours 52 minutes	3,224	11 hours 35 minutes	
8 hours 42 minutes	3,854	14 hours 28 minutes	

Table 6-6 shows the best-fit regression equations for the generated maturity-strength relationships. MATLAB® program was used to calculate the best-fit maturity-strength curves using the modified exponential function which was recommended by ASTM C 1074. The maturity-strength curves were determined by the program by minimizing the sum of squared error (SSE). As can be seen from Table 6-6, the regression equations for both maturity-strength curves compare well to the plots of actual strength versus calculated equivalent age with R-square values higher than 0.99.

Table 6-6. Results of Regression Analysis for Two Maturity-Strength Relationship Using the Modified Exponential Function

Field Maturity-Strength Curve	Laboratory Maturity-Strength Curve
$f(x) = a \times \exp(-(b/x)^c)$	$f(x) = a \times \exp(-(b/x)^c)$
a = 14,020	a = 6,097
b = 18.22	b = 8.436
c = 0.793	c = 1.449
SSE: 514.4	SSE: 102.2
R-square: 0.9999	R-square: 1
Adjusted R-square: 0.9998	Adjusted R-square: 1
RMSE: 22.68	RMSE: 10.11

Figure 6-14 shows the comparison of the developed maturity-strength plots from the project concrete and the laboratory concrete. It can be seen that both batches of concrete have an identical trend at the critical strength range of 2,000 to 2,500 psi.

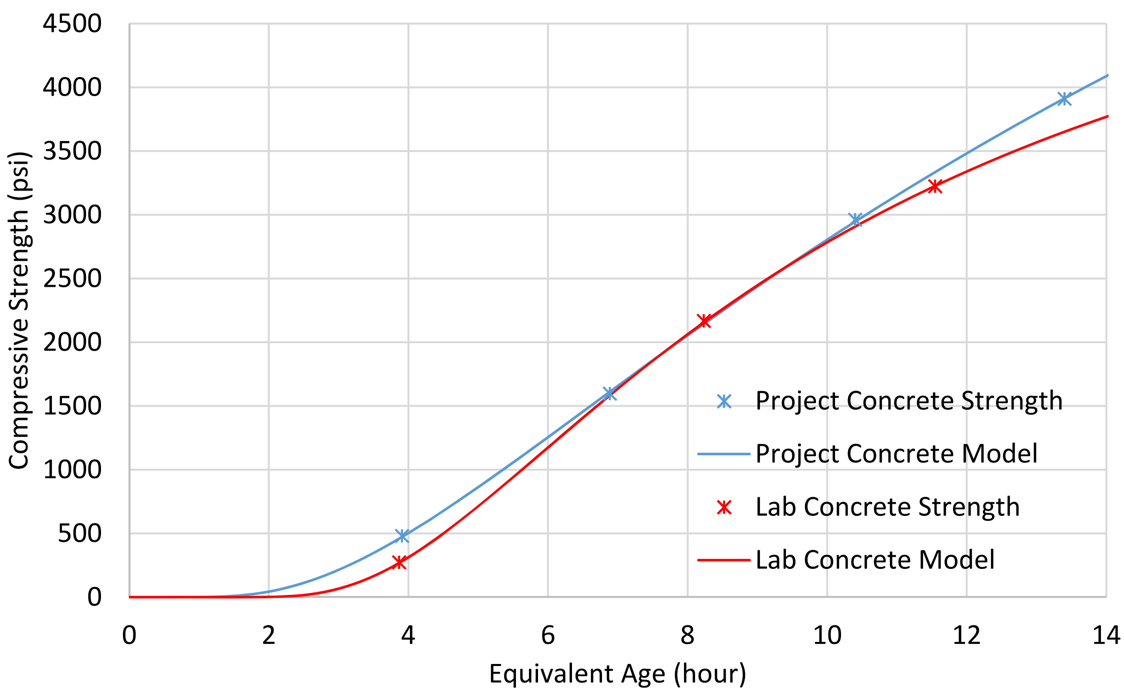


Figure 6-14. Developed maturity-strength plots from different batches of concrete before waiting time adjustment.

Table 6-7 shows the recorded times for the preparation of concrete batches at the project site and in the laboratory. Due to unexpected delay at the project site, the project concrete had waited for nine more minutes than the laboratory concrete before it was placed in the replacement slab. However, the strength prediction made by the project concrete's maturity-strength curve was identical to the strength prediction made by the laboratory maturity-strength curve. This was due to the fact accelerator was not added at the project until six minutes before concrete placement, which was actually three minutes shorter than that for the laboratory concrete mixture. The accelerator increases the rate of cement hydration by up to 20 times ("Set Accelerator", 2012).

Table 6-7. Recorded Time for Preparation of Field and Laboratory Concrete

Project Concrete (Oct. 9 2013)			Laboratory Concrete (Sep. 26 2013)		
Activity	Time	Elapsed Time (minute)	Activity	Time	Elapsed Time (minute)
Mix Start	2:02 am	0	Mix Start	1:11 pm	0
Depart from Batch Plant	2:10 am	8	Slow Mix Start	1:16 pm	5
Arrive at Field	2:25 am	23	Add Accelerator	1:41 pm	30
Add Accelerator	2:44 am	42	Producing Specimens	1:50 pm	39
Concrete Placement	2:50 am	48			

6.3.4 Comparisons of the Strength Predictions at Different Locations of the Concrete Slab

For the second field study, the temperature histories of the concrete in the replacement slab were monitored at four different locations, and the temperature histories of the protection specimens were also monitored. The predicted strengths of the protection specimens and the in-place concrete at four different locations were compared to each other to determine the strength differences.

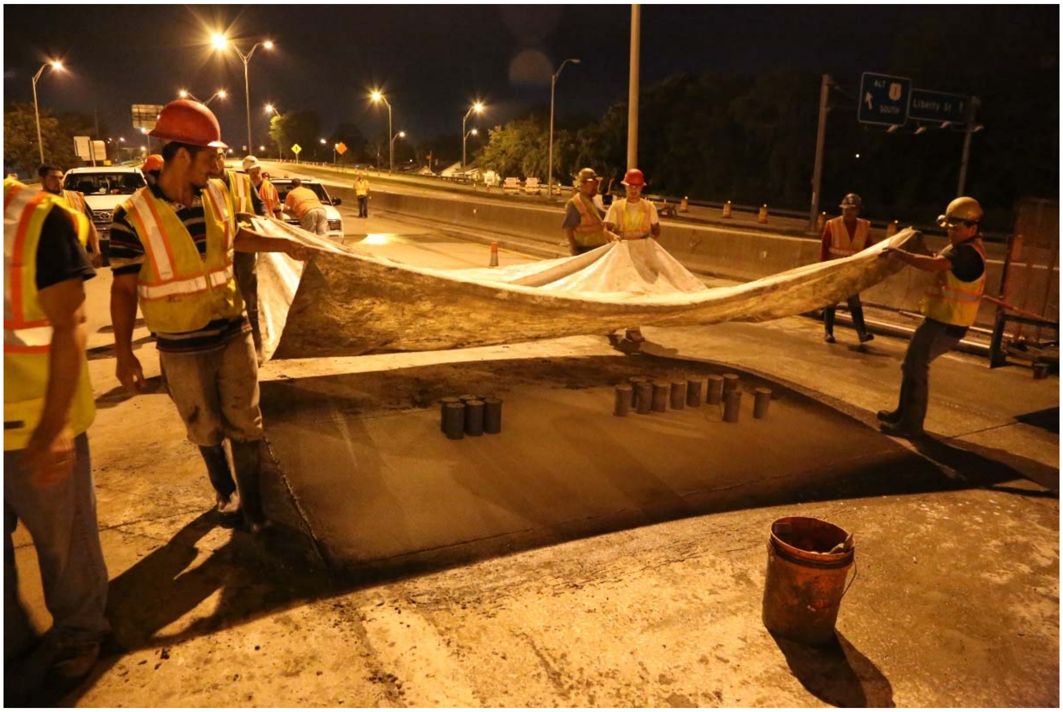


Figure 6-15. Curing of the concrete specimens and the replacement slab.

As shown in Figure 6-15, protection specimens were cured on the replacement concrete slab. The strength of the protection specimens were used to estimate the strength of the replaced concrete slab. Figure 6-16 shows the comparison of the temperature-time plots for the in-place concrete at different locations of the replacement slab and the protection specimens. Though the in-place concrete and the protection specimens seemed to cure under the same curing condition, the in-place concrete at different locations of the concrete slab and the protection specimens have totally different plots of temperature histories. These different temperature histories would result in different rates of strength development.

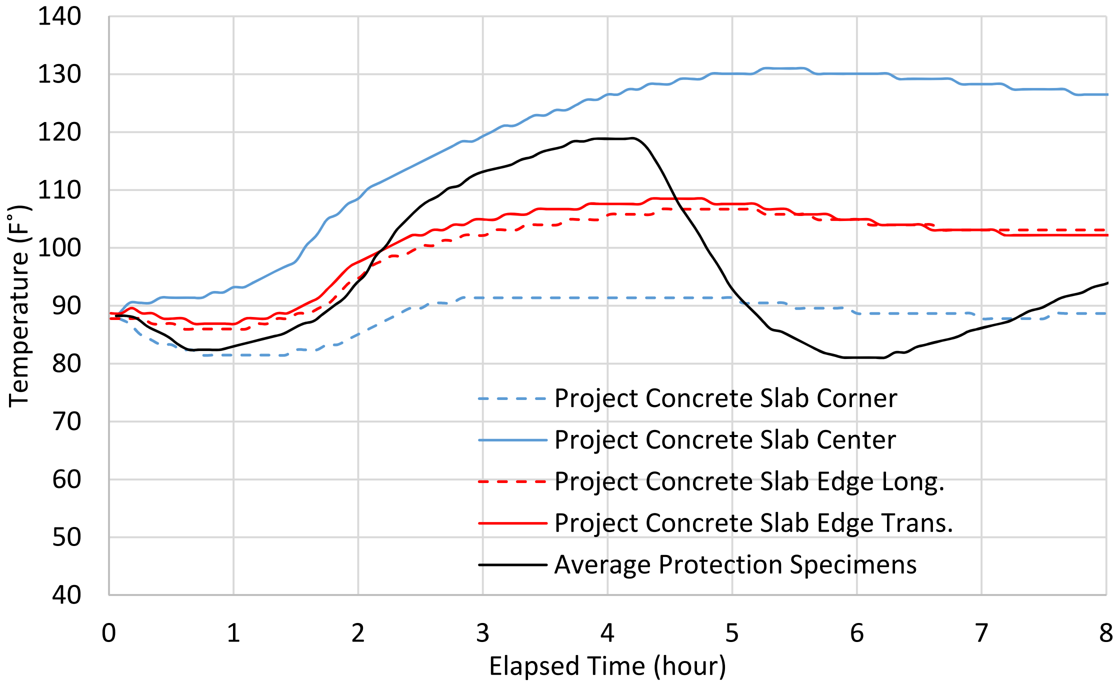


Figure 6-16. Comparison of the temperature-time plots for the concrete at different locations of the slab and the protection specimens.

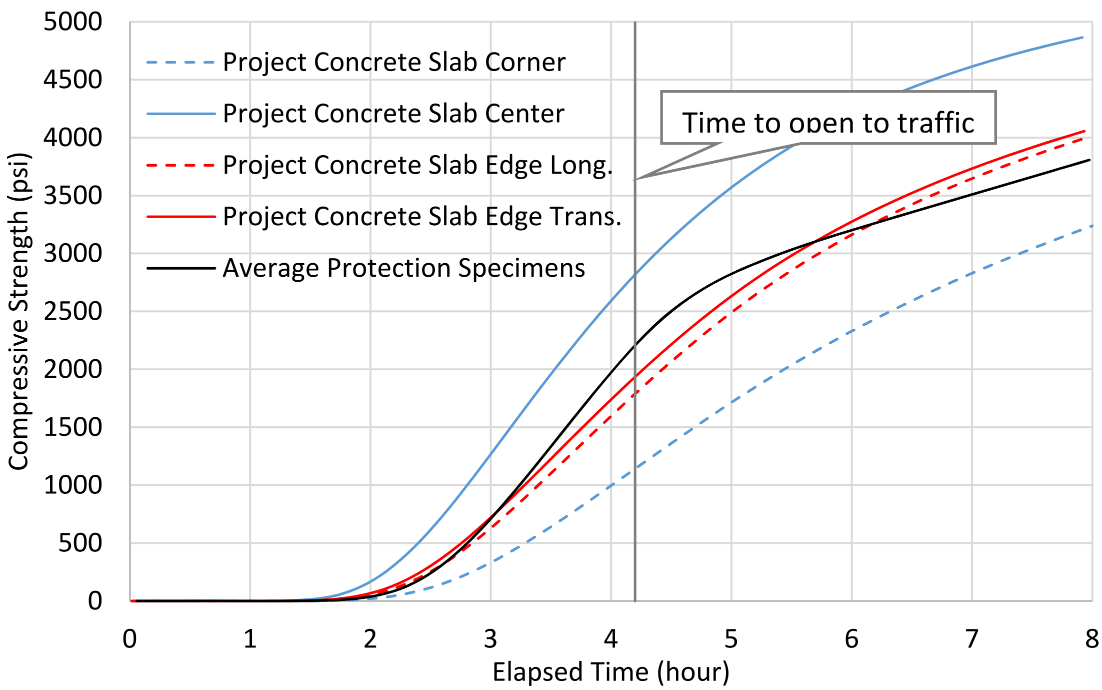


Figure 6-17. Comparison of the predicted strength-time plots for the concrete at different locations of the slab and the protection specimens.

Figure 6-17 shows comparison of the predicted strength-time plots for the concrete at different locations of the replacement slab and the protection specimens. Strength predictions for both the in-place concrete and the protection specimens were made using the maturity-strength curve for the laboratory concrete.

As can be observed in Figure 6-17, the strength of the protection specimens is almost two times the lowest strength of the in-place concrete at early age. At the project site, the contractors had to wait until the time when the protection specimens reached a compressive strength of 2,200 psi before they opened the concrete slab to traffic in accordance with FDOT slab replacement specifications. However, at the time to open to traffic, the strength of the in-place concrete at the slab corner was less than 1,200 psi. Thus, using the strength of the protection specimens as strength determination may result in over-prediction of concrete strength and result in too early opening of the replacement slab to traffic.

6.3.5 Performance of the Replaced Concrete Slabs in the Second Field Study

The project site for the second field study was visited again on January 20, 2014, approximately three and a half months after concrete placement to observe the condition of the replacement slabs. Figure 6-18 shows a picture of the replaced slab, and Figure 6-19 shows a picture of replaced slab and its neighboring slabs. It can be observed that the replaced slab was in excellent condition with no sign of distress.

Figure 6-18. Picture of the replaced concrete slab in the second field study taken on 1/20/14.

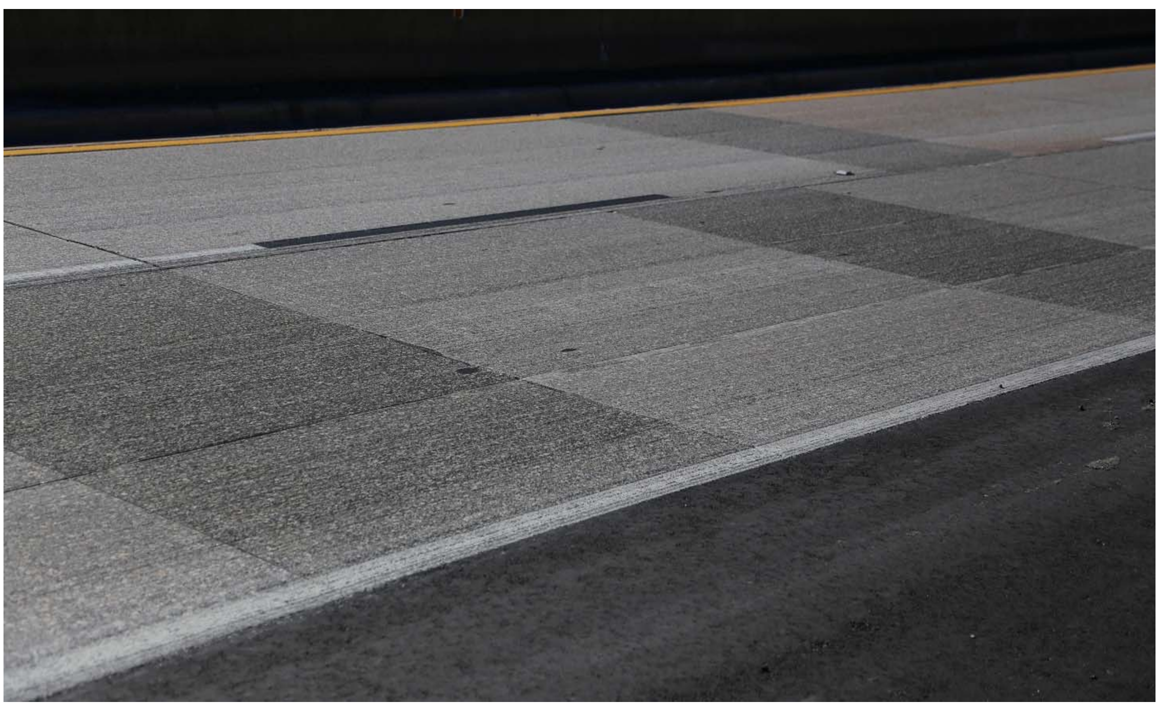


Figure 6-19. Picture of the replaced slab and its neighboring slabs in the second field study taken on 1/20/14.

6.4 Curing Time Adjustment for Maturity-Strength Curve

6.4.1 Overview

To be able to make concrete strength prediction in the field using the maturity method, the maturity-strength curve for the concrete must be available prior to the placement of the concrete in the field. As observed in both field studies, different time frames for preparation of the laboratory and project concrete could result in errors in maturity-strength prediction. Therefore, it is recommended to use an accurately estimated time frame for use in the preparation of the laboratory concrete with considerations of possible factors, including batching and delivery time.

When more or less time has been taken to place concrete at the project site than the estimated time frame which was applied to produce the laboratory concrete, the maturity-strength curve generated from the laboratory concrete would need to be adjusted by adding or subtracting the amount of equivalent age caused by the time difference.

6.4.2 Proposed Curing Time Adjustment

In both field and laboratory studies, a total of three maturity-strength curves were obtained. They were the maturity-strength curves generated from the lab-prepared concrete, the project concrete from the first field study, and the project concrete from the second field study. The batches of concrete used to generate the maturity-strength curves were produced and cured in different environments, and thus, the generated maturity-strength curves can be used to assess the reliability of the maturity-strength prediction. Table 6-8 shows the fresh concrete properties right before adding accelerator. Since three different batches of concrete had very similar fresh concrete properties, the three maturity-strength curves developed by the three batches of concrete could be used for the maturity-strength prediction without making any adjustments for variations in fresh concrete properties.

Table 6-8. Fresh Concrete Properties of the Three Batches of Concrete

Batches of Concrete	1st Field Study Project Concrete (Sep. 17, 2013)	2nd Field Study Project Concrete (Oct. 9 2013)	Laboratory Concrete (Sep. 26, 2013)	Specification (FDOT Mix No. 353-128)
Slump (in)	3.0	2.5	3.5	1.5 - 4.5
Air Content (%)	1.9	N/A	2.1	1.0 – 6.0

Figure 6-20 shows the comparison of the three maturity-strength curves obtained from both field studies. The developed maturity-strength curves were compared to one another and used to predict strength of the protection specimens tested by the contractors for the first field study.

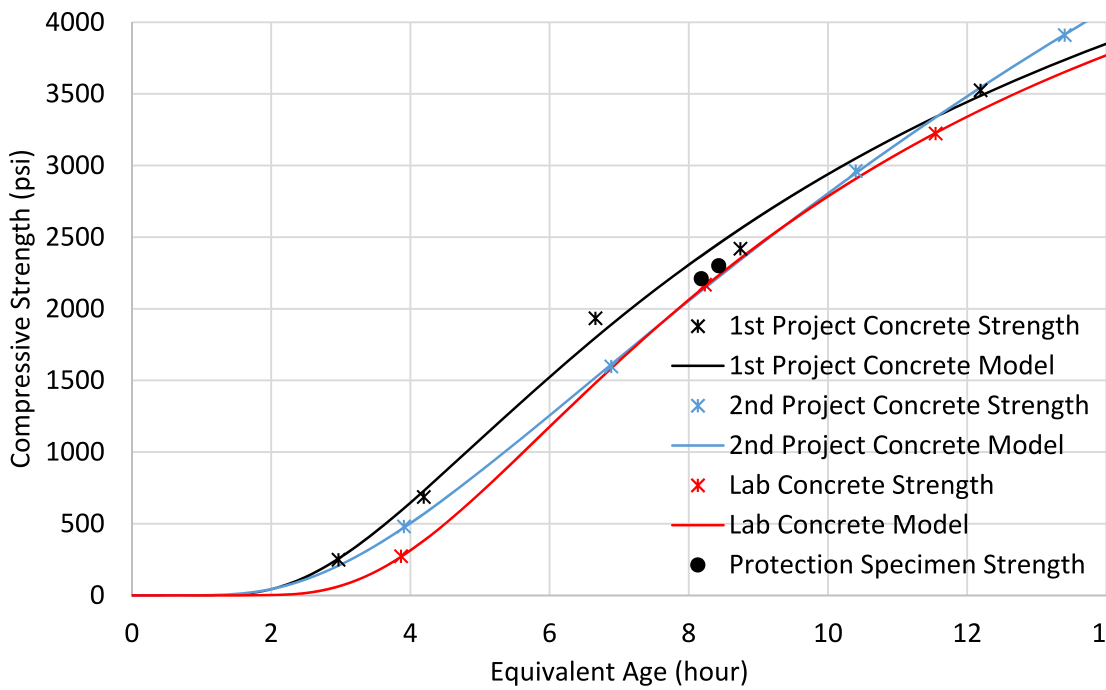


Figure 6-20. Comparison of the different maturity-strength curves and plots of protection specimens.

Maturity-strength predictions for the protection specimens made by using the maturity-strength curve from the laboratory concrete and the maturity-strength curve from the second project concrete appear to give good accuracy with less than 3 % prediction errors. However, the maturity-strength curve from the first project concrete shows more than 6 % errors in its strength prediction.

In general, ready-mix concrete is placed as soon as the concrete mixer truck arrives at the project site. However, as shown in Figure 6-21, the concrete in the first field study had longer waiting time after the addition of accelerator than the other concrete. This longer waiting time allowed more time for hydration of the cement before its temperature history was recorded, and it could explain the bigger error in strength prediction made by the maturity-strength curve from the concrete in the first field study.

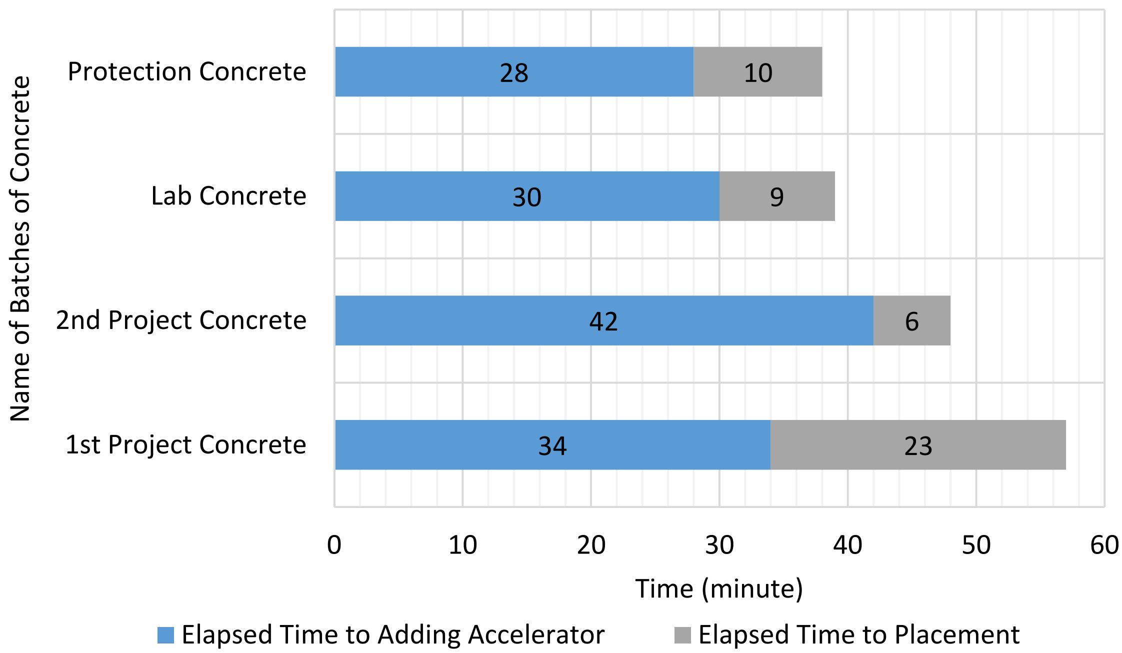


Figure 6-21. Preparation time frames for the different batches of concrete.

On the other hand, more waiting time of the concrete in the second field study seemed not to have any noticeable effect on its maturity-strength prediction. This can be explained by the fact that the hydration rate of the cement without the accelerator is much lower than the hydration rate of the cement with the added accelerator. Thus, it can be postulated that negligible amount of hydration took place in the concrete in the second field study during the additional waiting time since accelerator had not been added yet (“Set Accelerator”, 2012).

To minimize maturity prediction error due to unexpected waiting time at the project site, it is recommended that the waiting time elapsed from the time of addition of accelerator be incorporated as additional curing time in the application of the maturity-strength curve.

Relative to the protection specimen, the time difference from the time of addition of accelerator was +13, -4, and -1 minutes for the first project concrete, second project concrete, and the laboratory concrete, respectively. By adding the time differences to the curing time of the corresponding batches of concrete, maturity-strength curves can be adjusted. For instance, in the case of the first project concrete, the accounted curing time was started 13 minutes later than the protection concrete because of the waiting time difference. This un-accounted curing time was converted to an equivalent age of 23 minutes by applying the initial measurement of the concrete temperature. The converted equivalent age was added to the calculated equivalent ages at the time when the compressive strength tests were performed. Thus, the entire maturity-strength curve generated by the first project concrete was moved 23 minutes to the right side.

Figure 6-22 shows the adjusted maturity-strength curves for the three different batches of concrete (the first project concrete, the second project concrete, and laboratory concrete) after adjustment for the different waiting times. Relative to the protection specimen, the time difference were +13, -4, and -1 minutes for the first project concrete, second project concrete, and the laboratory concrete, respectively. These time differences were converted to the equivalent ages of 23, -6 and -1 minutes, and added to the equivalent ages of their maturity-strength curves.

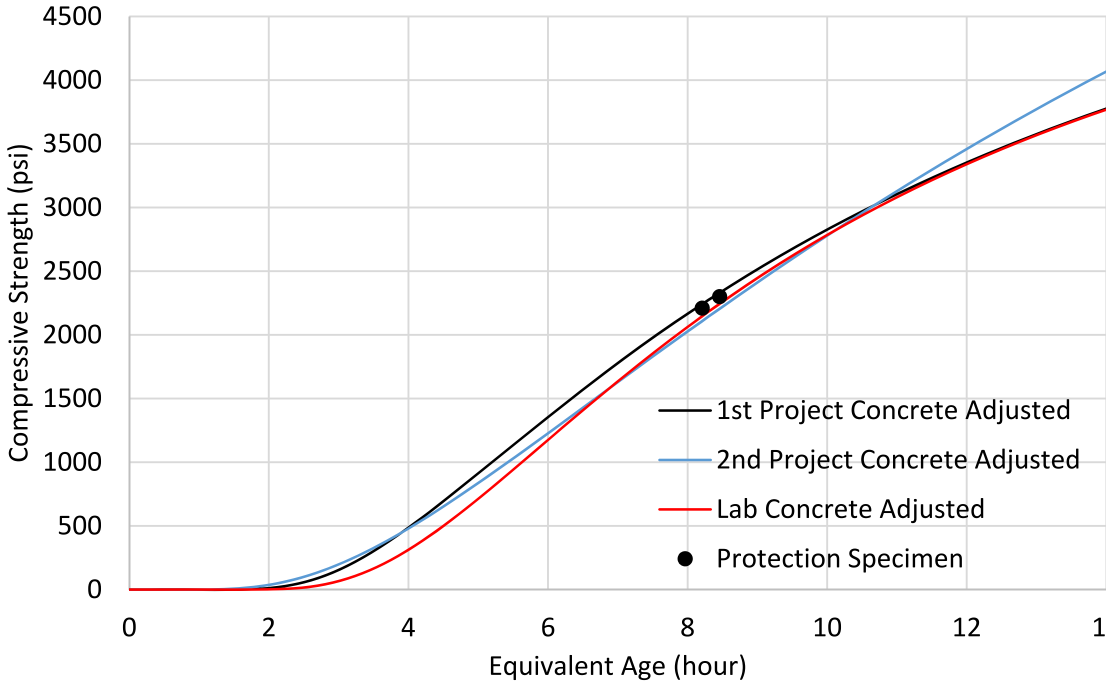


Figure 6-22. Comparison of developed maturity-strength curves and plots obtained from both field studies after adjustment of different waiting times.

From Figure 6-22, it can be observed that all the adjusted maturity-strength curves predict strength of the protection specimens well with lower than 3 % error.

Table 6-9. Maturity-Strength Predictions Made by Different Maturity-Strength Curves

	1st Field Maturity-Strength Curve		2nd Field Maturity-Strength Curve		Laboratory Maturity-Strength Curve	
	Strength (psi)	Prediction Error (%)	Strength (psi)	Prediction Error (%)	Strength (psi)	Prediction Error (%)
Without Time Adjustment	2,369	7.20	2,124	3.89	2,143	3.03
	2,455	6.74	2,222	3.39	2,241	2.57
With Time Adjustment	2,232	1.00	2,102	4.89	2,135	3.39
	2,321	0.91	2,195	4.57	2,234	2.87

Table 6-9 shows the comparison of the accuracy of strength predictions for the protection specimens having strengths of 2,210 and 2,300 psi at the curing times of three hours 47minutes and three hours 52 minutes, respectively, made by different maturity-strength curves with and without curing time adjustment. It can be seen that the accuracy of the strength predictions made by the 1st field maturity-strength curve with curing time adjustment was remarkably improved with prediction errors of 1 % and 0.91 %, as compared with the strength predictions made by the 1st field maturity-strength curve without curing time adjustment. On the other hand, the accuracy of the strength predictions made by the 2nd field maturity-strength curve with curing time adjustment was slightly decreased because the second project concrete had more waiting time prior to the time of addition of accelerator which was not considered in the recommended time adjustment due to its relatively slow hydration rate than those of the concrete with addition of accelerator. No remarkable change was observed for strength prediction made by the laboratory maturity-strength curve.

Though the proposed curing time adjustment did not consider the elapsed time prior to the addition of accelerator, it made a remarkable reduction of the prediction error for the 1st field maturity-strength curve. Also, all strength predictions made by the adjusted maturity-strength curves had a very reliable accuracy with prediction errors of less than 5 % at the critical strength range of 2,000 to 2,500 psi.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Findings

7.1.1 The First Set of Laboratory Experiments

The main objectives of the first set of laboratory experiments were to evaluate the effectiveness of four different concrete maturity measuring systems, namely Humboldt, Command Center, Intelli-Rock, and COMA meter, under various curing temperatures and to select the most appropriate one to be used in the maturity-strength prediction. Also, the differences between the results from 6″×12″ specimens and those from 4″×8″ specimens were evaluated to determine the most effective specimen size to be used for the rest of the study.

The main findings from the first set of experiments in this study are summarized as follows:

- The Intelli-Rock and Command Center temperature sensors appeared to show the greatest accuracy with little or no detectable error. The Humboldt maturity meter appeared to give an error of 2 to 4˚F.
- The Command Center temperature sensor had a resolution of 1˚F, while the Intelli-Rock temperature sensors and Humboldt maturity meter had a resolution of 2˚F.
- The Intelli-Rock temperature sensors appeared to have a longer reaction time (delay time) than the Command Center temperature sensor and Humboldt maturity meter.
- The Intelli-Rock temperature sensors were relatively larger in size than the Command Center temperature sensor and Humboldt maturity meter, and the embedded Intelli-Rock temperature sensors had a negative effect on strength of the concrete specimens.
- Other temperature sensors were relatively small as compared to the concrete specimens. So, the strength of the concrete specimens was not significantly affected by the other embedded temperature sensors.
- The Intelli-Rock temperature sensors needed to be pre-set at the factory for their frequency of temperature reading, while the Command Center temperature sensors could be set by the user conveniently.

- The Intelli-Rock and Command Center temperature sensors were more convenient to use in the field than the Humboldt maturity meter, since the temperature sensors did not need to be connected to the maturity meter continuously during the test.

- The COMA meter was very easy and convenient to use. However, it had to be read manually and provided only measurements in equivalent age of concrete using a fixed reference temperature of 20˚C and a fixed activation energy of 40,000 J/mol.

- The temperature of the 6″×12″ specimens were 10 to 12˚F higher than those of the 4″×8″ specimens at the peak point.

- The 4″×8″ specimens reached the highest temperature approximately 1 hour earlier than the 6″×12″ specimens, for the concrete mixes used in this study.

- The different trends of the temperature histories for both size of specimens caused different trends of the maturity-time plots, but there was no difference detected in the generated maturity-strength relationships.

Based on the consideration of accuracy, resolution, response time, and convenience of use, it was decided to use the Command Center maturity system for measuring the temperature history of the concrete, and to use 4″×8″ concrete specimens for maturity-strength calibration in the second set of experiments and field studies.

7.1.2 The Second Set of Laboratory Experiments

The main objectives of the second set of experiments were to evaluate the possible effects of different placement and curing environments on the predicted strength of concrete from the maturity method and to determine the most appropriate procedure to be used to obtain accurate predicted strength of concrete. Two maturity functions, namely the Nurse-Saul and Arrhenius maturity functions, were evaluated. The effects of variation of fresh concrete properties on the predicted strength of the concrete were also evaluated to achieve the goal of the second set of experiments.

The Arrhenius maturity function with an activation energy of 33,500 J/mol was chosen to be used for maturity-strength prediction because it showed consistent maturity-strength relationships developed by various groups of specimens cured under various curing conditions.

It was also found that different curing conditions did not have any significant effect on the Arrhenius maturity-strength relationships at early age while variation in fresh concrete properties could have substantial effects on the maturity-strength relationships. Based on the results of laboratory experiments, ASTM C143, and ASTM C231 specifications, it is recommended that when the actual concrete used at the project site has different water-cement ratio, or fresh concrete properties differing by more than ±1 inch in slump and/or ±1 % in air contents from those of the concrete used in developing the maturity-strength relationship, the developed maturity-strength relationship should not be used to make maturity-strength prediction.

Based on the test results, observations, and experience gained from the second set of experiments, the testing protocol for the generation of maturity-strength curves for prediction of early-age compressive strength of concrete used in slab replacement projects are summarized as follows:

- The laboratory concrete mixtures which are to be used to develop maturity-strength curves have to be produced using the same mix design and the same time frame to simulate the concrete to be used in an actual project.
- The fresh concrete properties of the laboratory produced concrete have to be determined before the addition of accelerating admixture to simulate the testing of the concrete at the actual project.
- Two of the concrete specimens made are to be instrumented with temperature sensors to record temperature at a frequency of once every 5 minutes.
- All the concrete specimens made are to be cured in cylindrical molds during the entire curing time at the same location. These specimens are to be taken out of the molds just right before they are tested for compressive strength.
- A minimum of twelve $4'' \times 8''$ cylindrical specimens are tested for compressive strength at four different testing times around the estimated time when the concrete is expected to have a compressive strength of 2,200 psi. Three specimens are to be tested at each testing time.
- Arrhenius maturity function with activation energy of 33,500 J/mol is recommended to be used to calculate equivalent age. Either the hyperbolic function or the exponential

function can be used curve-fit the maturity strength data to develop the maturity-strength curve.

7.1.3 Field Study

The main objective of the field study was to evaluate the effectiveness and reliability of the proposed maturity method for prediction of concrete strength at early age for slab replacement applications. The maturity-strength curves developed from the field-sampled concrete were compared to the maturity-strength curve developed from the laboratory-prepared concrete to see how close the laboratory concrete can simulate the project concrete. Also, the predicted strength of the in-place concrete at different locations of the replacement slab was compared to the actual strength of the protection specimens to evaluate the reliability of using the strength of 4″×8″ cylindrical specimens as the estimated strength of the concrete in the slab.

The results of the field study indicate that the maturity-strength prediction showed great accuracy when the same concrete preparation time was applied for both concrete batches, namely the concrete batch used to develop the maturity-strength curve and the other batch used in the replacement slab. When it took more or less time from the time of addition of accelerator to place the concrete at the project site than the estimated preparation time applied to the concrete batch used to develop the maturity-strength relationship, it is recommended to adjust the maturity-strength relationships by adding or subtracting the amount of maturity index (equivalent age) caused by the time difference.

In both field studies, the protection specimens showed higher strength than the strength of the concrete at the slab corner at the time to open the slab to traffic. Using the strength of the protection specimens as strength determination is unreliable and may result in over-prediction of the strength of the in-place concrete. This could result in opening the replacement slab to traffic before the strength requirement was met.

7.2 Conclusions

Using the strength of the protection specimens as strength determination of the in-place concrete is unreliable and may result in over-prediction of its strength. The maturity method using the Arrhenius maturity function was found to be quite reliable and convenient for use in predicting the early-age compressive strength of concrete in replacement slab applications. Some limitations of maturity-strength prediction such as the strength loss due to high curing temperatures and insufficient moisture supply were observed in the laboratory studies in this research project. However, these limitations were observed at the later age of the concrete when the compressive strength reached around 3,000 to 3,500 psi, and thus the observed limitations did not have any negative effect on the early-age-strength prediction of the concrete in the replacement slab.

7.3 Recommendations

Based on the test results, observations, and experience gained from the laboratory experiments and field studies, the maturity method using the Arrhenius maturity function and using the monitored temperature of the in-place concrete at the mid edge of the concrete slab is recommended for use to estimate the early-age compressive strength of concrete in slab replacement applications. In the event that there is extra waiting time before the concrete is placed, the maturity-strength curve which is used to make strength predictions must be adjusted for the extra waiting time. However, this recommended adjustment in the maturity-strength curve is applicable only when the delay does not cause any problem in the proper placement of the concrete.

In the event that differences in fresh concrete properties, with more than ±1 inch in slump and ±1 % in air contents, are observed between the actual concrete used at the project site and the concrete which has been used to develop the maturity-strength curve, the maturity-strength curve should not be used to make strength predictions without proper adjustment of the predicted strengths due to the effects of the variations in the fresh concrete properties. However, if the developed maturity curve is to be used to make maturity-strength prediction, it is recommended that an additional 200 psi be added to the target compressive strength of the in-place concrete for every 1% increase in air content or for every 1 inch increase in slump of the fresh concrete. The adjusted target strength of the concrete would then be used to determine the adjusted required equivalent age of the in-place concrete before opening to traffic.

It is recommended that a follow-up laboratory study be conducted to establish the appropriate adjustments to the maturity-strength curves to account for the effects of variations of fresh concrete slump, air content, and water-cement ratio, so that the maturity method could be effectively used for determination of the strength of in-place for these various conditions.

LIST OF REFERENCES

Alawode, O. and Idowu, O. I. (2011). "Effects of Water-Cement Ratios on the Compressive Strength and Workability of Concrete and Lateritic Concrete Mixes." *The Pacific Journal of Science and Technology*, 12(2), 99-105.

Alexander, K. M. and Taplin, J. H. (1962). "Concrete Strength, Paste Strength, Cement Hydration, and the Maturity Rule." *Australian Journal of Applied Science*, 13, 277-284.

ASTM Standard C1064M (2012). "Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete." *ASTM International*, DOI: 10.1520/C1064_C1064M-12, West Conshohocken, PA.

ASTM Standard C1074 (2004). "Standard Practice for Estimating Concrete Strength by the Maturity Method." *ASTM International*, DOI: 10.1520/C1074-04, West Conshohocken, PA.

ASTM Standard C138M (2010). "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete." *ASTM International*, DOI: 10.1520/C0138_C0138M-10a, West Conshohocken, PA.

ASTM Standard C143M (2012). "Standard Test Method for Slump of Hydraulic-Cement Concrete." *ASTM International*, DOI: 10.1520/C0143_C0143M-12, West Conshohocken, PA.

ASTM Standard C231M (2012). "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method." *ASTM International*, DOI: 10.1520/C0231_C0231M-12, West Conshohocken, PA.

ASTM Standard C191 (2008). "Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle." *ASTM International*, DOI: 10.1520/C0191-08, West Conshohocken, PA.

ASTM Standard C31M (2003). "Standard Practice for Making and Curing Concrete Test Specimens in the Field." *ASTM International*, DOI: 10.1520/C0031_C0031M-03, West Conshohocken, PA.

ASTM Standard C39M (2005). "Standard Practice for Compressive Strength of Cylindrical Concrete Specimens." *ASTM International*, DOI: 10.1520/C0039_C0039M-05, West Conshohocken, PA.

Bagheri-Zadeh, S., Kim, H., Hounsell, S., Wood, C. R., Soleymani, H., and King, M. (2007). "Field Study of Concrete Maturity Methodology in Cold Weather." *Journal of Construction Engineering and Management*, 133(11), 827-835.

California Department of Transportation (CADOT). (2004). "Slab Replacement Guideline."

Carino, N. J. and Malhotra, V. M. (1991). "The Maturity Method." *Handbook on Nondestructive Testing of Concrete,* 2nd Ed., CRC Press: Boca Raton, FL., 101-146.

Carino, N. J., Lew, H. S., and Volz, C. K. (1983). "Early Age Temperature Effects on Concrete Strength Prediction by the Maturity Method." *ACI Journal*, 80(2), 93-101.

Cordon, W.A. (1946). "Entrained Air-A Factor in the Design of Concrete Mixes." *Materials Laboratories Rep. No. C-310*, Research and Geology Division, Bureau of Reclamation, Denver, CO.

Florida Department of Transportation (FDOT). (2010). "Standard Specifications for Road and Bridge Construction." Gainesville, FL.

Freiesleben-Hansen, P. and Pedersen, E. J. (1977). "Maturity Computer for Controlled Curing and Hardening of Concrete." *Journal of the Nordic Concrete Federation*, 1, 21-25.

Gonnerman, H.F. and Shuman, E. C. (1928). "Flexure and Tension Tests of Plain Concrete." *Report of the Director of Research*. Portland Cement Assn, Skokie, IL., 149-163.

Guo, C. (1989). "Maturity of Concrete: Method for Predicting Early-Stage Strength." *ACI Materials Journal*, 86(4), 341-353.

McIntosh, J. D. (1949). "Electrical Curing of Concrete." *Magazine of Concrete Research,* 1(1), 21-28.

Mindess, S., Young, J. F., and Darwin, D. (2003). *Concrete*, 2nd Ed., Pearson Education, Inc., Upper Saddle River, NJ.

Mohsen, J. P., Roach, B. L., and Kessinger, D. T. (2004). "Maturity Method Applied to Highway Construction." *Transportation Research Record: Journal of the Transportation Research Board*, 1900, National Research Council, National Academy Press, Washington, D. C., 79-85.

Nixon, M. N. (2006). "Evaluation of the Maturity Method to Estimate Concrete Strength in Field Application." Master thesis, Auburn University, Auburn, AL.

Nixon, J. M., Schindler A. K., Barnes, R. W., and Wade, S. A. (2008). "Evaluation of the Maturity Method to Estimate Concrete Strength." *Research Report for ALDOT, Contact No. 930-590*, Auburn University, Auburn, AL.

Nurse, R. W. (1949). "Steam Curing of Concrete." *Magazine of Concrete Research*, 1(2), 79-88.

Rastrup, E. (1954). "Heat of Hydration in Concrete." *Magazine of Concrete Research*, 6(17), 79-92.

Saul, A. G. A. (1951). "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure." *Magazine of Concrete Research*, Mar., 127-140.

"Set Accelerator." (2012). <http://www.targetproducts.com/UserContent/SpecSheets/setacc.pdf> (Oct. 23, 2013).

Soutsos, M. N., Bungey, J. H., and Long, A. E. (2000). "In-Situ Strength Assessment of Concrete -The European Concrete Frame Building Project." *Proc., 5th Int. Conf.,* NDT in Civil Engineering, T. Uomoto ed. Tokyo: Elsevier Science, 583-592.

Struble, L., and Hawkins, P. (1994). *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, 4th Ed., Fredericksburg, VA, 449-461.

Tank, R. C. and Carino, N. J. (1991). "Rate Constant Functions for Strength Development of Concrete." *ACI Material Journal*, 88(1), 74-83.

Tepke, D. and Tikalsky, P. J. (2007). "Concrete Maturity Progress: Survey of Departments of Transportation." *Transportation Research record*, 1775, Transportation Research Board, Washington, D. C., 125-132.

Tia, M. and Manakhoon, K. (2008). "Evaluation of Early Strength Requirement of Concrete for Slab Replacement Using APT – Phase II." *Research Report for FDOT, Contract No. D099558*, University of Florida, Gainesville, FL.

Van Dam, T. J., Peterson, K. R., Sutter, L. L., Panguluri, A., Sytsma, J., Buch, N., Kowli, R., and Desaraju, P. (2005). "Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation." *NCHRP Report 540*, Transportation Research Board, Washington, D.C.

Wade, S. S., Schindler S. K., Barnes, R. W., and Nixon, J. M. (2006). "Evaluation of the Maturity Method to Estimate Concrete Strength." *Research Report for ALDOT, Contact No. 930-590*, Auburn University, Auburn, AL.

Wade, S. (2005). "Evaluation of the Maturity Method to Estimate Concrete Strength." Master thesis, Auburn University, Auburn, AL.

"Florida." (2013). <http://en.wikipedia.org/wiki/Florida> (Sep. 25, 2013).

Wilson, M. L. and Kosmatka, S. H. (2011). *Design and Control of Concrete Mixtures*, 15th Ed., Portland Cement Assn, Skokie, IL.

APPENDIX A
TEST RESULTS ON THE MIX #2 IN THE FIRST SET OF EXPERIMENTS

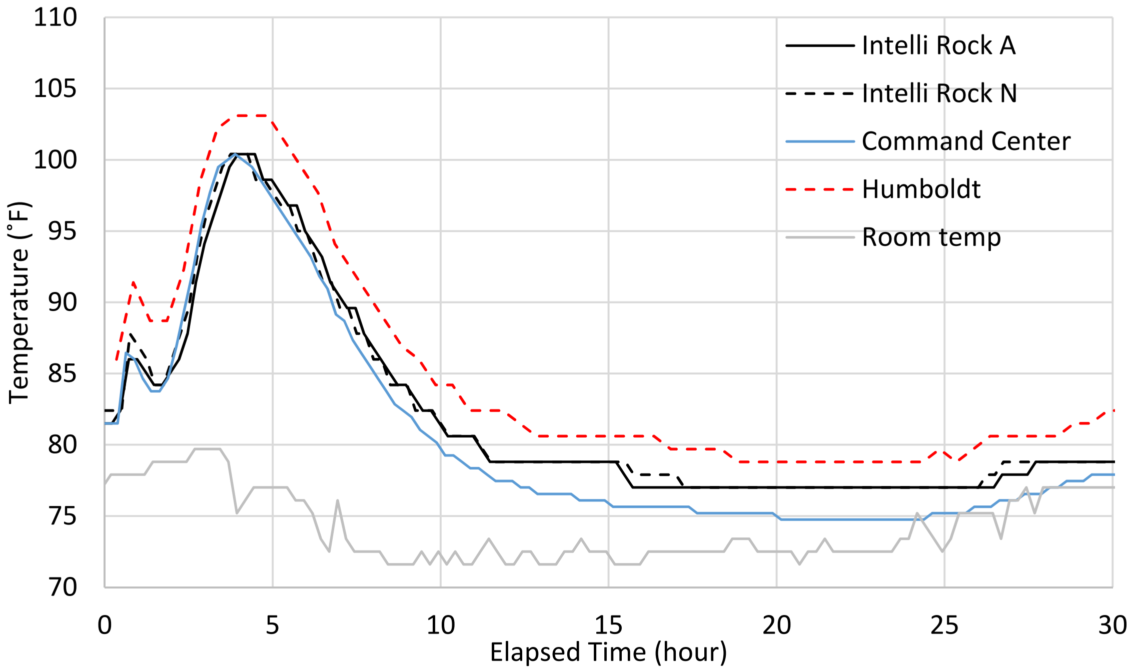


Figure A-1. Temperature-time plots of 4”×8” concrete specimens cured under ambient laboratory condition.

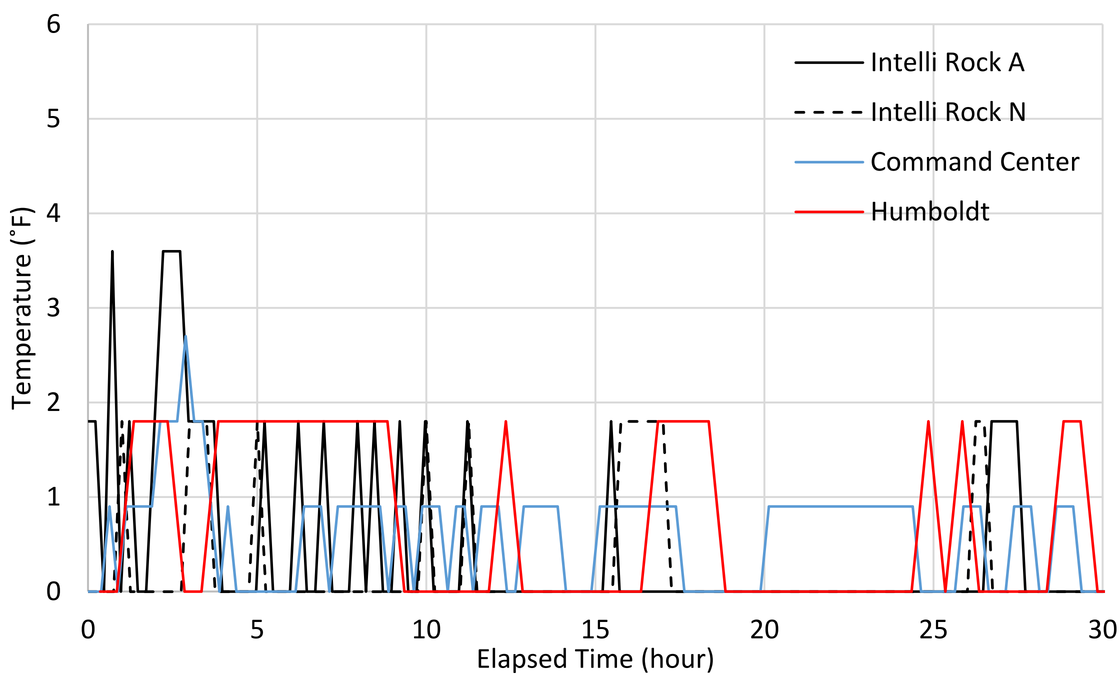


Figure A-2. Variations of temperature measurements from same temperature sensors cured under ambient laboratory condition.

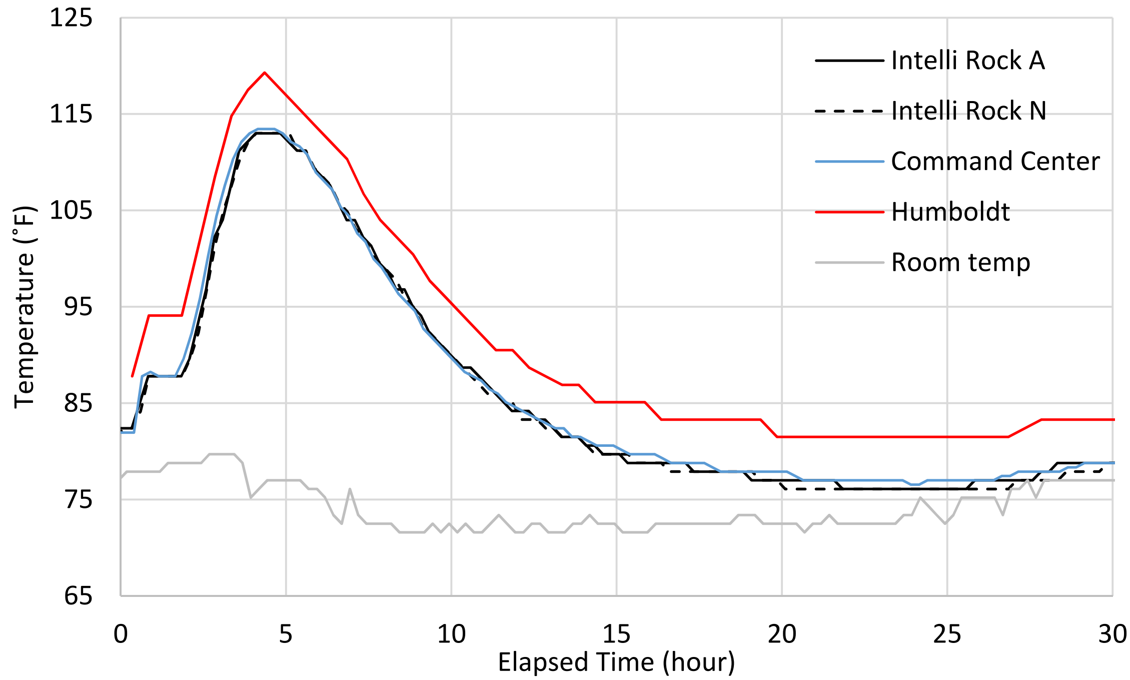


Figure A-3. Temperature-time plots of 6”×12” concrete specimens cured under ambient laboratory condition.

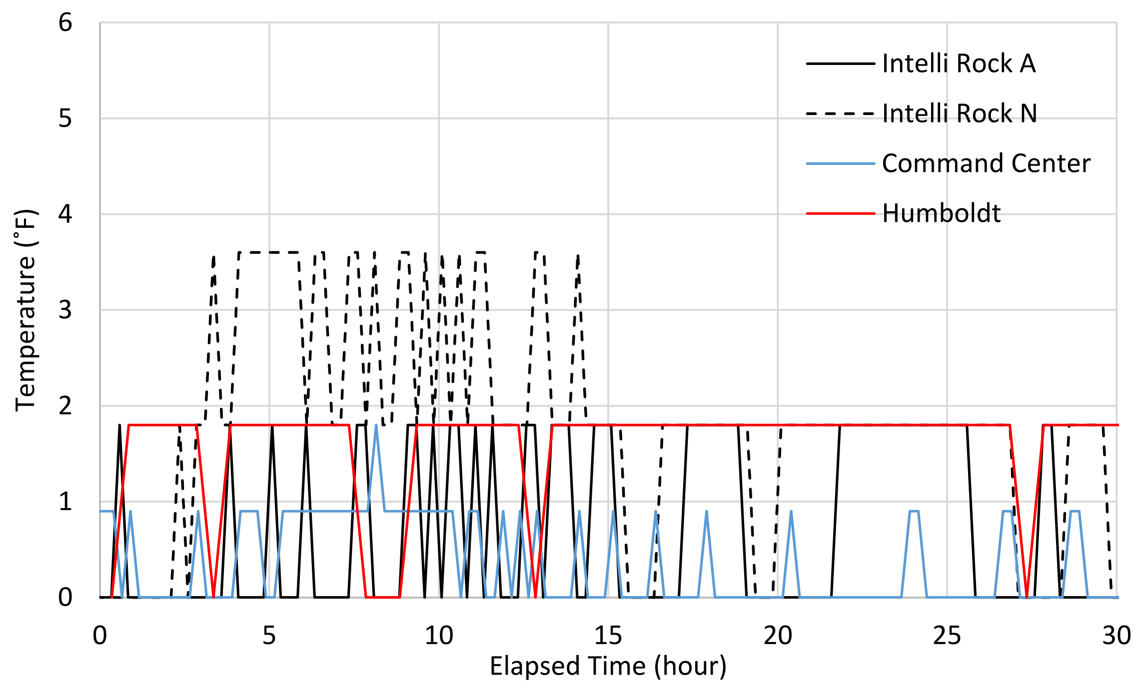


Figure A-4. Variations of temperature measurements from same temperature sensors cured under ambient laboratory condition.

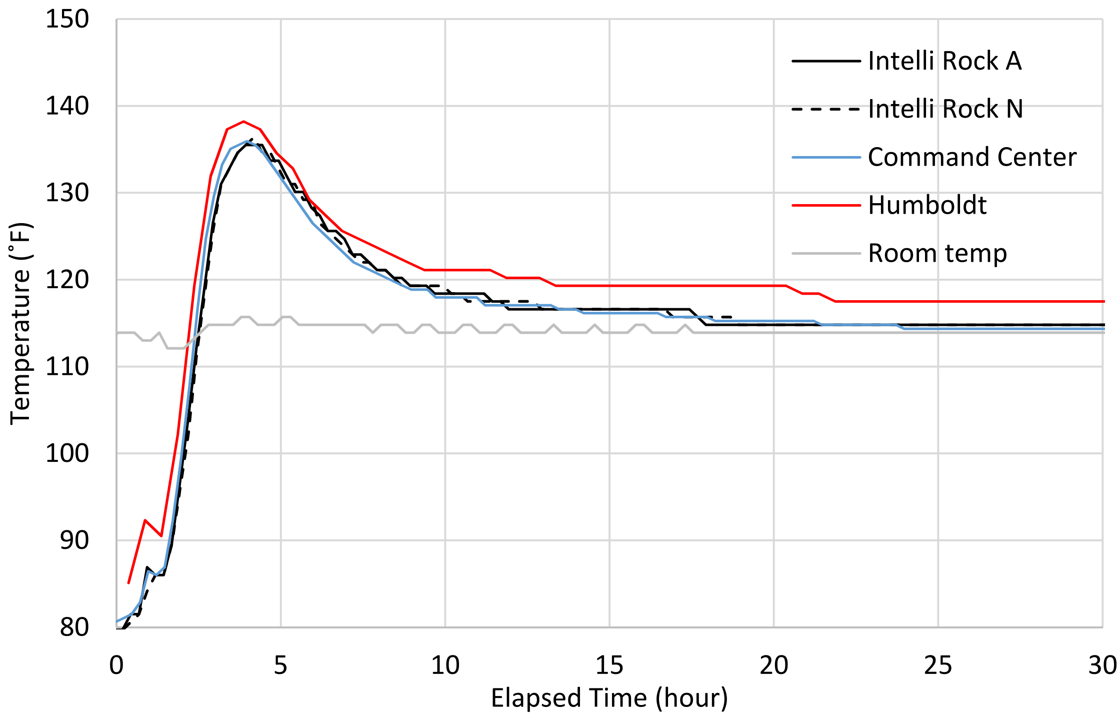


Figure A-5. Temperature-time plots of 4”×8” concrete specimens cured in 113˚F environment-control chamber.

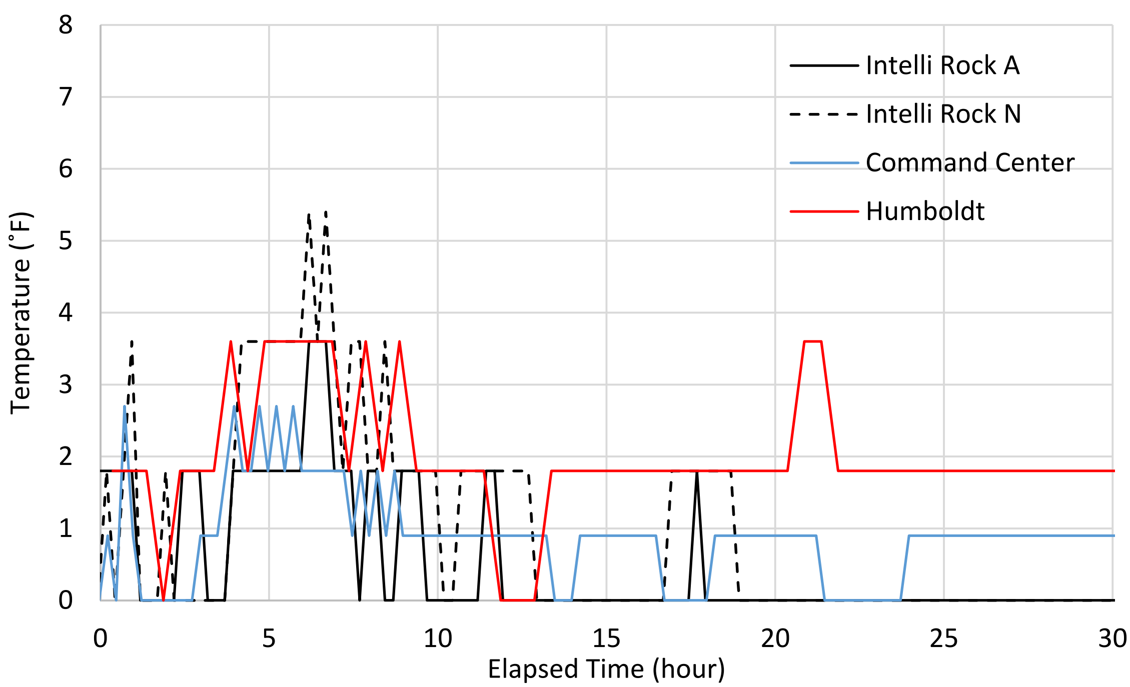


Figure A-6. Variations of temperature measurements from same temperature sensors cured in 113˚F environment-control chamber.

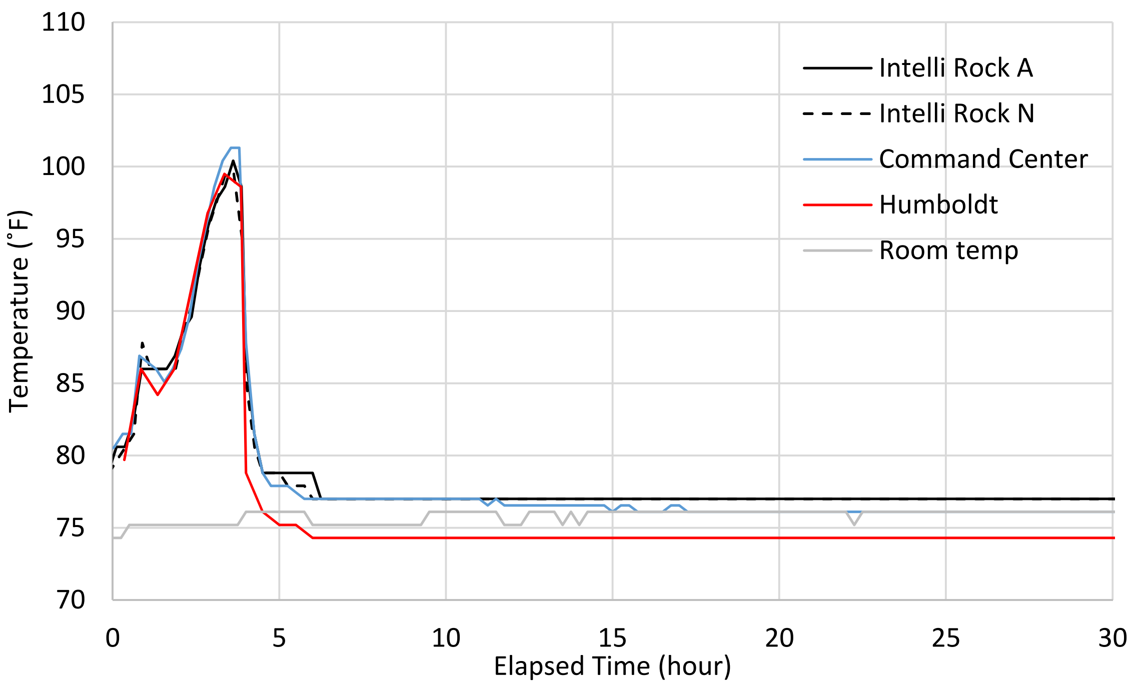


Figure A-7. Temperature-time plots of 4”×8” concrete specimens cured in standard curing tank.

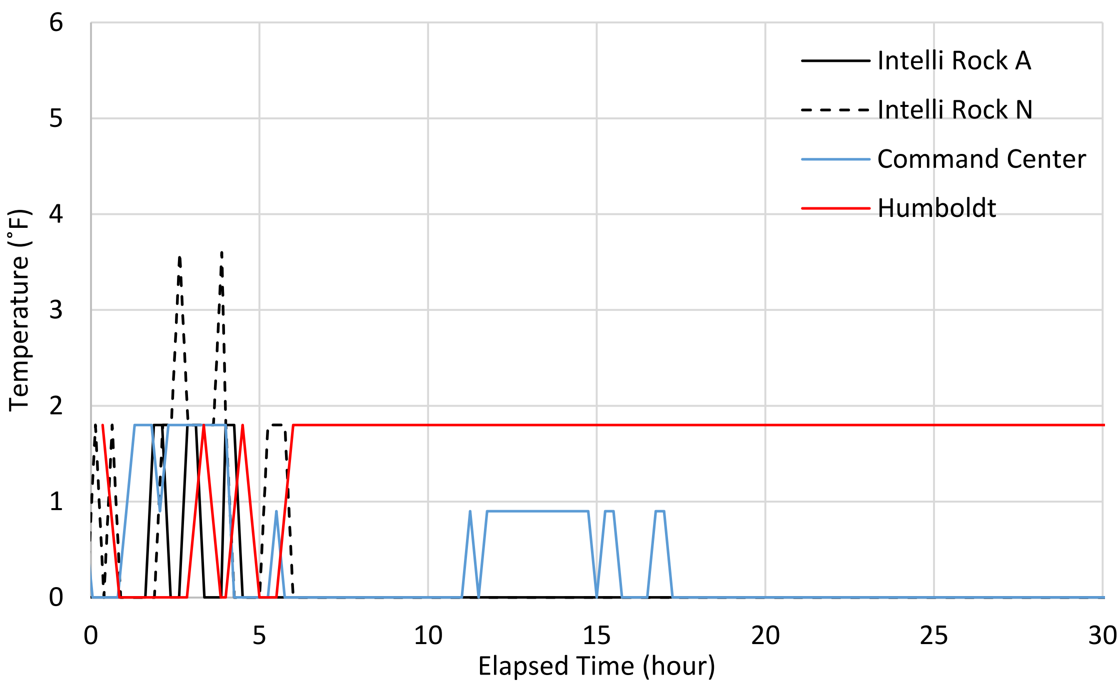


Figure A-8. Variations of temperature measurements from same temperature sensors cured in standard curing tank.

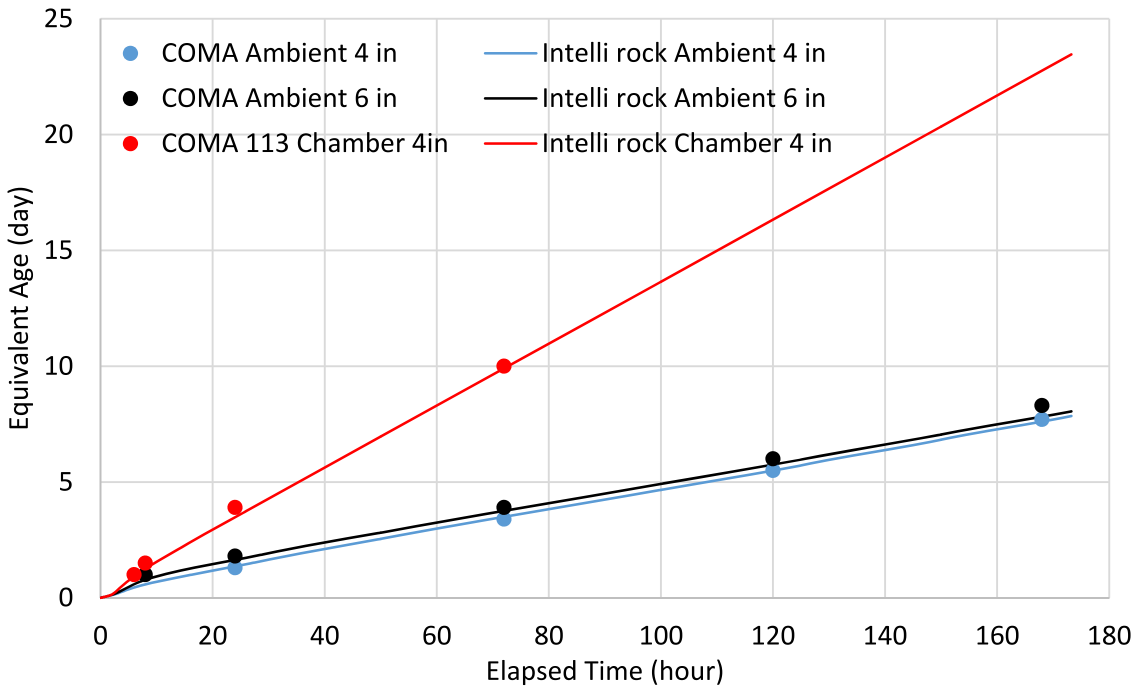


Figure A-9. Equivalent ages from COMA meter and Intelli-Rock maturity system under three different curing conditions.