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Martin O'Malley, *Governor*
Anthony G. Brown, *Lt. Governor*

State Highway Administration
Maryland Department of Transportation

Beverley K. Swaim-Staley, *Secretary*
Melinda B. Peters, *Administrator*

STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

IMPLEMENTATION OF THE CONCRETE MATURITY METER FOR MARYLAND

ROBERT JOHNSON, PH.D
AKYIAA M. HOSTEN

MORGAN STATE UNIVERSITY

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16.Abstract

The process of waiting for concrete to attain its desired strength for certain construction applications can pose one of two problems. The concrete strength may be overestimated, which creates a safety concern for workers and the general public. The concrete strength may also be underestimated, which incurs extensive costs because of delays due to the curing of the concrete. The maturity method takes into account the combined effects of temperature and time on the curing of concrete. Furthermore, when used in concert with accepted ASTM standards, the maturity method serves as a tool to determine when the desired strength is achieved so that appropriate testing can be carried out at that time. This investigation evaluated the maturity method for use in Maryland pavement applications and provides guidelines for its use.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

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This final research report is dedicated to the memory of the late Dr. Robert Johnson.

EXECUTIVE SUMMARY

A thorough investigation, specific to Maryland, was needed to develop a framework for the practical use of nondestructive methods for concrete testing. In particular, the maturity method was viewed as a viable option for determining concrete strength, since it requires only the concrete's temperature history to estimate in-place strength.

When using traditional methods of concrete testing, engineers must wait for pre-determined time intervals to perform compression testing. With the maturity method, the exact time at which the concrete reaches the minimum acceptable strength is estimated, and this estimation can be verified with compression testing at that time. As such, this method allows for concrete roadways and/or bridges to be opened to traffic at a potentially earlier time, reducing costs due to extended waiting periods.

The results obtained from this investigation highlighted the need for precision when using the maturity method. Even the slightest deviation in protocol may result in outcomes that are not representative of the concrete sample. When carrying out the maturity method study, it was found that the estimation of concrete strengths that were developed using the calibration deviated from the data obtained in the field by a margin greater than the maximum allowable value of 10 percent, as specified by ASTM 1074. This discrepancy could be attributed to one of many factors. To account for such discrepancies, the ASTM specifications require that the maturity method be used in concert with other accepted methods of concrete strength testing.

Two sets of verification cylinders were used in this maturity method application. Both sets of verification cylinders were poured in the field. The first set was removed from the field and cured in the lab, and the second set remained in the field. It was found that the strength gain in the two sets of verification cylinders closely matched each other, further indicating that the concrete originally poured in the lab was the anomaly. As such, the set that was cured in the lab was used as the new calibration set, while the set that was cured on site was used as the verification set. Since the percent differences between these results were less than the maximum allowable value of 10 percent, as stipulated by ASTM 1074, the results were accepted and the in-place strength of the bridge deck was estimated using this relationship.

The maturity method has the potential to be a powerful tool that can allow for the nondestructive testing of concrete to determine in-place strength. This method is extremely sensitive to concrete mixture proportions and constituent materials, so a strength-maturity relationship must be developed for every application. Special care must be taken to ensure that the concrete used for calibration and the concrete poured in the field are exactly the same. This method is more efficient than traditional methods, because the time taken for concrete to reach its desired minimum strength is known beforehand. Therefore, compression tests may be carried out at that time, eliminating the need to wait until predetermined intervals to test the concrete. As shown in this investigation, the Arrhenius method more accurately estimates the maturity of concrete, and the hyperbolic graph best represents the strength-maturity relationship. In order to achieve maximum accuracy when using the maturity method, it is imperative that the determination of constants is carried out for each maturity application.

INTRODUCTION

The public often has to tolerate inconvenient detours when traffic is rerouted or lanes are closed as concrete bridge decks and roadways are repaired or reconstructed. This inconvenience creates a desire to safely expedite the concrete curing process in order to open the roadway to traffic. The strength of newly placed concrete must be known, so that safe pavements and roadway structural members can be available to the travelling public. Once the concrete has reached the required concrete strengths, the roadway maybe opened to traffic.

The cost of detours incurred by the general public is due to the expense associated with the additional cost of fuel required to traverse the detours. This expense may be minimized by opening the roadway to traffic at an earlier time. Knowing when curing concrete has reached the strength requirement that allows traffic to move safely can result in cost savings for state highway agencies and construction contractors, because the construction schedule can be shortened. Knowledge of this in-place concrete strength allows use of the bridge deck, pavement, or roadway structural member, whether the desire is for opening the highway to traffic, removing concrete construction forms, or planning other construction activities for which curing of concrete is a predecessor.

Strength is developed in concrete as a result of chemical reactions that occur during the curing process. The reactions are exothermic (i.e., heat generating), resulting from a hydration process of the cement. The temperature increases as the hydration rate increases with strength gain. Monitoring this heat development requires a procedure to estimate the strength gain by measuring the curing concrete's temperature history. This strength gain is estimated by monitoring the thermal history of locations within the structure that are deemed to be critical with respect to location and structural requirements.

The maturity method is one technique that can be used to estimate early age strength development, encompassing and spanning the 28-day design strength. This report analyzes the procedures and safe use of this method for state highway agencies. This study is a continuation of a previous one that reviewed the maturity method approach and compared maturity meter systems (Peebles, 2007). The previous study concluded that a wireless maturity system was viable to use for the maturity method. The current study evaluates the maturity method and its procedures during the placement of fresh concrete. A concrete bridge deck was used for testing the maturity method and to provide data for analyzing and evaluating the results. The maturity method procedures were developed into a procedures protocol.

Engineers designing concrete pavements are concerned with determining concrete curing requirements and construction procedures, when to remove forms from a concrete structure and when to open freshly cured concrete pavement safely to traffic. The maturity method can be used to estimate the strength of the concrete as it is curing, in order to provide a safely constructed product and to expedite the construction process. This study examines protocol and tests theory to understand the best way to use the method and to manage engineering variability, human error, and quality control. The research and analyses seek to use the most appropriate equipment and procedures to provide the best engineering product for state agency personnel, construction contractors, and the public. Safety is also paramount in accomplishing the following tasks:

1. Use a wireless maturity meter on a newly constructed bridge in the state of Maryland.
2. Use the tag sensors in the wireless maturity meter and locate sensors in the deck of the newly constructed bridge to monitor curing temperatures of freshly placed Maryland State Mix Six[1] concrete.
3. Use the maturity method to estimate compressive strengths during curing of the freshly placed Mix Six concrete.
4. Establish a protocol for the application of the maturity method in the state of Maryland.

[1]The Maryland State Mix Six concrete specifications are shown in Appendix A.

LITERATURE REVIEW

Estimating Strength Values

Traditionally, the strength of a concrete mixture is estimated using data obtained from concrete cured under laboratory conditions. At early curing ages, temperature has a significant effect on strength development (Malhotra and Carino, 2004). During the critical early curing stages, concrete cured in remote locations under standard laboratory conditions does not reflect the temperature variations in the on-site concrete. These traditional methods of estimation, therefore, do not take into account the sensitive response of the concrete to variations in external temperature. According to ASTM C 1074, the strength of concrete must be known before formwork can be removed or before roadways can be opened to traffic (ASTM C 1074, 2010). There may be detrimental consequences, if concrete strength is overestimated. Concrete may crack or concrete structures may even collapse. Alternately, the costs of a project can increase significantly, if concrete strength is underestimated. The proposed maturity method is a more reliable way to evaluate concrete's strength, because it takes into account the combined effects of time and temperature on strength development (Malhotra and Carino, 2004).

The maturity method considers the temperature history and its effect over time on the development of early age compressive strengths in freshly placed, curing concrete. An understanding of this method and its associated theory gives insight to the appropriateness and suitability of the use of this method (Carino and Lew, 2001). Assuming that there are no errors in batch mixing proportions of the mix design and satisfactory quality control, the compressive strength is appropriately estimated within 28 days of the mix design. When using the maturity method, this 28-day estimation utilizes mathematical models, functions, or equations whose parameters are developed using temperature history during strength development over this time span. Among popular uses of the maturity method, two functions have emerged from past investigations for estimations of the curing strength of freshly placed concrete. The two functions are the Nurse-Saul maturity function and the Arrhenius equation. Both functions have been used for the maturity method to estimate early curing concrete strengths (Trost, 2006). When using these functions to estimate concrete's compressive strengths, there are model parameters, referred to as maturity constants that must be developed. The procedure follows specification ASTM C 1074, which was explicitly explained and demonstrated in a 2001 report by Tikalsky et al.

The Nurse-Saul function computes the temperature-time factor, and the Arrhenius function computes the equivalent age at a specified temperature (ASTM C 1074, 2010). The temperature-time factor function was developed by Nurse and Saul in 1951 (Malhotra and Carino, 2004). The equivalent age function, which was developed by Freiesleben, Hansen, and Pedersen in 1977, is based on the Arrhenius equation (Malhotra and Carino, 2004).

When concrete cylinders are cast in the field and transported to the laboratory to be cured in a moist chamber, the controlled temperature environment of the moist chamber does not replicate the temperatures to which the field-cured concrete is exposed (Anderson et al., 2009). The curing temperature of the freshly placed field concrete is affected by ambient weather conditions and the insulating formwork's effectiveness (Russell, 1998). Yet, laboratory-controlled cylinders are cured and tested to represent the strength in the structure over 28 days. This procedure does not replicate the environmental temperature conditions experienced by the concrete at the construction site. The concrete placed in the field will gain maturity at a faster rate than the cylinders in the lab (Mohsen, 2004). The cylinders are used as a quality control procedure to estimate the development of the field-cured concrete's strength over 28 days.

Conditions naturally exist where there is variability in testing and measurement due to a number of factors. The factors might be human in nature as well as mathematical, where real time data approximates portions of the model derived when performing maturity method calculations. The constants for each equation are derived from a methodology that follows ASTM C 1074 specifications, using cubes made from cement mortar that replicates the mix design of the curing concrete placed in the field.

When using the Nurse-Saul equation, the in-place curing concrete's temperature is monitored with embedded sensors. The embedment locations are selected with regard to exposure conditions, member geometry, surface to volume ratio, and structural requirements. This concrete temperature history allows use of the Nurse-Saul maturity function with a datum temperature of five degrees Celsius to estimate conservative strength values (Trost, 2006). The Arrhenius equivalent-age maturity function, which can be used for strength estimation, is influenced by the composition of the "cementitious" materials in the system (Brooks, 2007). One should be conservative in the use of these models for estimating concrete strengths.

Arrhenius Equation

The Arrhenius equation is a nonlinear equation based on chemical reaction theory. This equation was used to develop an equivalent age of the curing concrete with respect to a specified reference temperature (Schindler, 2004). The equivalent-age equation contains a parameter known as the activation energy, E_a. For a concrete mixture in which a combination of constituents is used to produce the proportions of the mix design, E_a is a parameter that varies from one mix design to another. This variability is a result of differences in the proportions of the mix design. Furthermore, the Arrhenius equation was used to develop the equivalent age, and the Arrhenius law is based on a single phase reaction (Zhang, 2008). While conducting research to investigate properties other than compressive strengths, Zhang found that different properties might have different E_a values within the same concrete. This activation energy is related to the curing temperature and estimation of the setting time (Wade, 2010).

Nurse-Saul Equation

The Nurse-Saul equation is based on the sum of the difference between an average concrete curing temperature and a datum temperature that is multiplied by a time interval selected over the time of interest while concrete is curing. This function takes care of the combined effect of temperature and time on strength, and it results in the determination of a "maturity index or temperature time factor" (Ansari et. al, 1999).

METHODOLOGY

Application Process

To prepare for the maturity method, lab tests must be conducted to develop the parameters required for use in the equations for the selected method. Topcu investigated the admixture's effect on strength using the maturity relationship and the Nurse-Saul maturity function. His results indicated that the use of this function for in situ applications is simpler than the Arrhenius function (Topcu, 2007). To apply the maturity method, three phases must be completed: calibration, verification, and onsite application. These aforementioned processes, the proper placement of the temperature sensors, and the batching process must be monitored for quality control and to produce a satisfactory and safe concrete product.

Among other considerations when determining the critical locations of the sensors is the surface area to volume ratio (SA/R) of structural members (Myers, 2000). Wind speed and solar radiation are among these considerations, with the concrete curing temperature being the factor related to strength development (Kim, 2008).

Advantages

The advantages of the maturity method listed in ASTM 1074 are as follows:

- The maturity method can be used to estimate in-place strength of concrete to allow the start of critical construction activities.
- The maturity method may be used to estimate the strength of laboratory cylinders that have been cured under non-standard temperature conditions.

Limitations

The limitations of the maturity method listed in ASTM 1074 are as follows:

- The concrete must be maintained in a condition that allows for complete hydration of the cement.
- The maturity method does not account for the effects of early-age temperature on long-term concrete strength.
- The accuracy of the estimated strength depends heavily upon the appropriate maturity function and constants for that particular concrete mixture.
- Constituent materials (source materials) for concrete mix must remain the same. Changes in constituent materials will nullify previous maturity results and will require testing of the new constituent material to establish a new maturity curve.

To accommodate these limitations, ASTM 1074 requires that the maturity method be supplemented by other accepted concrete testing methods.

Cube Preparations and Lab Testing

Two-inch cubes were prepared by proportioning the mortar, based on the concrete of the State Mix 6 design. This design of the concrete was used for the in-situ field concrete of the Charles Street bridge deck, where the sensors were placed within the curing concrete to monitor the temperature history. The bridge is located on Charles Street (across I-695) in Towson, Maryland.

Three sets of six mortar cubes were cured in saturated limewater baths, yielding a total of eighteen cubes. The baths were maintained at 32°C (maximum), 4°C (minimum), and 18°C (average). The temperatures represent the range expected at the bridge's construction site. During this procedure, ASTM C 403 was used with the cubes. The baths' temperatures were maintained with curing tank heaters in heavy-duty galvanized steel concrete curing tanks. The compression strength data is in Appendix B.

Cylinder Preparations and Lab Testing

The concrete cylinders were made in the field in accordance with ASTM requirements. The requirements are a quality control measure that helps determine whether the design mix is accomplishing the concrete strength design and the desired job specifications. Field-cured cylinders are used, in general, to determine when a structure is ready for service and when its forms can be removed. However, the maturity method can be used for this purpose as well.

The cylinder samplings of the concrete placed in the bridge deck were made using 6-inch by 12-inch cylinders. Two sets of samples were made during the placement of the deck's concrete. One set of cylinders was cured in the field for 24 to 48 hours, and then moved to the laboratory where the set was placed in temperature-controlled (21°C), moist-cure chamber. This set of cylinders is referred to as the lab-set cylinders. The other set of cylinders was made during the placement of the deck's concrete, and it remained at the field site. This set of cylinders is referred to as the field-set cylinders.

Lab-Set Cylinders

Nineteen lab-set cylinders were made in the field during the placement of the concrete. After the first 24 hours, the cylinders were removed from the field, demolded, and placed in a water bath. The lab-set cylinders were removed from the moist-cure chamber and their compression strengths were tested on Day 1, 3, 5, 7, 14, and 28. The compression-strength data is in Appendix D. One of the cylinders in this set was instrumented with a sensor tag to monitor the temperatures during the cylinder curing period. This curing period monitored the internal temperatures from the time the cylinders were made until the compression-strength tests were conducted.

Field-Set Cylinders

Forty-nine field-set cylinders were made in the field during the placement of the concrete. These cylinders, which remained in the field, were placed in a wooden cure box that protected them from radiant heat and sunlight. The field-set cylinders were removed from the cure box, taken to the lab, and demolded at designated times. The compression strength of the field-set cylinders was tested on Day 7, 10, 14, and 28. The compression strength data is in Appendix E**.** One of the cylinders in this set was instrumented with a sensor tag to monitor the temperatures during the cylinder curing period.

ANALYSIS AND FINDINGS

Determination of Maturity Constants

The ASTM 1074 specification outlines three different methods to determine the *k*-values for each curing temperature. All three methods were used in this investigation, and the constants obtained from each method were used to develop the strength-maturity relationships. The method that fit the data most accurately was accepted as the ideal method to be used in future applications. These three methods are outlined below.

<u>Method 1</u>

The final setting times of the cubes at the three different temperatures were recorded. A prepared graph set the reciprocal of strength as the y-axis and the reciprocal of age as the x-axis. For each curing temperature, the reciprocal of the average cube strength was plotted against the reciprocal of the age beyond time of final setting. The slope and the intercept of the best-fit line for each curing temperature were determined. For each line, the value of the intercept was divided by the value of the slope. These quotients are the *k*-values used to calculate datum temperature or activation energy. The graph is shown in Figure 1.

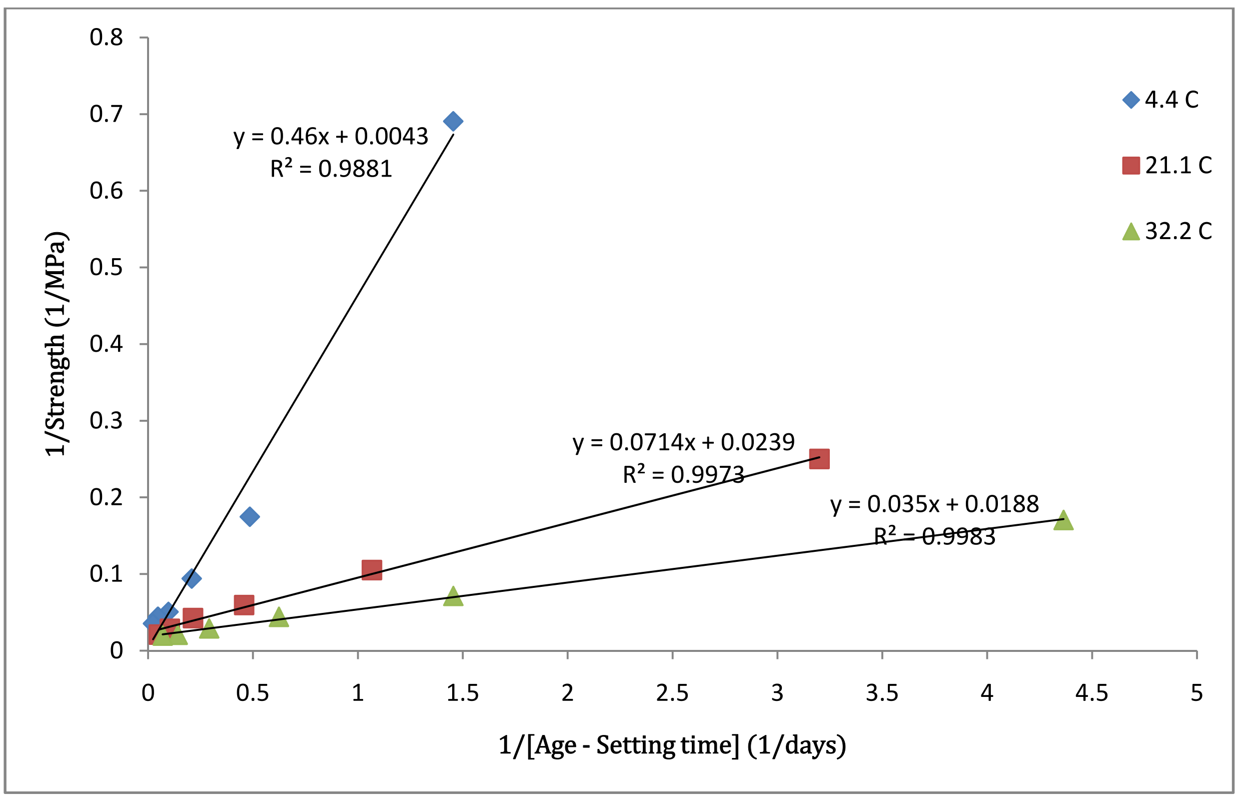

Figure 1: Reciprocal of Strength versus Reciprocal of Age Beyond Time of Final Setting

As an alternative to the aforementioned procedure, the *k*-values may be estimated with two other methods that do not require the use of the final setting time. These methods are outlined in the following sections.

Method 2

The *k*-values were also estimated by fitting a general equation to the data obtained from this study using computer software. Microsoft Excel was selected to perform this task. The general strength-age equation for each curing temperature is as follows:

$$S = S_u \frac{k(t - t_0)}{1 + k(t - t_0)}$$

Equation 1: General Strength-Age Equation

where
S = average cube compressive strength at age t
t = test age
S_u = limiting strength
t_0 = age when strength development is assumed to begin
k = the rate constant

Microsoft Excel's Solver add-in calculated the best-fit values of S_u, t_0, and k.

Method 3

Using the strength-age data for the last four test ages, the reciprocal of strength was plotted versus the reciprocal of age. The inverse of the y-intercept was the limiting strength, S_u. This procedure was repeated for each curing temperature, and is shown in Figure 2.

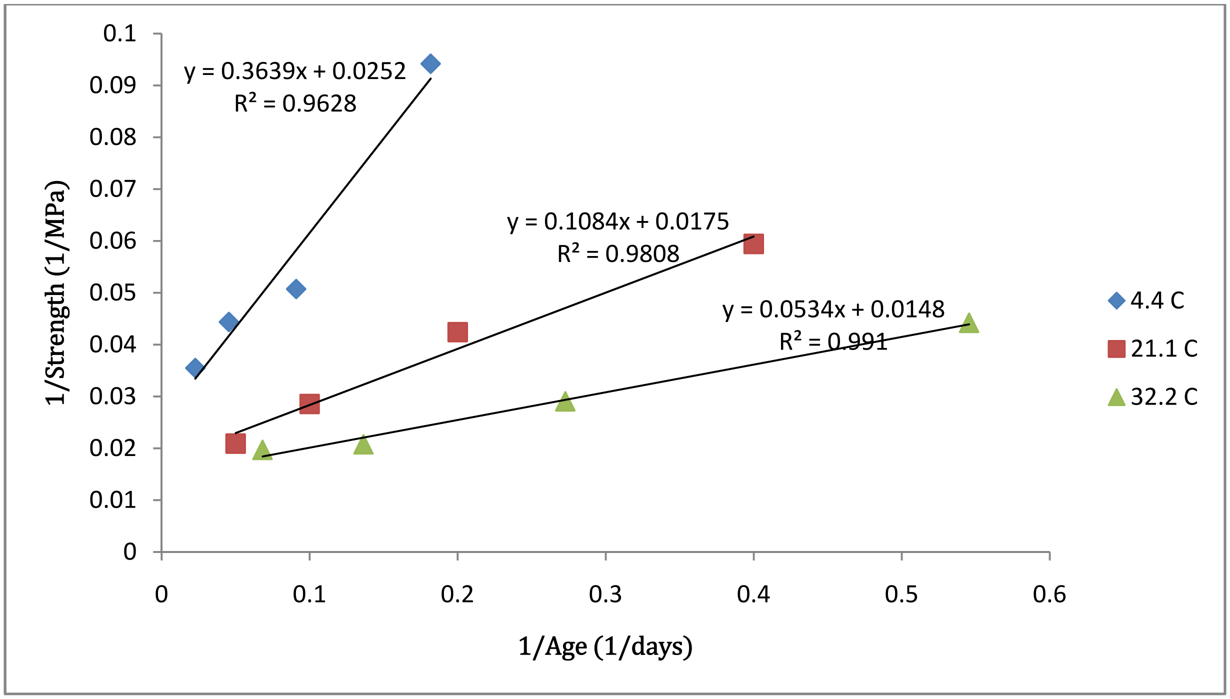

Figure 2: Reciprocal of Strength versus Reciprocal of Age for Four Last Test Ages

For each curing temperature, the strength-age data for the four earliest test ages and the value of S_u were used to compute the values for A for each strength value. A was calculated using the following equation:

$$A = \frac{S}{(S_u - S)}$$

Equation 2: Determination of A

As shown in Figure 3, the values of A were plotted against age for each curing temperature. The slopes of the best-fit line for each of the curing temperatures were used as the *k*-values.

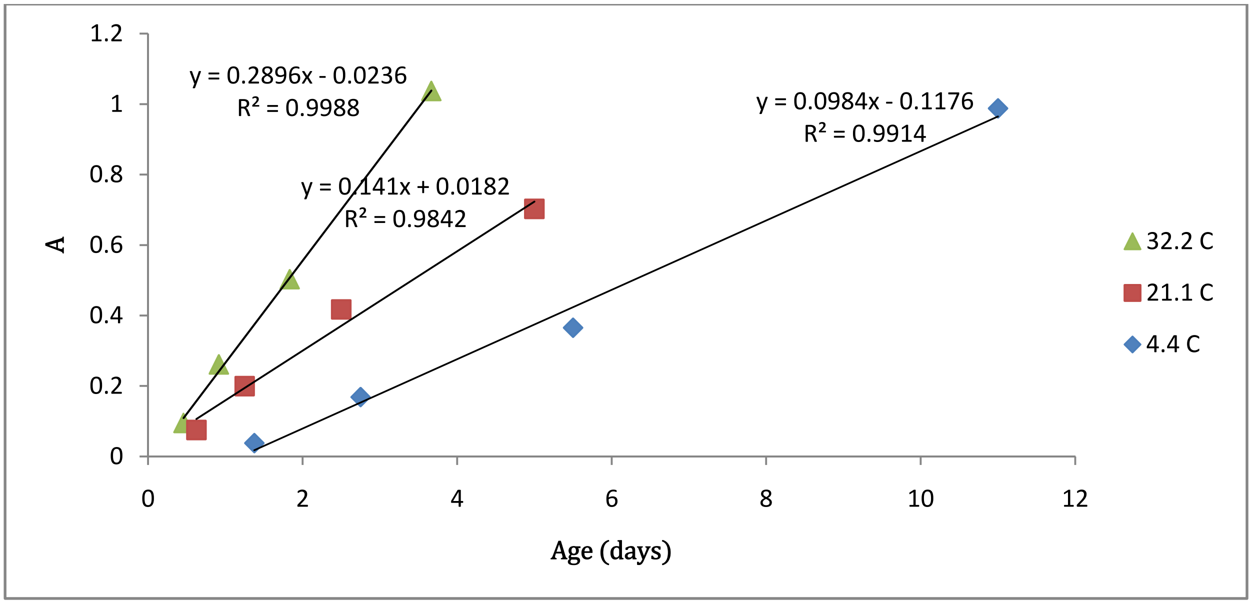

Figure 3: A versus Age for the Four Earliest Test Ages

Determination of Datum Temperature

For each method outlined in the previous section, the *k*-values were plotted as a function of the bath temperatures. The *x*-intercept of the best-fit line was used as the value for the datum temperature, T_0. This procedure is illustrated in Figures 4-6.

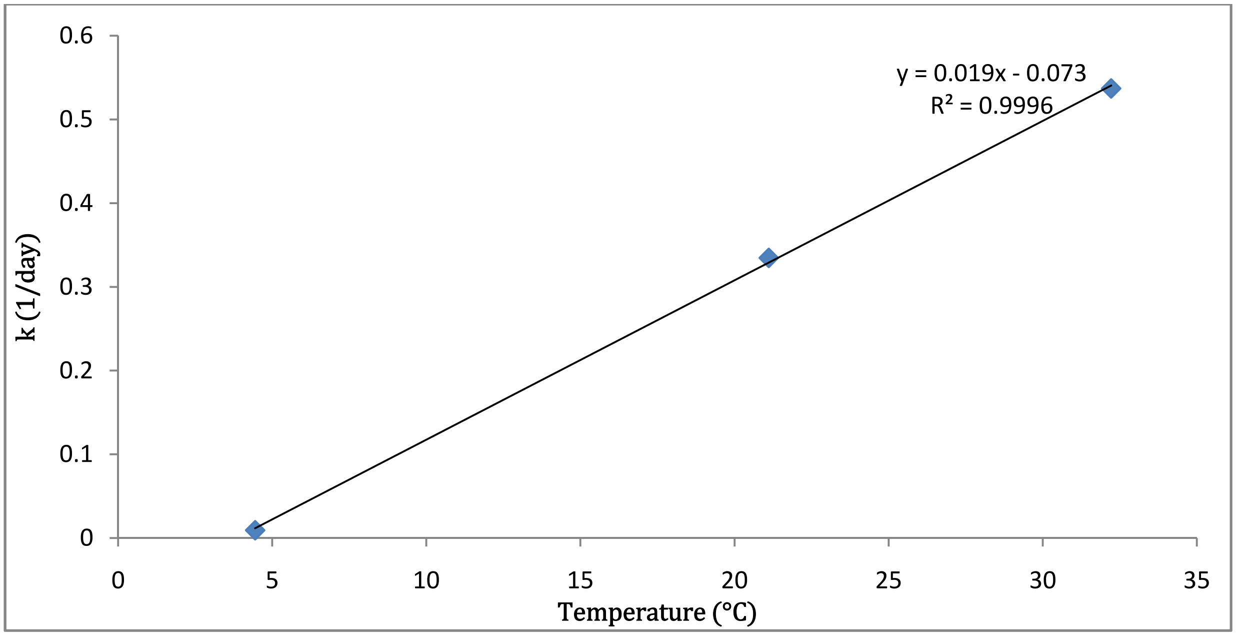

Figure 4: *k*-values versus Curing Temperature for Determining the Datum Temperature (Method 1)

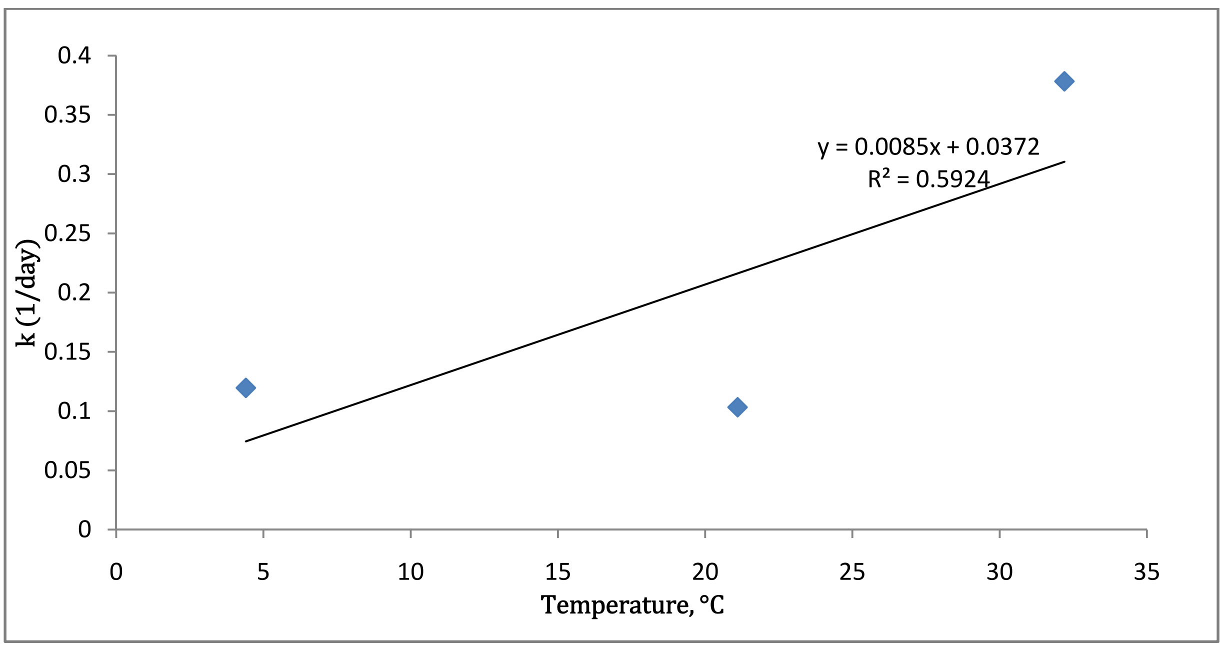

Figure 5: *k*-values versus Curing Temperature for Determining the Datum Temperature (Method 2)

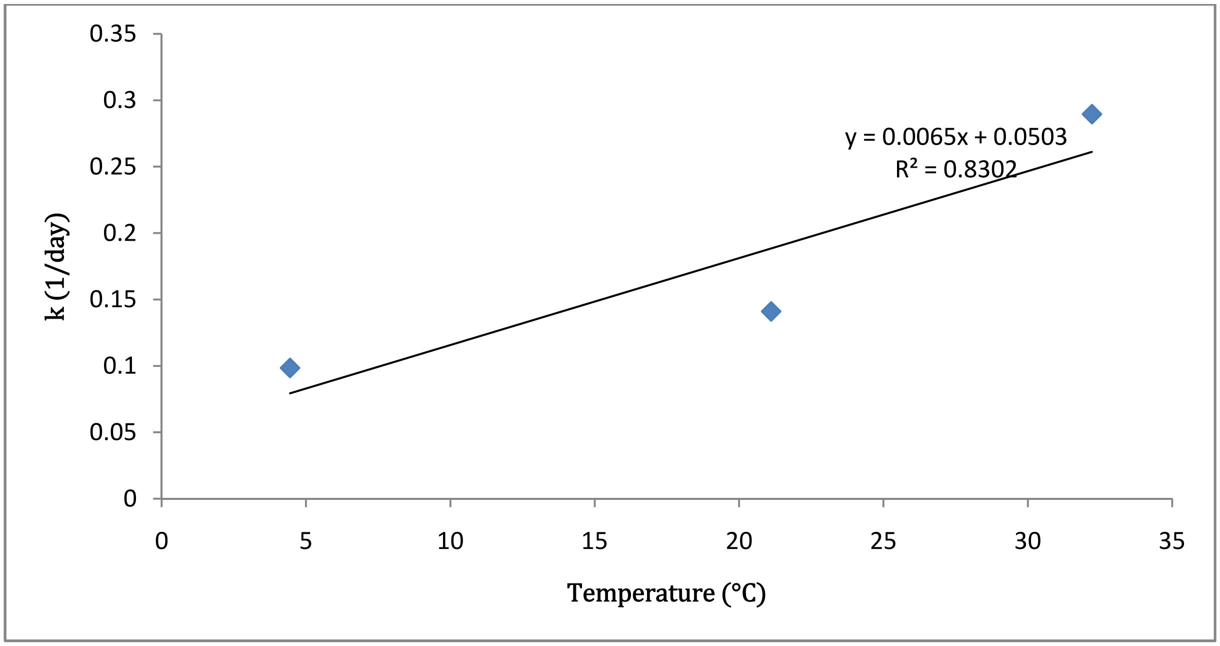

Figure 6: *k*-values versus Curing Temperature for Determining the Datum Temperature (Method 3)

The values of datum temperature, T_0, obtained using each method are as follows:

Method	T_0 (in Celsius)
1	3.8
2	-4.6
3	-7.7

Table1: Datum Temperature for Each ASTM 1074 Method

Determination of Activation Energy

For each method the natural logarithm of the *k*-values was plotted versus the reciprocal absolute temperature. The negative slope of the best-fit line through the points is the value of the activation energy divided by the gas constant, Q, used to compute equivalent age. This procedure is illustrated in Figures 7-9.

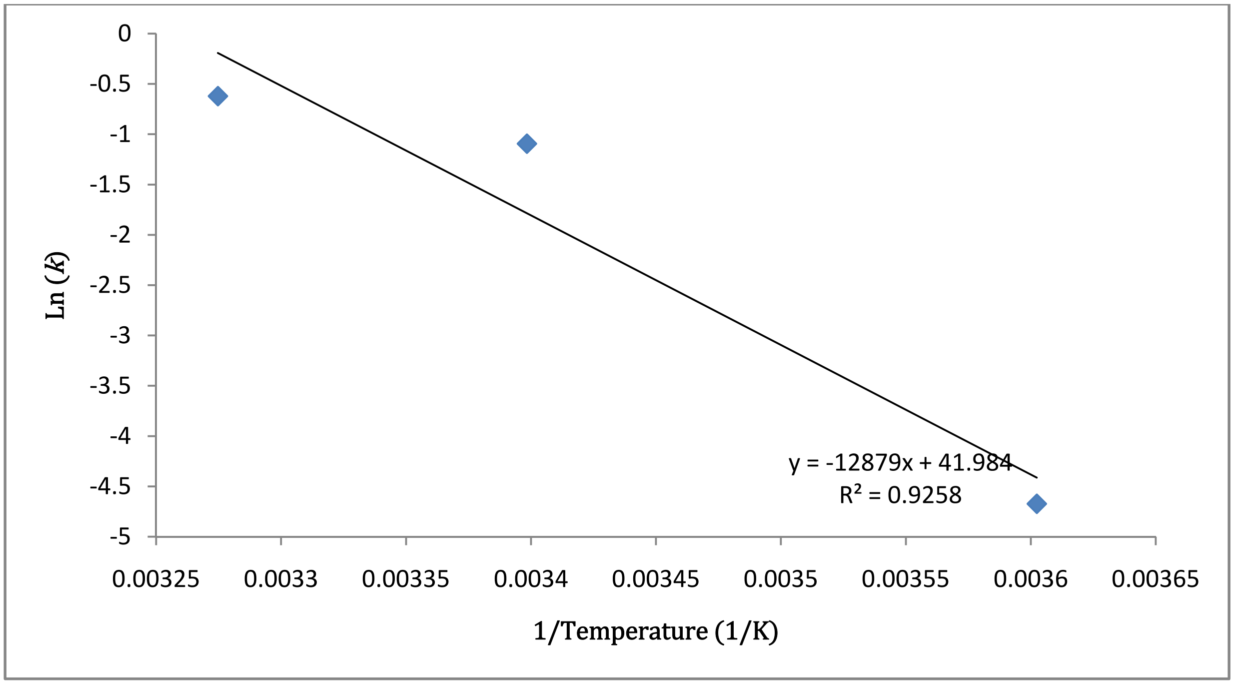

Figure 7: Plot of the Natural Logarithm of *k*-values versus the Inverse Absolute Temperature for Determining the Value of Q Used to Calculate Equivalent Age (Method 1)

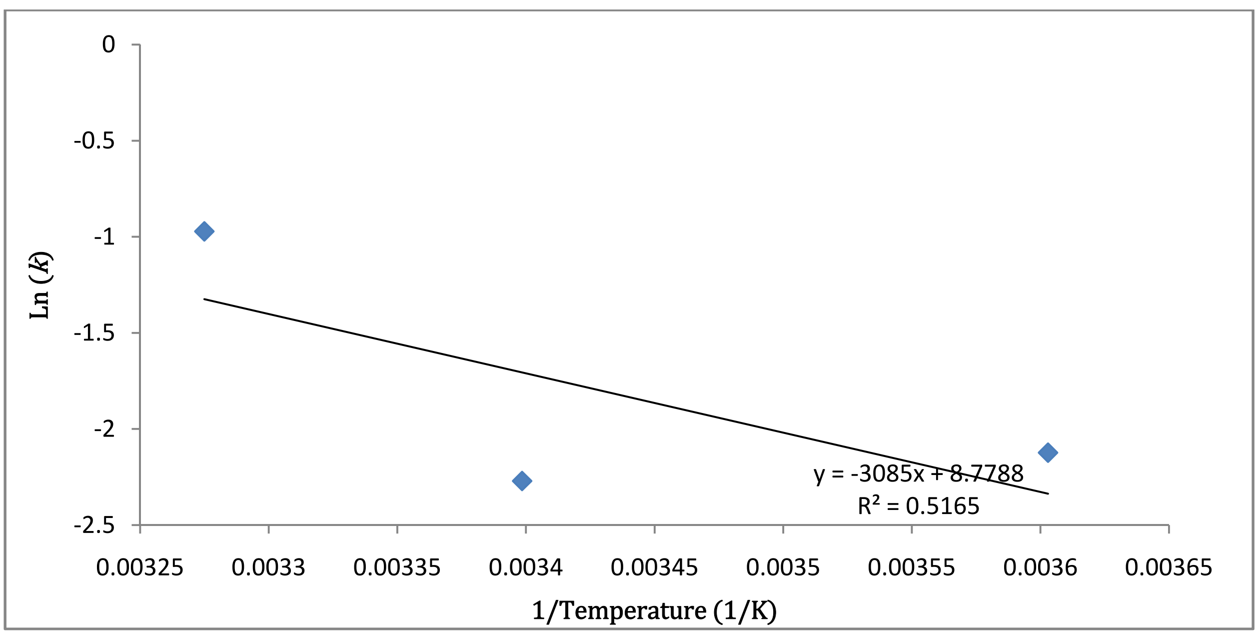

Figure 8: Plot of the Natural Logarithm of *k*-values versus the Inverse Absolute Temperature for Determining the Value of Q Used to Calculate Equivalent Age (Method 2)

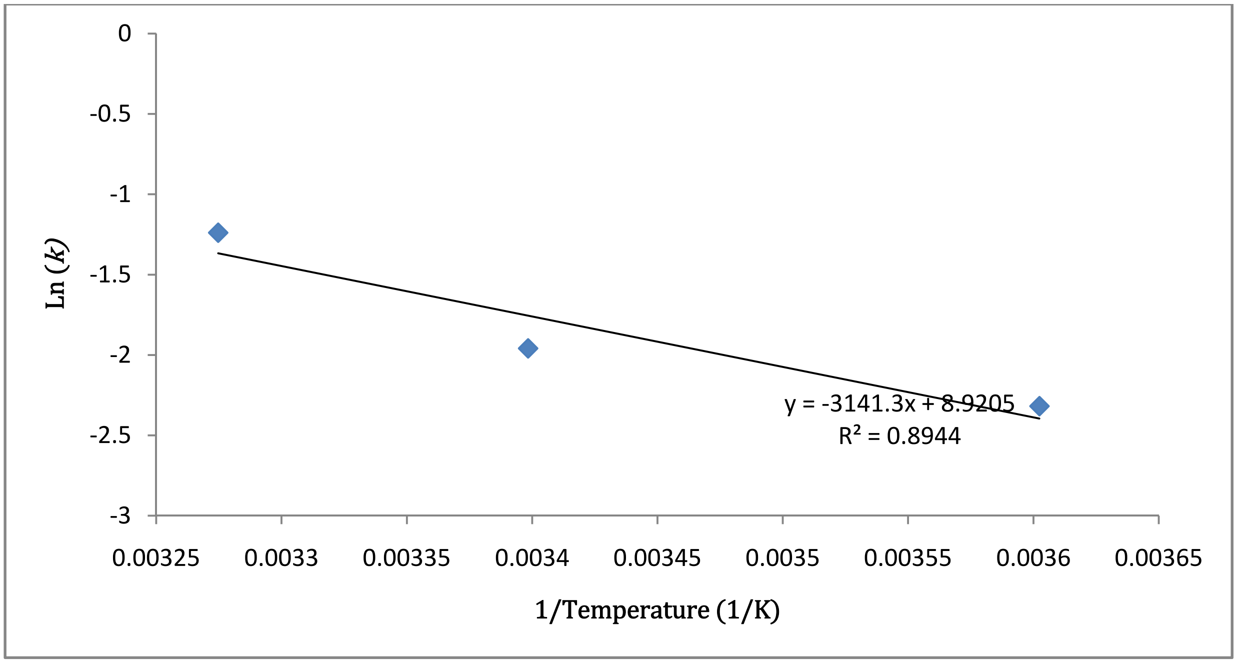

Figure 9: Plot of the Natural Logarithm of *k*-values versus the Inverse Absolute Temperature for Determining the Value of Q Used to Calculate Equivalent Age (Method 3)

The values of activation energy divided by the gas constant, Q, obtained using each method are as follows:

Method	**Q(K)**
1	12879
2	3085
3	3141

Table 2: Q values for each ASTM 1074 method

When the constants obtained from each of these three methods were calculated, it was evident that Methods 2 and 3 yielded similar datum temperature and activation energy values. Furthermore, Method 3 had larger regression constants than were found in Method 2. Therefore, the constants obtained from Method 3 were used for the maturity functions in this evaluation.

Maturity Functions

Maturity functions account for the effects of temperature and time on the strength development of concrete. Two accepted functions may be used to compute a concrete specimen's maturity. The Nurse-Saul function proposes that the maturity must be calculated with respect to a datum temperature, below which it is believed that strength gain ceases. This function is computed using the following equation:

$$M = \sum_{0}^{t} (T - T_0)\Delta t$$

Equation 3: Nurse-Saul Function

where
M = maturity (temperature-time factor) at age t (degree-hours)
T = average temperature of the concrete during time interval Δt (°C)
T_0 = datum temperature (°C)

The second maturity function uses the Arrhenius equation. The function states that the maturity must be used to determine the concrete's equivalent age at a specified temperature. This function is computed using the following equation:

$$t_e = \sum_{0}^{t} e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \Delta t$$

Equation 4: Arrhenius Function

where
t_e = equivalent age at a specified temperature (days)
Q = activation energy divided by the gas constant (K)
T_a = average temperature of concrete during time interval Δt (K)
T_s= specified temperature (K)
Δt = time interval (hours)

The strength-maturity relationship for a specific concrete mix should be calculated using the constants determined in the previously outlined procedures. Due to the sensitivity of the concrete curing process, new constants should be determined for each concrete maturity application to achieve the most accurate results. Ideally, this calibration procedure involves curing the evaluated concrete mix under standard lab-curing conditions. Seventeen cylindrical specimens should be prepared in accordance with ASTM Designation C192/C 192 M. Temperature sensors are to be embedded within two of the cylinders and connected to maturity instruments. All specimens are to be cured in a water bath or a moist-cure room in accordance with Specification C511. Concrete cylinders are to be compression tested in accordance with ASTM C39/C 39M on Day 1, 3, 7, 14, and 28. At each test age, the specimens' maturity is evaluated. The average compressive strength for each test age is plotted as a function of the maturity. This curve is the strength-maturity relationship used to estimate in-place strength of the concrete mix cured under different conditions.

Correlation Curves

The strength-maturity relationship can be described using both logarithmic and hyperbolic equations. From a mathematical standpoint, the hyperbolic equation is more suited to describe this relationship because the hyperbolic curve approaches a finite value: the concrete's ultimate strength. The logarithmic curve approaches infinity; therefore, it does not accurately represent the strength-maturity relationship. The hyperbolic trend line was used as the calibration curve: it was compared to the verification cylinders and used for estimation of in-place bridge strength. The correlation curves are shown in Figures 10 and 11.

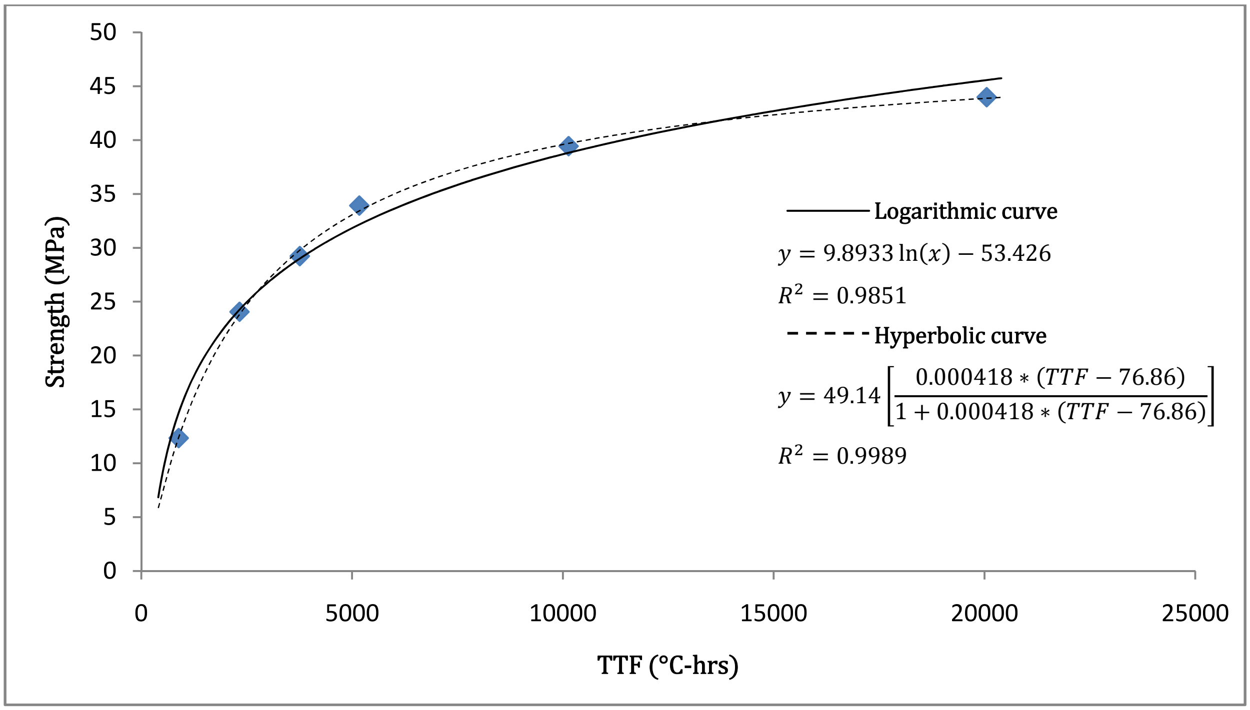

Figure 10: Correlation Curves Determined Using the Nurse-Saul Maturity Function

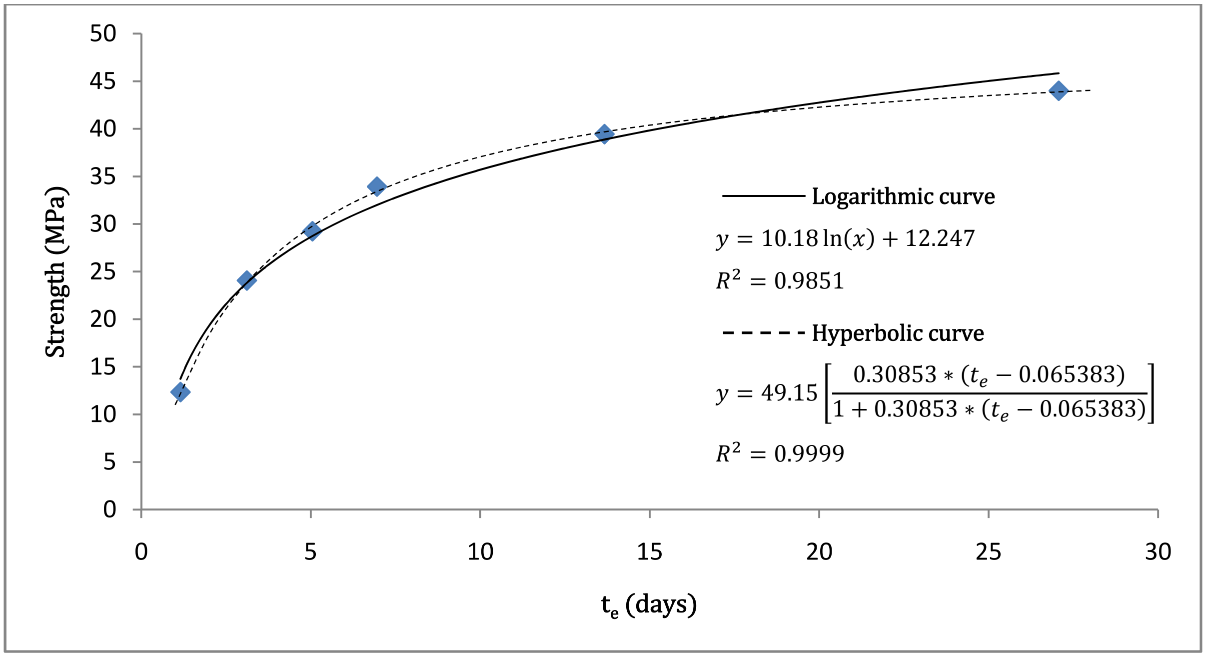

Figure 11: Correlation Curves Determined Using the Arrhenius Function

Because the Arrhenius relationship more accurately represented the strength-maturity relationship, the Arrhenius equation was the maturity function used for this investigation.

Verification of Relationship

To verify the strength-maturity relationship, the strength was plotted against equivalent age for the lab-set cylinders (Figure 12).

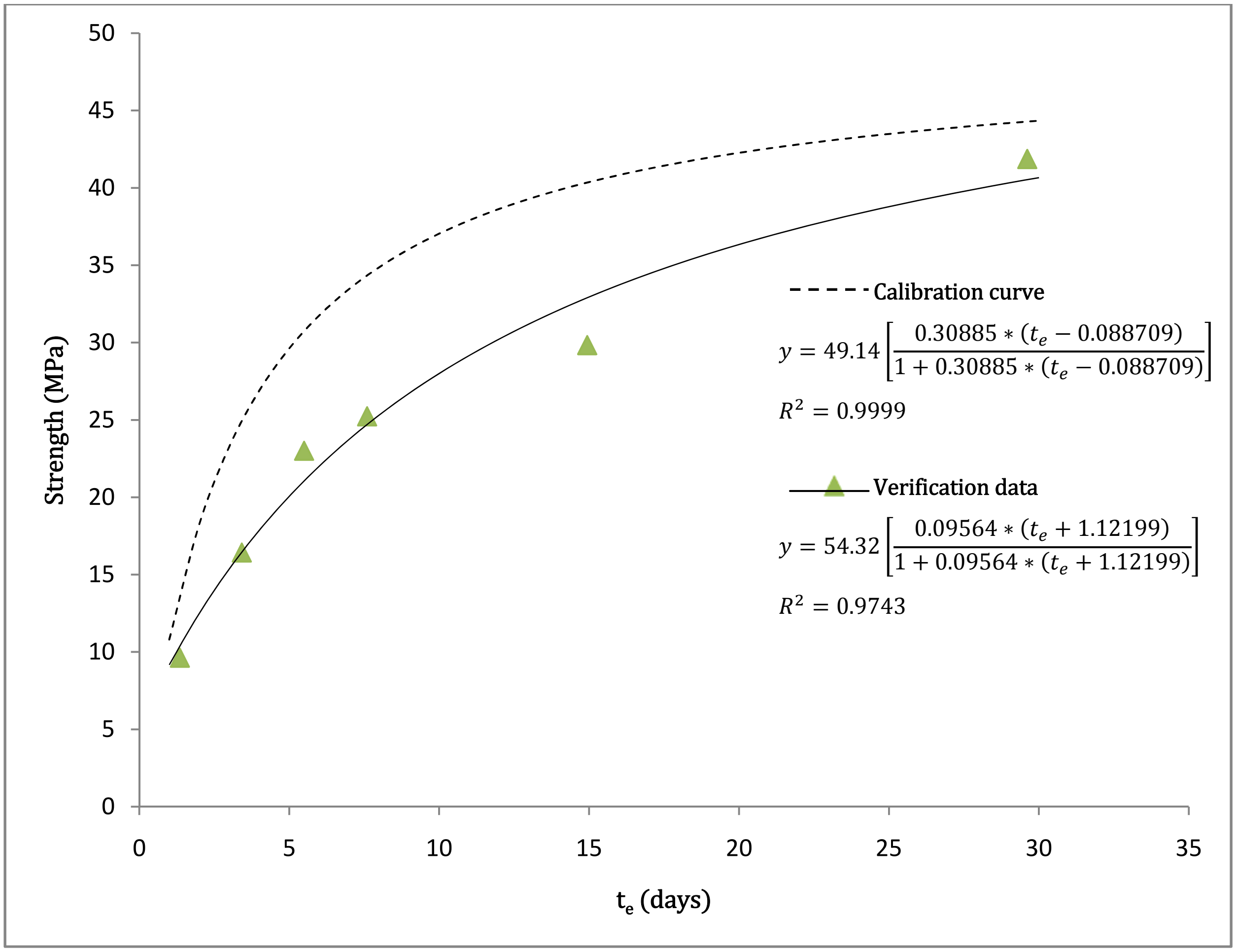

Figure 12: Strength versus Equivalent Age for Verification Cylinders

When the strength-maturity relationship of the calibration and verification cylinders was compared, it appeared as though the concrete did not have a unique strength-maturity relationship. However, if during the application of the maturity rule only the temperature of the concrete is measured, only the relative strength gain of the concrete can be estimated (Carino 2004). For situations like these, a modified maturity rule was developed using the following age conversion factor:

$$RS_{\infty} = \frac{S}{S_{\infty}} = \frac{k(t_e - t_0)}{1 + k(t_e - t_0)}$$

where
RS_∞ = a fraction of the limiting strength

Furthermore, the relative strength may be described in terms of the 28-day strength, which may be a more useful comparison. Twenty-eight days may be substituted for the value of t_e to obtain S_{28}/S_∞. The equation may be rewritten in the following manner:

$$RS_{28} = \frac{S}{S_{28}} = \frac{\left(S_\infty/S_{28}\right) k(t_e - t_0)}{1 + k(t_e - t_0)}$$

Equation 5: Relative Strength Equation

where
S_∞/S_{28} is the reciprocal of the value previously obtained for S_{28}/S_∞.

The relative strength-maturity relationship is shown in Figure 13.

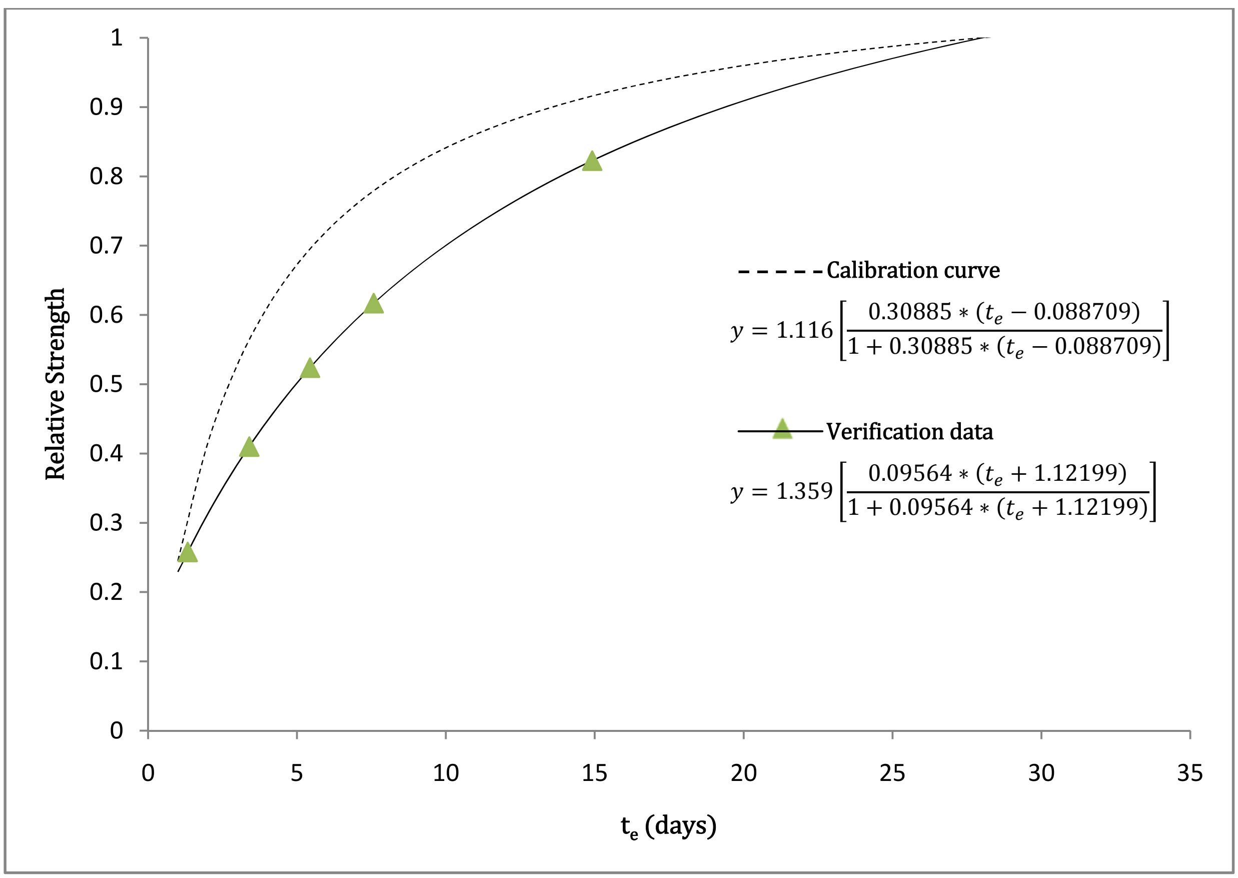

Figure 13: Relative Strength versus Equivalent Age for Verification Cylinders

After the relative strength data was calculated and this data was plotted against the equivalent age values, it was evident that the original calibration curve was not representative of the concrete placed in the field. According to ASTM 1074, the acceptable difference between expected values and experimental values is 10 percent. The difference for this particular application exceeded 10 percent; therefore, the original lab-calibration curve could not be used. Malhotra and Carino (2004) proposed four factors that may lead to discrepancies in expected values:

- batching errors that may reduce the potential strength of concrete
- high, early-age temperatures that reduce the ultimate strength of concrete
- concrete drying below a datum temperature, causing hydration to cease
- use of activation or datum temperatures that are not representative of the concrete mixture

It is difficult to specify exactly which of the aforementioned factors could have led to the unexpected results; however, it important to note that any one or a combination of those factors could have the potential to skew results. Due to the sensitive nature of this investigation, great care must be taken to ensure that all these situations are avoided.

As a result of these limitations, ASTM requires that the maturity method be used in concert with other accepted testing methods. In this maturity investigation, field-set cylinders were compression tested. The verification cylinders were used as the accepted strength-maturity relationship for this investigation, and the field-set cylinders were compared to this new maturity relationship. The result is shown in Figure 14.

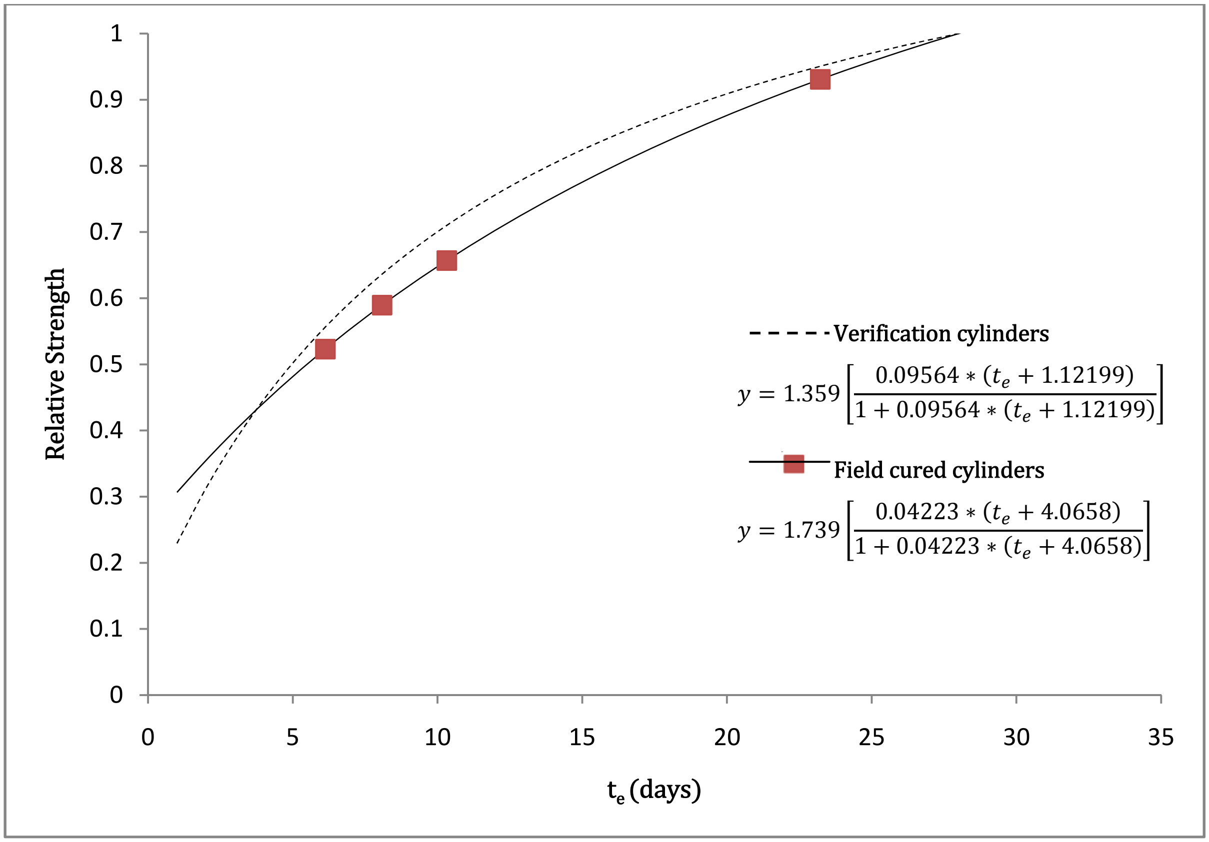

Figure 14: Relative Strength versus Equivalent Age for Bridge Cylinders

The expected values from the relative strength-maturity relationship derived from the verification cylinders matched closely the relative strength-maturity relationship of the field-cured cylinders.

Collection of Bridge Deck Temperatures

The bridge-deck temperatures were collected from maturity instruments (raw data is included in the attached disc) that were placed in the curing concrete. This temperature history was used to estimate relative strength values within the bridge. The estimated relative strength-maturity relationship for the bridge deck is shown in Figure 15.

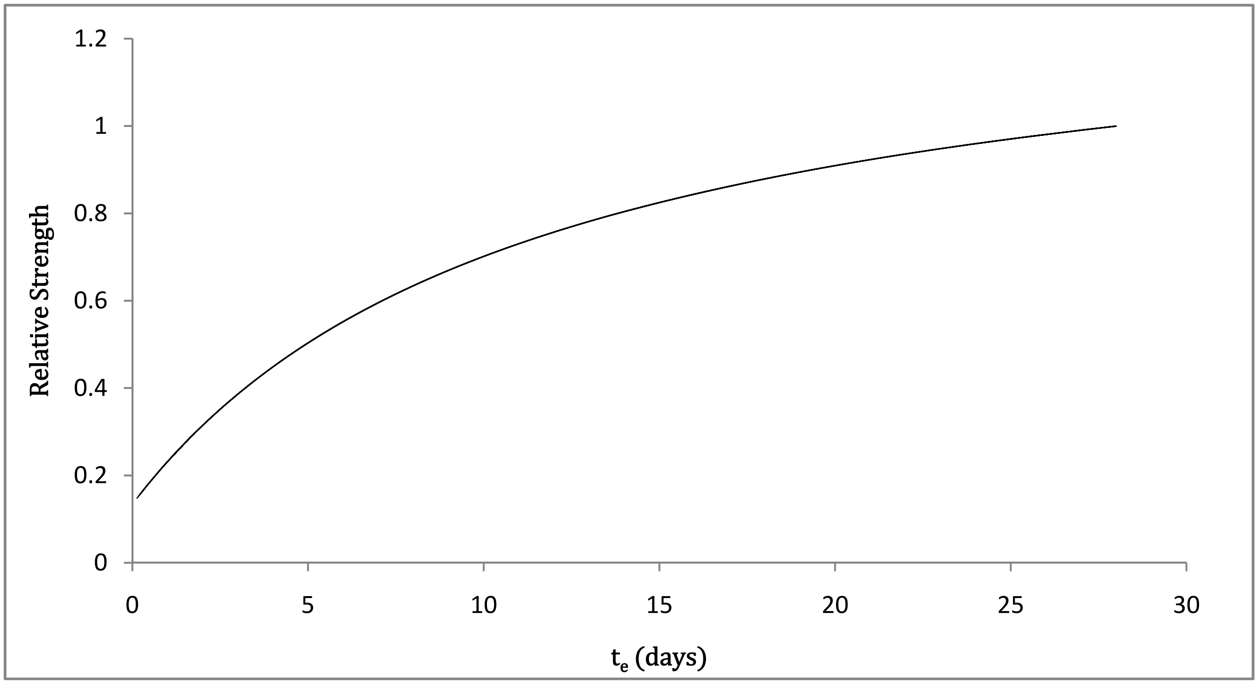

Figure 15: Relative Strength versus Equivalent Age for Bridge Deck

In practice when a specific relative strength of concrete is needed, this value may be used to determine the approximate equivalent age of the sample at that value for relative strength. Once this equivalent age is known, engineers may then perform compression tests of field-cured cylinders to determine whether the concrete has actually achieved its required strength.

CONCLUSIONS

The maturity method is a powerful tool that has the potential to allow for the nondestructive testing of concrete to determine in-place strength. This method is extremely sensitive to concrete mixture proportions, uniformity and sameness of individual mix constituents, and a strength-maturity relationship must be developed for every application. Special care must be taken to ensure that the concrete used for calibration and the concrete poured in the field are exactly the same.

In this project the strength-maturity relationship developed in the lab was not representative of the concrete that was placed in the field. When comparing the two sets of cylinders poured in the field, one set of which was transported to the lab while the other was left in the field, their strength-maturity relationships were consistent. The fact that these two sets of cylinders had comparable strength-maturity relationships shows that the strength of concrete can indeed be estimated even when there are different temperatures. The failure of the cylinders placed in the field to validate the initial calibration data, as expected, shows the degree of sensitivity of the method. Since the maturity method is highly mix-specific, the deviation from expected results could have been caused by unexpected differences between the concrete mix that was initially used in the lab and ultimately poured in the field.

This method is more efficient than traditional methods, because the time taken for concrete to reach its desired minimum strength is known beforehand. Therefore, compression tests may be carried out at that time, eliminating the need to wait for predetermined intervals to test the concrete. As shown in this investigation, the Arrhenius method more accurately estimated the maturity of concrete, and the hyperbolic graph best represented the strength-maturity relationship. In order to achieve maximum accuracy when using the maturity method, it is imperative that the determination of constants is carried out for each maturity application.

Engineers designing concrete pavements, bridges and other structures are concerned with determining satisfactory strength requirements, form removals, and concrete saw cuttings for opening highways safely to traffic. Specific strength requirements of concrete application must be known beforehand in order to optimize the use of the maturity method. For the maturity method concept associated with this study, engineers must select proper locations for temperature measurement and estimation of the critical strength of the in-place concrete. Sensors should be installed at locations within the structure that are critical in terms of exposure and structural requirements.

Traditionally, the compressive strength of concrete is used as a measure of its suitability; however, flexural strength may also be of interest for concrete pavement applications. Further research should be done to determine the applicability of the maturity method for determination of the in-place flexural strength of concrete slabs.

Lessons Learned

This project shows the importance of consistency in mixing of concrete. The strength-maturity relationship developed for one specific concrete mix cannot be used to accurately predict the strength of concrete that may have subtle differences in the mix, such as additives, admixtures, or other constituents. The two sets of concrete cylinders that were poured from the same batch of concrete had comparable strength-maturity relationships, whereas the concrete that was mixed and used for initial calibration did not accurately represent the strength-maturity relationships obtained in the field. (SHA's special note: additional specimens should be planned for calibration/verification purposes if future studies on maturity meter are conducted. ASTM 1074 allows for adjustments when there is more than 10% deviation when developing the Strength-Maturity Relationship. Unfortunately, there were no extra specimens available to conduct the adjustment in this study.)

APPENDIX A

STATE MIX 6 DESIGN PROPORTIONS

The concrete mixes shall conform to the following:

TABLE 902 A

PORTLAND CEMENT CONCRETE MIXTURES									
MIX NO.	28 DAY SPECIFIED COMPRESSIVE STRENGTH psi	STANDARD DEVIATION psi	CRITICAL VALUE psi	MIN CEMENT FACTOR lb/yd³	COARSE AGGREGATE SIZE M 43 / M 195	MAX WATER/ CEMENT RATIO by wt	SLUMP RANGE in.	TOTAL AIR CONTENT %	CONCRETE TEMPERATURE F
1	2500	375	2430	455	57, 67	0.55	2 5	5 8	70 ± 20
2	3000	450	3010	530	57, 67	0.50	2 5	5 8	70 ± 20
3	3500	525	3600	580	57, 67	0.50	2 5	5 8	70 ± 20
4	3500	525	3600	615	57, 67	0.55	4 — 8	N/A	70 ± 20
5	3500	525	3600	580	7	0.50	2 — 5	5 — 8	70 ± 20
6	4500	675	4770	615	57, 67	0.45	2 — 5	5 — 8	65 ± 15
7	4200	630	4420	580	57	0.50	1½ — 3	5 — 8	70 ± 20
8	4000	600	4180	750	7	0.42	2 — 5	5 — 8	65 ± 15
9	3000 (a)	N/A	N/A	800	57, 67	0.45	4 — 8	5 — 8	70 ± 20
10	4500	675	4770	700	¾" – No. 4	0.45	2 5	6 9	65 ± 15
11	4200	630	4420	—	57, 67	0.45	2 5	5 8	65 ± 15
12	4200	630	4420	—	¾" – No. 4	0.45	2 5	6 9	65 ± 15

Note 1: When concrete is exposed to water exceeding 15,000 ppm sodium chloride content, Type II cement shall be used. In lieu ofType II cement, a Type I cement may be used in combined form with an amount of up to 50 percent replacement with ground iron blast furnace slag, or an amount of up to 25 percent replacement with Class F fly ash. The Contractor shall submit to the Engineer the proposed mix proportions and satisfactory test results per C 1012 showing a sulfate resistance expansion not exceeding 0.10 percent at 180 days

Note 2: The temperature of Mix No. 6 when used for other than superstructure work as defined in TC-1.03 shall be 70 ± 20 F.

Note 3: Type A or D admixture shall be added to bridge, box culvert, and retaining wall concrete.

Note 4: Nonchloride Type C admixtures may be used when approved by the Engineer.

Note 5: Other Slump Requirements:
When a high range water reducing admixture Type F or Type G is specified, the slump shall be 4 to 8 in.
When synthetic fibers are specified, the slump shall be 5 in. maximum.
When concrete is to be placed by the slip form method, the slump shall be 2-1/2 in. maximum.
When the absorption of the coarse aggregate is greater than 10 percent, the slump shall be 3 in. maximum.

Note 6: Mix 9 shall contain a Type F high range water reducing admixture.

Note 7: Mix 10 and 12 shall be proportioned as specified in 211.2 of the ACI's Recommended Practices for Selection Proportions for. Structural Lightweight Concrete. The maximum average Density of Cured Concrete shall be 118 lb/ft³. Control testing for Density of Cured Concrete shall be two companion cylinders for each 100 yd³, or fraction thereof, as specified in M 195.

Note 8: Mix 11 and 12 shall also conform to all requirements as specified in Table 902 C.

(a) Acceptance will be based on a minimum compressive strength of 3000 psi in 24 hours. Design approval will be given based on trial batch obtaining a minimum compressive strength of 2500 psi in 12 hours. Testing shall conform to 902.10.08 except that cylinders shall remain in the molds until tests are conducted.

Coarse and fine aggregate having an expansion up to 0.10 percent when tested for alkali silica reactivity (ASR) MSMT 212 may be used without restriction. Aggregates having an expansion greater than 0.10 but less than 0.35 percent are considered reactive and may only be used when one of the options in table 902 B are employed. Those having an expansion of 0.35 percent and greater are prohibited.

APPENDIX B

MORTAR COMPRESSION TEST DATA

CUBE RESULTS: 4 °C
Initial time: 3/25/2010 at 10:30 am
Time of Final Set: 3/26/2010 at 3:00 am
Elapsed Time to Final Set: 16.5hrs

Time of Break	Age of Break	Average Strength (MPa)	Average Strength (PSI)
3/26/10- 7:30PM	33 hr	1.45	210
3/28/10- 4:30AM	66 hr	5.72	830
3/30/10- 10:30PM	132 hr	10.62	1540
4/05/10- 10:30AM	264 hr	19.72	2860
4/16/10- 10:30AM	528 hr	22.55	3270
5/08/10- 10:30AM	1056 hr	28.20	4090

CUBE RESULTS: 21 °C
Initial time: 3/25/2010 at 10:30 am
Time of Final Set: 3/25/2010 at 6:00 pm
Elapsed Time to Final Set: 7.5hrs

Time of Break	Age of Break	Average Strength (MPa)	Average Strength (PSI)
3/26/10- 1:30AM	15 hr	4.00	580
3/26/10- 4:30PM	30 hr	9.51	1380
3/27/10- 10:30PM	60 hr	16.82	2440
3/30/10- 10:30AM	120 hr	23.58	3420
4/04/10- 10:30AM	240 hr	35.03	5080
4/14/10- 10:30AM	480 hr	47.85	6940

CUBE RESULTS: 32 °C
Initial time: 3/25/2010 at 10:30 am
Time of Final Set: 3/25/2010 at 4:00 pm
Elapsed Time to Final Set: 5.5hrs

Time of Break	Age of Break	Average Strength (MPa)	Average Strength (PSI)
3/25/10- 9:30PM	11 hr	5.86	850
3/26/10- 8:30AM	22 hr	14.00	2030
3/27/10- 6:30AM	44 hr	22.61	3280
3/29/10- 2:30AM	88 hr	34.40	4990
4/01/10- 6:30PM	176 hr	48.13	6980
4/09/10- 2:30AM	352 hr	50.75	7360

APPENDIX C

CALIBRATION CYLINDERS COMPRESSION TEST DATA

Date	Age	Average Strength (MPa)	Average Strength (PSI)
03/26/2010	1 day	12.34	1790
03/28/2010	3 days	24.06	3490
03/30/2010	5 days	29.23	4240
04/01/2010	7 days	33.92	4920
04/08/2010	14 days	39.43	5720
04/22/2010	28 days	43.99	6380

APPENDIX D

LAB-SET CYLINDERS COMPRESSION TEST DATA

Date	Age	Average Strength (MPa)	Average Strength (PSI)
03/17/2010	1 day	9.63	1397
03/19/2010	3 days	16.43	2383
03/21/2010	5 days	23.01	3337
03/23/2010	7 days	25.23	3660
03/30/2010	14 days	29.83	4327
04/13/2010	28 days	41.87	6073

APPENDIX E

FIELD-SET CYLINDERS COMPRESSION TEST DATA

Date	Age	Average Strength (MPa)	Average Strength (PSI)
03/17/2010	7	24.67	3578
03/19/2010	10	28.01	4063
03/21/2010	14	30.98	4493
03/23/2010	28	44.02	6384

APPENDIX F

MATURITY METHOD GUIDELINES FOR APPLICATION IN MARYLAND

Cement Mortar Cube Testing Procedures

Mortar cubes with a two-inch diameter are to be prepared from the fresh concrete-mix cement paste, and sieved through a No. 4 sieve (square openings) to remove the coarse aggregate. Final setting time must be measured.

Three final-set mortar specimens are to be prepared using containers allowed by ASTM C 403/C 403 M. Prepare 18 cubes per set. There will be 54 (3x18) cubes in total.

One of the 3 sets (18 cubes per set) is to be placed in each temperature bath.

Three temperature baths are required. The temperature baths are the anticipated highest, lowest and mean temperatures to which the in-situ concrete will be exposed.

The specimens are to be demolded approximately one hour prior to the first compression test for that set.

Three mortar cubes from each set are to be compression tested in compliance with ASTM C 109/C109M when the concrete's age is twice the age at final setting (measured for the particular temperature condition).

A total of six sets of testing for each temperature condition are to be performed (For instance, if final set time occurs at 6 hours, tests would be completed at 12, 24, 48, 96, 192, and 384 hours).

The value of the activation energy divided by the rate constant, Q, is to be calculated using the procedure outlined in the Annex of ASTM 1074 2010 (Annex A1.1.8.2 and A1.3).

Concrete Cylinder Testing Procedures

Concrete cylinders are to be made from the same concrete as the mortar cubes.

Twenty cylinders are required (6 inches by 12 inches), and these cylinders should be made at approximately the same time as the cubes.

Two cylinders are to be made with temperature sensors placed in the center, and these are to be connected to the maturity meter to obtain a continuous temperature record.

Eighteen cylinders are to be made for compression testing.

Three cylinders are to be tested at 1, 3, 5, 7, 14, and 28 days, for a total of 3 cylinders tested on each of the six designated testing days.

Concrete cylinders are to be made in accordance with ASTM C 192/ C192 M, and they are to be compression tested in accordance with ASTM C 39/C 39 M.

Water storage tanks are to comply with ASTM 511 (water saturated with calcium hydroxide). Based on the temperature history of the cylinders, the equivalent age of the concrete may be calculated using the Arrhenius equation, which is equation 2 in ASTM 1074 2010. A 30-minute interval is to be used. The strength of the cylinders may then be plotted against the equivalent age. The hyperbolic trend line is to be used, and the general form is shown below:

$$S = S_u \frac{k(t_e - t_0)}{1 + k(t_e - t_0)}$$

Furthermore, the relative strength is determined by dividing both sides of the equation by the 28-day strength. This relative strength expresses the actual strength as a fraction of the 28-day strength, and must be used when the temperature is the only maturity data gathered in the field.

$$RS_{28} = \frac{S}{S_{28}} = \frac{\left({}^{S_u}/_{S_{28}} \right) k(t_e - t_0)}{1 + k(t_e - t_0)}$$

Estimating In-Place Strength

The required strength of the bridge deck should be divided by the expected 28-day strength. This quotient is the value of the required relative strength. Using this value of relative strength, the value for the expected equivalent age may be read from the graph.

Temperature sensors should be embedded within the bridge deck at locations that are deemed critical for exposure and structural requirements. The temperature history is to be recorded, and the equivalent age calculated. As soon as the concrete has attained the required equivalent age, bridge cylinders should be compression tested. If the difference between expected strength and measured strength consistently exceeds 10 percent, a new strength-maturity relationship must be developed. If the percent difference is below 10 percent, the strength-maturity relationship is accepted, and construction work may proceed.

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