



# Development of a Concrete Maturity Test Protocol

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Research Project  
Final Report 2013-10

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# Table of Contents

<b>Chapter 1. Introduction.....</b>	<b>1</b>
Report Outline .....	1
<b>Chapter 2. Review of Current Research and Technology.....</b>	<b>3</b>
Maturity Method .....	3
<i>Nurse-Saul Method.....</i>	<i>3</i>
<i>Arrhenius Method.....</i>	<i>5</i>
<i>Selected Method.....</i>	<i>6</i>
Mathematical Models for Maturity Curves .....	6
Use of Supplementary Cementing Materials .....	8
Maturity Method with Flexural Strength .....	8
Evaluation of Available Technology.....	8
<i>Wired Sensors.....</i>	<i>9</i>
<i>Wireless Sensors.....</i>	<i>10</i>
<i>Installation.....</i>	<i>11</i>
<b>Chapter 3. Field Testing .....</b>	<b>12</b>
Site Selection.....	12
Site Visit Activities .....	13
<i>Sensor Placement in Concrete.....</i>	<i>13</i>
Test Standards .....	16
<i>Preparing and Testing Concrete Specimens .....</i>	<i>16</i>
<i>Site Visits .....</i>	<i>18</i>
2009.....	18
2010.....	20
2011.....	20
<i>Three-Year Summary of Site Visits.....</i>	<i>21</i>
<i>Compilation of Maturity Curves.....</i>	<i>22</i>
<b>Chapter 4. Laboratory Testing.....</b>	<b>26</b>
Test Standards .....	26

Development of Testing Matrix .....	27
<i>Testing Matrix</i> .....	27
<i>Number of Samples</i> .....	28
Flexural Beam Testing .....	28
Discussion of Results .....	28
<i>Quantity of Total Cementitious Material</i> .....	29
<i>Quantity of Cement (No Fly Ash)</i> .....	30
<i>Fly Ash Replacement</i> .....	31
<i>Water-Cement Ratio</i> .....	32
<i>Additional Admixtures</i> .....	33
Flexural Beams.....	34
<i>Opening to Traffic Criteria</i> .....	39
<i>Field Application</i> .....	40
Conclusion.....	41
<b>Chapter 5. Maturity Curve Selection .....</b>	<b>42</b>
<i>Statistical Analysis</i> .....	42
<i>Model Development Discussion</i> .....	49
<b>Chapter 6. Development of a Maturity Database .....</b>	<b>60</b>
Population of Maturity Database.....	60
Maturity Curve Viewer Development.....	60
<b>Chapter 7. Recommendations for Specification Development .....</b>	<b>63</b>
Concrete Pavement Maturity in other States.....	63
Recommendations .....	64
<i>Maturity Curve Development</i> .....	64
<i>Maturity Curve Usage in Construction</i> .....	65
<i>Maturity Curve Validation</i> .....	65
Suggestions for Consideration .....	65
<b>Chapter 8. Conclusions.....</b>	<b>66</b>
<b>References .....</b>	<b>68</b>

**Appendix A: Draft Construction Specification**

**Appendix B: Maturity Curve Development and Validation Spreadsheets**

**Appendix C: Draft laboratory Manual**



## List of Figures

Figure 1: intelliRock wired temperature/maturity sensor and data collector.....	9
Figure 2: iButtons – Untreated and ready for connection (scale is inches). .....	10
Figure 3: iQtag sensor and data collector. ....	11
Figure 4: iQtag sensor installation on dowel basket. ....	13
Figure 5: IntelliRock sensor installation. ....	14
Figure 6: IntelliRock sensor installation. ....	14
Figure 7: IntelliRock sensor installation. ....	15
Figure 8: Set of 15 beam molds for maturity curve development. ....	16
Figure 9: Location of iButton sensor in flexural beam specimen. ....	17
Figure 10: Maturity curve – MN 7, near Montevideo, MN (2009). ....	19
Figure 11: Maturity curve – I-90, near Alden, MN (2009).....	19
Figure 12: Daily consistency test results – MN 7, Montevideo, MN (2009).....	20
Figure 13: Flexural strength maturity curves – all sites – approximately 28 days. ....	23
Figure 14: Flexural strength maturity curves – all sites – approximately seven days. ....	23
Figure 15: Flexural strength maturity curves – best fit (using up to 14 or 28 days of data).....	24
Figure 16: Maturity relationships with varying cementitious content (cement and fly ash). ....	30
Figure 17: Maturity relationships with varying cement content and 0% fly ash. ....	31
Figure 18: Maturity relationships with varying fly ash replacement, about 7 days.....	31
Figure 19: Maturity relationships with varying fly ash replacement, about 28 days.....	32
Figure 20: Maturity relationships with varying w/cm, about 7 days. ....	32
Figure 21: Maturity relationships with varying w/cm, about 28 days. ....	33
Figure 22: Maturity relationships with varying air entraining admixture dosage. ....	33
Figure 23: Maturity relationships with varying water reducing admixture dosage. ....	34
Figure 24: Beam test results and exponential regression line, up to about 7 days. ....	35
Figure 25: Beam test results and exponential regression line, about 28 days.....	36
Figure 26: Maturity relationships, varying fly ash content, beams, 7 days. ....	37
Figure 27: Maturity relationships, varying fly ash content, beams, 28 days. ....	37
Figure 28: Maturity relationships, varying cement content (0% fly ash) in beams. ....	38
Figure 29: Maturity relationships, varying cement content (0% fly ash), beams, 28 days.....	38

Figure 30: Opening to traffic criteria, mixes with varying fly ash content.....	39
Figure 31 Opening to traffic criteria, mixes with varying cement content (0% fly ash). .....	40
Figure 32: Linearized logarithmic regression model, using data from the Albert Lea site. ....	44
Figure 33: Un-transformed logarithmic model, using data from the Albert Lea site. ....	45
Figure 34: Linearized hyperbolic regression model, using data from the Albert Lea site.....	47
Figure 35: Un-Transformed hyperbolic model, using data from the Albert Lea site. ....	47
Figure 36: Linearized exponential regression model, using data from the Albert Lea site. ....	48
Figure 37: Un-transformed exponential model, using data from the Albert Lea site.....	49
Figure 38: Logarithmic model, using data from the Woodbury site.....	50
Figure 39: Hyperbolic model, using data from the Woodbury site. ....	50
Figure 40: Exponential model, using data from the Woodbury site.....	51
Figure 41: Logarithmic model, using Moose Lake data, up to 2,000 C-hr.....	52
Figure 42: Hyperbolic model, using Moose Lake data, up to 2,000 C-hr. ....	53
Figure 43. Exponential model, using Moose Lake data, up to 2,000 C-hr. ....	53
Figure 44: R <sup>2</sup> values for each mix tested in field sites (includes all data). ....	54
Figure 45: R <sup>2</sup> values for each mix tested in field sites (includes data only up to 7 days).....	55
Figure 46: Maturity database sheet. ....	61
Figure 47: Close-up of maturity database graph.....	61
Figure 48: Close-up of maturity database selection pane. ....	62
Figure 49: Maturity database information entry form. ....	62

## List of Tables

Table 1 Field sites visited. ....	12
Table 2 Testing schedule for maturity curve development.....	17
Table 3: Summary of site visit data collection over three years.....	21
Table 4: Summary of batch proportions. ....	22
Table 5: Age when required opening to traffic strength is met. ....	25
Table 6 Field sites – Time to meet opening to traffic criterion. ....	40
Table 7: Summary of NRMSE for maturity models, all data. ....	56
Table 8: Summary of NRMSE for maturity models, maturity < 10,000 C-hr.....	56
Table 9: Summary of advantages and disadvantages of each model.....	58

## **Executive Summary**

An extensive field and laboratory project was undertaken to evaluate the applicability for using the concrete maturity method to predict opening to traffic criteria for portland cement concrete paving operations in Minnesota. The field study included visits to, sampling of concrete from, and testing hundreds of flexural beams from 18 paving projects in the state over a three-year period. At each of those projects, different equipment for measuring concrete temperature, and methods for computing maturity were evaluated. In the laboratory study, about 700 hundred two-inch mortar cubes were tested to develop sensitivity analyses related to the proportions of cementitious materials, water-cementitious materials ratio, and other components.

The study also evaluated different mathematical models and their ability to predict concrete strength relative to the computed maturity. In addition, a database of concrete mixes and their associated maturity curves were developed with a small tool in the form of a spreadsheet for viewing maturity curves and entering new information into the database. A draft construction specification was developed along with a draft laboratory manual for creating a maturity curve for use on construction projects.

The results of this project include recommendations for maturity meters and/or temperature data loggers, the method and ages for testing flexural beams when developing and validating maturity curves, the use of the exponential model for maturity curves, and suggestions for a construction specification and a laboratory manual. While this project focused on the applicability of the maturity method to concrete paving construction projects, further data collection and evaluation should be conducted by MnDOT as the method is implemented into standard practice. Appropriate modifications should then be made to ensure the method's ability to predict traffic opening and to enhance the effectiveness of paving operations.

# Chapter 1. Introduction

Since gaining popularity in the 1970s, and through subsequent research through the 1990s, the maturity method for estimating concrete strength has become more widely used in many aspects of the concrete industry. The maturity method is a non-destructive procedure that has been used to relate concrete strength to its maturity – the area under the time-temperature curve as the concrete cures. The maturity method can be used to estimate when the concrete has gained sufficient strength to sawcut joints, remove forms, and open a pavement to traffic loads.

Relationships between strength and maturity are common for many standard portland cement concrete (PCC) pavement mixes, although most paving mixes used in Minnesota use various combinations of pozzolanic materials and chemical admixtures and often low water-cement ratios (w/c). The rate of hydration (and therefore the rate of heat generation), the total amount of hydration eventually achieved, and other factors related to concrete mixes are all dependent on the quantity and proportions of cement, supplementary cementing materials (SCMs), aggregates and w/c. Other factors that can play major roles in the hydration characteristics are the temperature and humidity of the ambient air at the time of placement and during curing, and the measures taken by the paving contractor to protect the fresh concrete from adverse weather conditions.

This report describes the efforts of the research team to develop strength-maturity relationships for various high-SCM and low w/c mixes often utilized by the Minnesota Department of Transportation (MnDOT), and presents analyses of the effects of the different components in those mixes. A procedure for using the maturity method in the field is also included in this report. The project team visited 18 concrete paving job sites and instrumented them with maturity meters, cast and tested 270 full-size flexural beams in the field and another 75 in the lab, and produced and tested over 600 two-inch mortar cubes as part of the research discussed in this report.

The field validation sites as well as the laboratory testing program used commercially-available maturity meters and temperature data loggers, and utilized both wired and wireless technology for data transfer. Several of these data loggers are currently owned by MnDOT. Laboratory testing was conducted at Minnesota State University, Mankato, using an environmental chamber and standard concrete testing equipment.

## Report Outline

This report begins with a review of existing literature about maturity, and maturity specifications for concrete paving available from other states. It then describes the field testing program and the various paving sites visited by the project team. The laboratory testing program is then presented, followed by a discussion on appropriate mathematical functions with which to model the strength development in paving concrete in relation to its maturity.

Chapter 6 describes the development of a potential maturity database and curve viewer tool for the mixes observed and tested in the laboratory and field testing programs. It also allows the Concrete Office to add new mixes to the database for future comparisons and reference.

The seventh chapter presents recommendations for specifications to implement the maturity method on concrete paving projects using flexural beams. It also presents suggestions for worksheets which contractors and the MnDOT Concrete Office may use to develop maturity curves for a specific mix, as well as to conduct validations of the same mix during the construction process.

## Chapter 2. Review of Current Research and Technology

This chapter includes a basic review of the literature regarding the maturity method in general and in its use in concrete pavements in particular. Other sections in this chapter review the use of flexural strength testing with the maturity method and the types of sensors commonly used in its implementation.

### Maturity Method

The maturity method has increased in popularity in recent decades due to its ability to help advance the rate at which concrete construction can be completed. Since the publication of the first standard methods for maturity by the American Society of Testing and Materials (ASTM) in 1987 (subsequently updated as recently as 2011) [1], the use of time-temperature relationships have helped to determine early-age strength gain in concrete pavement [2]. The use of the maturity method in paving projects helps contractors predict proper curing time and avoid overestimating the time required for concrete to gain sufficient strength. One result of this is that highway agencies can open concrete pavements to traffic earlier, making the construction process more efficient in terms of the time required. By taking advantage of the information produced with the maturity method, contractors are better able to estimate time for joint sawing, form removal, as well as removal of protective practices such as cold weather insulation [2]. The maturity method does have limitations that must be considered, however. Any particular maturity relationship is only valid for a specific concrete mix, and any changes to the mix are likely to require the development of a new maturity curve. The evaluations using the maturity method focus mainly on the short-term strength development of the concrete. Another limitation is that the method only takes into account the time-temperature relationship and does not account for consolidation or other contributing factors [2]. There are two basic methods for applying the concepts of maturity – the Nurse-Saul method and the Arrhenius methods. The maturity developed through the use of these methods can be correlated with the strength gain of the concrete at a particular time.

#### *Nurse-Saul Method*

Often known as the *Temperature Time Factor* (TTF), the Nurse-Saul method is the most commonly used method for computing maturity. The widespread use of this method is attributed to its ease of calculation. Saul developed the following principle through his research that is now known as the maturity rule, stating that *Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity* [3]. According to ASTM C1074 the equation for the maturity index or time-temperature factor is as follows:

$$M(t) = \sum (T_a - T_0)\Delta t$$

Where:

M(t) = the maturity index, or time-temperature factor at age t, degree-days or degree-hours, also known as the Time-Temperature Factor,

- $\Delta t$  = a time interval, days or hours,
- $T_a$  = average concrete temperature during time interval,  $\Delta t$ , °C, and
- $T_0$  = datum temperature, °C.

One limitation to this equation is that the time-temperature factor is a linear approach to the maturity method. This is acceptable as long as the curing temperature does not vary widely during the period of concrete strength gain. If there is a large variation, errors in the computations begin to become evident. As stated by Carino and Lew [3], “It is based on the assumption that the initial rate of strength gain (during the acceleratory period that follows setting) is a linear function of temperature.” In most cases though, it follows more of an exponential than linear relationship. According to Chanvillard and D’Aloia [4] the use of this linear relationship leads to an underestimation of the influence of higher temperatures on the strength gain of concrete over short periods of time, and an overestimation of strength at later ages.

The Nurse-Saul method is dependent upon the selection of an appropriate datum temperature. The datum temperature is that corresponding to the start of significant strength gain within the concrete. Once the temperature of the mixture exceeds this datum temperature the strength gains that follow are considered significant and can be modeled by the Nurse-Saul method. The most commonly used values for this datum temperature are -10 and 0 C [5], but the only way to obtain a correct datum temperature is through the performance of a regression analysis on experimental data. According to Tank and Carino [6] this temperature is associated with a rate constant of zero taking the rate constant as:

$$k(T) = C(T - T_0)$$

Where:

- $k(T)$  = rate constant function,  $\text{day}^{-1}$ ,
- $T$  = curing temperature °C,
- $C$  = regression constant, corresponding to the strength of a sample at a given age, and

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

Where:

- $S(t)$  = strength at time  $t$ ,
- $S_u$  = limiting strength at infinite age,
- $k_t$  = rate constant at the curing temperature  $T$ ,  $\text{day}^{-1}$ ,
- $t$  = chronological age at temperature  $T$ , days, and
- $t_0$  = age when strength development is assumed to begin, days.



According to Carino [7] the preceding equation can be written in the following form.

$$S = \frac{S_u k_t (M - M_0)}{1 + k_t (M - M_0)}$$

Where:

- $k_t$  = rate constant at the curing temperature  $T$ ,  $\text{day}^{-1}$  (the original equation uses “A” rather than  $k_t$ ),
- $M$  = maturity index at age  $t$ , and
- $M_0$  = maturity index at age  $t_0$ .

The Nurse-Saul method of computing the concrete maturity index can also be used with the logarithmic or exponential methods. Even with the use of an experimentally obtained datum temperature Carino and Tank indicate that this method is not as accurate as the approach using the Arrhenius Method.

### ***Arrhenius Method***

Known as the *Equivalent Age Method*, the Arrhenius method was developed as an alternative to Nurse-Saul in an effort to develop a more precise maturity model. The equivalent age method obtains its name from the way that it approaches maturity. Tank and Carino [6] state that “it represents the age at a reference curing temperature that would result in the same fraction of the limiting strength as would occur from curing at other temperatures.” One limitation with this method is that the development of this approach yielded a complex equation that is much more difficult to implement than the Nurse-Saul approach to maturity, discussed previously. The Arrhenius method is also reliant upon the use of absolute temperature (K), and activation energy, which makes its use inconvenient. The initial Arrhenius approach was developed in 1977 by Freiesleben, Hansen and Pedersen, referenced by Carino and Lew [3]. This equation given by Tank and Carino [6] is shown as follows.

$$t_e = \sum \left[ e^{-Q \left( \frac{1}{T} - \frac{1}{T_r} \right)} \right] \Delta t$$

Where:

- $Q$  = activation energy of the mix divided by the universal gas constant,
- $T$  = average temperature at the given interval (K),
- $t_e$  = equivalent age at a specific reference temperature (hrs.),
- $T_r$  = reference temperature (K), and
- $\Delta t$  = time interval.

The quantity:

$$e^{-Q\left(\frac{1}{T}-\frac{1}{T_r}\right)}$$

is known as the affinity ratio ( $\gamma$ )

In an attempt to simplify this method Carino proposed a variation of this approach that is referred to as the exponential approach. This variation transforms the affinity ratio to the following [6]:

$$\gamma = e^{B(T-T_r)}$$

Where:

B = temperature sensitivity factor  $C^{-1}$ .

Combining terms yields the following version of the equivalent age method.

$$t_e = \sum e^{B(T-T_r)} \Delta t$$

The advantage of this approach is that it is dependent upon temperature values in C rather than K, and requires the use of a temperature sensitivity factor rather than the previous equation's use of the activation energy divided by the gas constant.

### ***Selected Method***

Based on the discussion in the previous sections, and the relative advantages and disadvantages of the two methods, the remainder of this report uses the Nurse-Saul method for computing concrete maturity. This is in line with the previous research conducted by Rohne and Izevbekhai at MnDOT, on the I-694/I-35E interchange [8].

## **Mathematical Models for Maturity Curves**

This section introduces the three mathematical models that are evaluated in more detail in Chapter 5. Each of them has advantages and disadvantages, which are also discussed in detail in that chapter. The three mathematical models are the logarithmic, hyperbolic, and exponential forms. For determining the values of the coefficients in the models, each of them are linearized and a linear regression is performed to find the best fit for the actual data collected in the field or in the laboratory.

The logarithmic model for the maturity-strength relationship is:

$$MR = m \ln(TTF) + b$$

Where:

- MR = modulus of rupture, or flexural strength, psi,
- TTF = time-temperature factor, using the Nurse-Saul method of modeling concrete maturity, degree-hours, or C-hr,
- m = slope of the linearized logarithmic model, and
- b = y-intercept of the linearized model.

In this model, the  $m$  and  $b$  values are coefficients that are determined through the regression analysis.

The hyperbolic model is:

$$MR = S_{\infty} \left[ \frac{k_t (TTF - t_0)}{1 + k_t (TTF - t_0)} \right]$$

Where:

- $S_{\infty}$  = long-term strength, psi,
- $k_t$  = rate constant, 1/(C-hr), and
- $t_0$  = age at beginning of strength development, C-hr [20, 21].

Each of these three components of the model is determined through the regression analysis.

The exponential model, sometimes called the sigmoidal model, is given as

$$MR = S_u e^{-\left(\frac{\tau}{TTF}\right)^{\alpha}}$$

Where:

- $S_u$  = ultimate expected flexural strength, psi
- $\tau, \alpha$  = time and shape coefficients.

As with the hyperbolic model, the three coefficients above are determined through a best-fit regression analysis.

As mentioned above, each of these models is evaluated in more detail in Chapter 5. In that chapter, the exponential model is recommended for use in describing the maturity-strength relationship. However, in the first year of the field study, the logarithmic model was used. After the additional investigation into the different mathematical models, however, the exponential model was selected for the remainder of the project.

## **Use of Supplementary Cementing Materials**

In the application of the maturity method, a primary limitation is that each maturity curve is specific to a single concrete mix, and the rate of strength gain will change based on the different material compositions and quantities in the mix. Each particular curve is representative solely of the particular concrete mixture from which it was developed. The use of supplementary cementing materials in concrete has created a very broad range of mix designs that serve varying purposes. SCMs are very beneficial in the development of specific characteristics within concrete. When it comes to strength development, however, they can create some issues that must be understood. The use of SCMs in concrete has been shown by Juenger, et al. “to increase setting time and decrease early strength gain” [9]. This complication is yet intensified when lower air temperatures are present [9]. In the State of Minnesota, the combination of SCMs usage and low temperatures is widespread [8]. This combination, coupled with low water/cement ratios can create some unique issues that must be resolved prior to the production and placement of such concretes.

## **Maturity Method with Flexural Strength**

Since concrete pavements often fail in flexure, it is important to have a knowledge of how the flexural strength develops in concrete during those critical early hours. One advantage of using the maturity method with respect to flexural strength is that it gives a better representation of the strength compared to the stresses to which it may be subjected. Research using the correlation of flexural strength and maturity has been limited. The use of compression tests with cylinders is the common method in the development of maturity curves because it is thought that there is lower variability associated with the results obtained from a compressive test than from a flexural test [2]. The research results presented in this report will focus on the correlation of flexural strength to maturity to help expand knowledge of this correlation even further.

## **Evaluation of Available Technology**

Within the construction industry, advances in technology have led to better monitoring of the materials and structures that make up transportation infrastructure. In regard to the application of the maturity method to determine in-situ strength of concrete pavements, microprocessors have been implemented to automatically record and store concrete temperatures at previously determined intervals. These sensors are designed at a size that allows them to be placed inside of the plastic concrete to obtain accurate results [2]. Some sensors such as the IntelliRock and the iQtag apply maturity concepts directly to the data they collect in order to output a pre-computed maturity value. Most of the sensors used in this project apply the Nurse-Saul method and can provide maturity values directly. However, for the purposes of this project, actual concrete temperature data were downloaded from the sensors.

There are two general types of temperature sensors or loggers – wired and wireless. Wired sensors provide a direct link to the data collector while allowing the sensor to be placed at a critical location in the concrete. Wireless sensors have a built-in transmitter and a handheld receiver with which to download the information. Each has its advantages and disadvantages for use in concrete pavement applications.

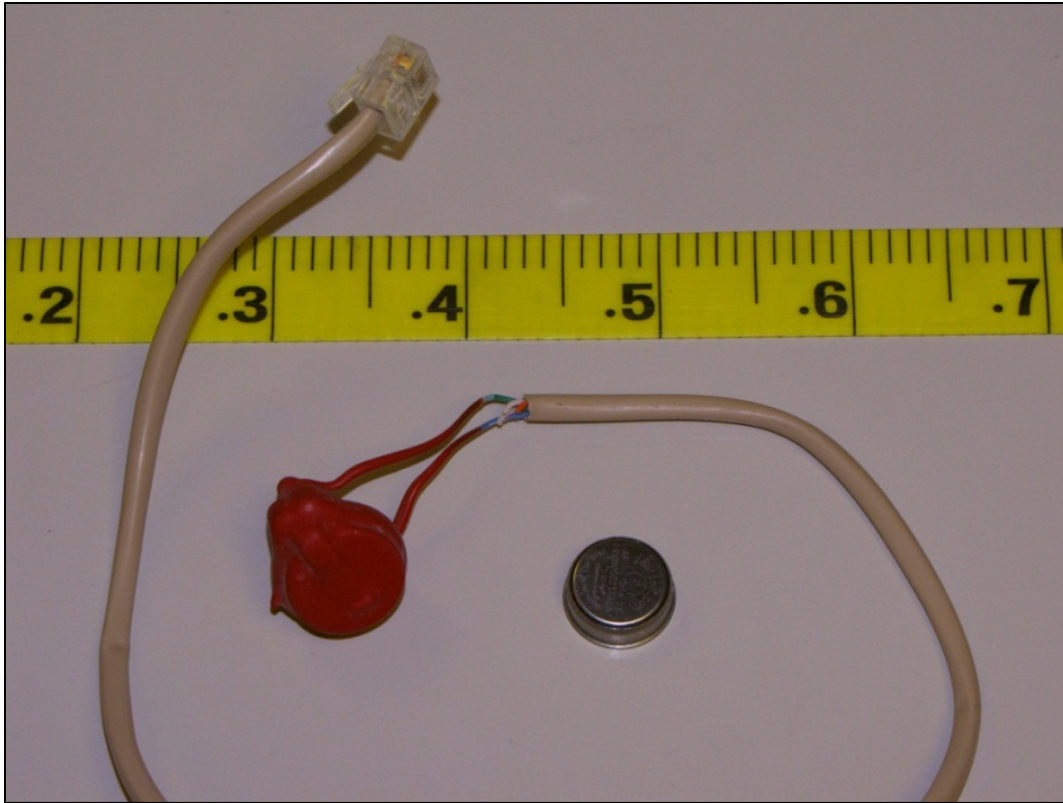
## *Wired Sensors*

These sensors communicate with the data receivers through wires that are attached and which must be protected during the construction activities. The wires can also limit the location of the sensor within the concrete, although for concrete pavements, sensors placed at mid-depth and approximately 18 inches from the edge of the pavement are acceptable. Two wired sensors were used in this project, for different purposes. The IntelliRock sensor was used in the field construction sites at each location to simulate the installation during actual construction and testing, and is shown in Figure 1. This is a commercially-available product and can be purchased with a data collector [10]. The IntelliRock sensor collects temperature data at various intervals depending on the time after activation, for up to 28 days. It saves the information for download at a later time, and the data collector computes the maturity values upon data download.



**Figure 1: IntelliRock wired temperature/maturity sensor and data collector.**

The other type of wired sensor is the iButton Thermochron [11]. Figure 2 shows two iButtons – one as it arrives from the manufacturer and one that has been connected to a telephone wire and treated for protection from the harsh environment inside the fresh concrete slab. The iButton collects temperature data but does not automatically compute concrete maturity. This type of sensor was used in the laboratory testing, and in the concrete samples cast on site and delivered to the lab for later testing.



**Figure 2: iButtons – Untreated and ready for connection (scale is inches).**

One of the main disadvantages of the wired sensors, especially those used in the construction environment, is that the wires must be protected after the sensor has been installed. On structural or mass concrete applications this may not be a great concern, since the concrete is placed and not disturbed. In concrete pavements, however, the sensors are placed in the slab, near ground level, and the concrete is exposed with no physical protection from construction activities. The wires must be protected from the paver, finishers, curing spray equipment, and other equipment. If the wires are protected throughout the paving process, the data must be collected prior to the shouldering operations or the wires may be either cut or buried in the shoulder material.

### ***Wireless Sensors***

The development of wireless sensors in the determination of concrete temperature has allowed for easier and more reliable data collection. With the use of devices such as iQtags [12] the use of a hand held data collector and proper installation of sensors allow wireless readings to be taken within a limited range of the sensor. This type of sensor eliminates the wire and its inherent problems. The wireless sensors generally cost about twice as much as the IntelliRock sensors, but allow for significant savings in labor (installation and data collection) and in decreasing the probability of lost data (due to unprotected wires). One disadvantage of the wireless sensor is that although its data transmission range can be up to 50 feet without concrete cover, when placed inside a concrete pavement, the range is decreased to about 10 feet. Proper markings must be placed in order to locate the sensor so that data collection can be successful after the concrete is placed and cured.



**Figure 3: iQtag sensor and data collector.**

Another advantage of this particular wireless sensor is that it is completely programmable, in that the data collection interval can be set by the user, and changed during the testing period. For example, the sensor can be programmed to collect temperature data every 15 minutes in the early ages of the concrete, and then changed to collect data every 60 minutes after an initial period of time. Similar to the IntelliRock, this sensor computes maturity values and can plot data in real time or export data to a computer with actual temperatures and computed time-temperature factors.

### ***Installation***

The application of these sensors requires that the sensors be placed at approximately mid-depth and about 18 inches from the pavement edge. In construction practice, the sensors are placed at a specified interval based on the quantity of concrete delivered, by the number of square yards of pavement placed, or by some other determination. One report mentions the placement at a distance of between 500 and 1000 feet along the length of the pavement [2]. For this project, sensors were placed in two to three locations each day that the project team was on site. The desired interval should be written into the construction specifications to allow for accurate and consistent placement of sensors throughout the project. A suggestion of one sensor every 1,400 feet of paving is made near the end of this report.

## Chapter 3. Field Testing

This chapter describes the identification of project sites, development of the field procedure for the sensor placement and specimen preparation for the field sites that were conducted at each field site over the three construction seasons (2009 – 2011) during this project.

### Site Selection

The initial plan for the project was to visit five sites each year. However, due to some problems with construction schedules and other arrangements, only four were completed in 2009. Five sites were visited in 2010, and in 2011 several other problems occurred which caused the project staff to add more sites. Some of these problems were related to data collection (and the loss of data).

An initial selection of relevant construction projects was made prior to each season by the MnDOT Concrete Office. Once approximately 10 sites were approved, the project staff contacted the MnDOT Resident Engineers for each project to obtain estimates of paving schedules and other specifics. Through this process the project sites were scheduled and others recommended by the resident engineers were contacted for further information.

Table 1 lists the locations the project team visited over the three-year duration of the project.

**Table 1 Field sites visited.**

Construction Season	Site Location
2009	MN 7 – Montevideo (Chippewa County)
	MN 23 – Marshall (Lyon County)
	I-90 – Albert Lea (Freeborn County)
	I-90 – Alden (Freeborn County)
2010	MN 61 – Cottage Grove (Washington County)
	MN 56 – Dodge Center (Dodge County)
	MN 23 – Marshall (Lyon County)
	US 14 – Waseca (Waseca County)
	I-90 EB – Winona (Winona County)
	I-94 – Woodbury (Washington County)
2011	CSAH 10 – Dover (Olmsted County)
	I-94 – Barnesville (Clay County)
	I-35 – Moose Lake (Carlton County)
	CSAH 22 – Rochester (Olmsted County)
	CSAH 25 – Hutchinson (McLeod County)
	I-90 – Centerville (Winona County)
	MN 23 – Granite Falls (Renville County)
	I-94 – MnROAD Cell 6



## Site Visit Activities

The following activities were undertaken at each of the construction sites visited throughout the project. Some minor variations are noted at the end of this section.

- Most sites were instrumented for four days
- Three maturity stations were established per day
- Two temperature sensors were installed per maturity station (one IntelliRock and one iQtag)
- 15 flexural strength beam specimens (6x6x21-inch beams) on one day
- 15 compressive strength cylinder specimens (4x8-inch cylinders) on one day (at the same time as the beams)
- 2 additional cylinders each day on site

These and other necessary items are included in the description for the field projects.

### *Sensor Placement in Concrete*

At each maturity station, one IntelliRock and one iQtag sensor were placed. In order to ensure placement of the sensors at the mid-depth of the slab, the iQtag sensors were attached to dowel baskets, between two dowels, with plastic ties. This arrangement is shown in Figure 4.



**Figure 4: iQtag sensor installation on dowel basket.**

The installation of the IntelliRock sensors was more problematic. Initially the sensors were placed using a wooden dowel with a depth marker, and then the wire was buried inside the concrete and routed through the side of the slab. This process is depicted in Figures 5 through 7.



**Figure 5: IntelliRock sensor installation.**



**Figure 6: IntelliRock sensor installation.**



**Figure 7: IntelliRock sensor installation.**

Due to several difficulties in installing the IntelliRock sensors in this way, other methods were attempted. The best method, after several trials was to insert the IntelliRock wire into a two-foot section of  $\frac{1}{2}$ " steel pipe, hold the sensor tight to the end of the pipe, by pulling the wire at the other end, and inserting the sensor in the edge of the slab to the correct distance. This minimized the disruption to the surface of the slab, and ensured proper sensor location and protection of the wire.

At each location, both sensors were placed at the same longitudinal station, and within two feet of each other laterally to ensure accurate temperature data collection. The physical location of each maturity station was marked or recorded in three ways: temporary paint marking, recording of nearby landmarks (telephone poles, mailboxes, etc.), and GPS coordinates. At later dates, in order to download the maturity data, the sensor locations were found by the GPS coordinates, and then the nearby landmarks. At that point, the data collector was used to “ping” the sensors to determine their precise location. In some cases, the paint marking was still visible, which aided in locating the sensor.

## Test Standards

Appropriate test standards for the field work were followed, including:

- ASTM C 172 – Standard Test Method for Sampling Freshly Mixed Concrete [13],
- ASTM C 31 – Making and Curing Concrete Test Specimens in the Field [14],
- ASTM C 78 – Flexural Strength of Concrete Using Simple Beam with Third-Point Loading [15], and
- Others as referenced by the above standards.

### *Preparing and Testing Concrete Specimens*

For each project site visited, a set of flexural beams was created. The first objective was to develop the maturity curve for the concrete mix used on the construction project. The second objective of making the beams was to help establish processes and specifications for future requirements for using the maturity method on concrete pavement projects.

The maturity curve development was conducted according to ASTM C 1074 (Estimating Concrete Strength by the Maturity Method) with minor modifications. Each set of beams consisted of 15 samples, prepared in accordance with ASTM C 172 (Sampling Freshly Mixed Concrete) and ASTM C 31 (Making and Curing Concrete Test Specimens in the Field). According to the testing schedule to be discussed below, a modified version of ASTM C 78 (Flexural Strength of Concrete Using Simple Beam with Third-Point Loading) was followed. Beam molds prepared for casting specimens at one of the projects are shown in Figure 8.



**Figure 8: Set of 15 beam molds for maturity curve development.**

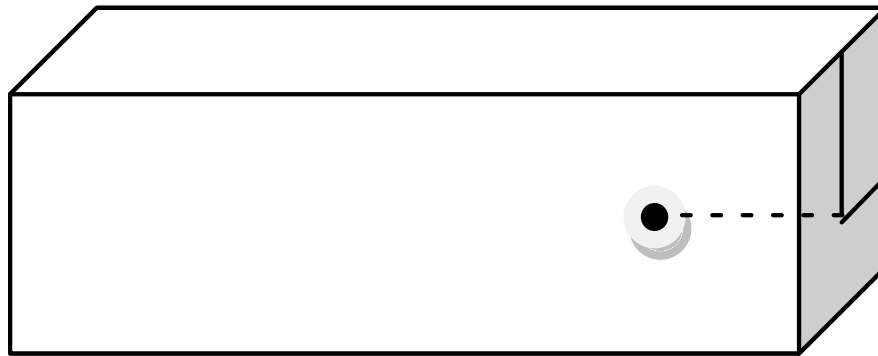
Once the beam samples were cast, they were protected on site for 24 hours, again according to ASTM C 31, at which time the testing began according to the schedule shown in Table 2, below. There were two testing schedules, depending on the concrete mix. For high early strength mixes, the first set of beams was tested at an age of only 12 hours. For normal concrete mixes, the first set was tested at 24 hours. For the first maturity curve with high early strength concrete the standard mix schedule was followed. It was found later that since so much of the strength developed in the first 12 hours, much of the information needed for the maturity curve development had been lost. For subsequent high early strength mixes, the modified schedule was followed.

Each test consisted of three beams, which were tested according to a modified version of ASTM C 78. For the flexural testing, three beams were tested at each age, and the results of all three were used where possible. Procedures in C 1074 were followed to determine if strength values could be used.

In two of the beams in each set of 15, an iButton temperature sensor was embedded in one of the outer thirds of the specimen, as indicated in Figure 9.

**Table 2 Testing schedule for maturity curve development.**

Test Set (3 beams per set)	Approximate Age, days	
	Standard Mix	High Early Strength Mix
1	1	0.5
2	3	1
3	7	3
4	14	7
5	28	28



**Figure 9: Location of iButton sensor in flexural beam specimen.**

The temperature of the concrete in the two beams was recorded at 30-minute intervals, and the time-temperature factor for the maturity calculation was computed according to ASTM C 1074. The maturity curve development and mathematical models for predicting strength based on the maturity method will be discussed in a later chapter.

## *Site Visits*

This section describes the site visits conducted during the three construction seasons (2009 – 2011) and some of the findings during each year. Although the project team planned to conduct each site visit and the sampling and testing schedule as described in the previous section, this was not always possible due to changes in construction schedule, weather, sensor failures, and other reasons. Deviations from the field sampling and testing plan are described in each of the subsections below.

### **2009**

During the first year of the project, several plans were made which were changed in subsequent years due to lessons learned while on site. The first year also required the development of the field procedures and analyses that would be used throughout the project.

Major equipment was purchased, including the iQtag reader and adequate sensors to be used throughout the three-year term of the project. Other equipment that was purchased or acquired include the iButton sensors and data collectors, IntelliRock sensors (most were purchased, but some were obtained from the MnDOT Concrete Office, in addition to the IntelliRock data collector). Concrete sampling and testing equipment was also purchased, including 15 beam molds, a portable third-point flexural testing apparatus, and many of the incidental equipment and tools that were not already available in the concrete lab at MSU.

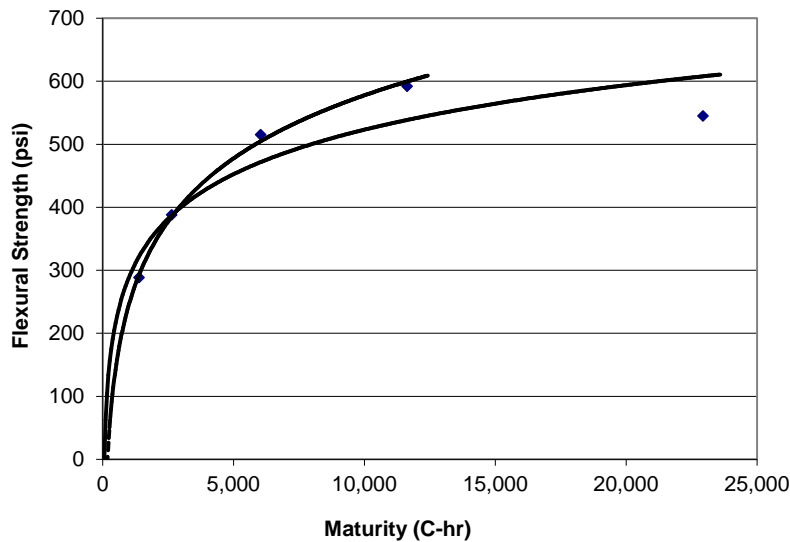
As previously mentioned, the standard field site visit plan was to stay four days at each project, instrument three maturity stations each day, and install one IntelliRock and one iQtag at each station. The plan also called for the sampling and casting of 15 flexural strength beams and 15 compressive strength cylinders, and two additional cylinders each day (to test for consistency).

The project team was at the first site (MN 7 near Montevideo) on the first day of concrete paving. Several problems in the installation of temperature sensors caused the team to decide to begin the four-day time period on the next day on site. Other problems with the concrete, however, caused the construction to be delayed and thus the field team returned to Mankato to wait for paving operations to resume.

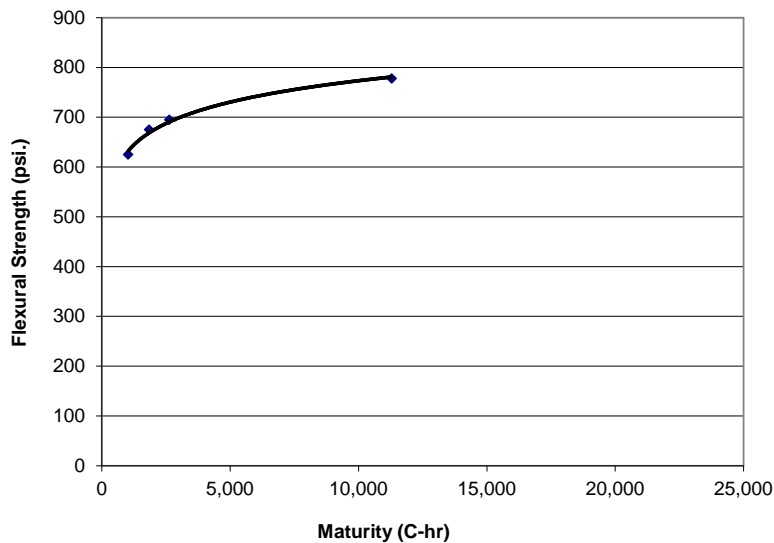
After the initial problems in installing the sensors and acquiring data from them were resolved, the project team conducted the site visit without problems and was able to install all 12 maturity stations and cast the beams and cylinders as expected. The other site visits were instrumented that season, with nearly the same success. The project team stayed at the Alden (I-90) site only three days due to a shortened paving schedule.

The initial results of the Montevideo maturity curve are shown in Figure 10, which includes the maturity and flexural strength values at 1, 3, 7, 14, and 28 days. The solid line indicates the best-fit line for all of the data. However, the data of primary interest in the maturity curve is in the early ages (for determining an appropriate time for opening to traffic) and the maturity curve best-fit lines often perform better when excluding the 28-day data. For these reasons, dashed line is included which indicates the best-fit for the maturity-strength relationship up to the testing conducted at 14 days of age.

As discussed previously, there was one problem in the data related to the first high-early strength site (at Alden, MN). The nature of the high-early strength mix is such that much of the strength is achieved in the first 24 hours. Thus, the flexural strength testing should have been conducted on the revised schedule indicated in Table 2, rather than on the standard schedule developed for the project. Because the first test was conducted at about 24 hours old, there is very little early-age information in the maturity curve as can be seen in Figure 11. In fact, if extended to 0 C-hr, the intercept of the regression curve, which should be negative so that it crosses the x-axis at some maturity value greater than 0 C-hr, is actually positive for this mix. In subsequent sites, other high-early mixes were tested earlier to determine an appropriate regression curve.



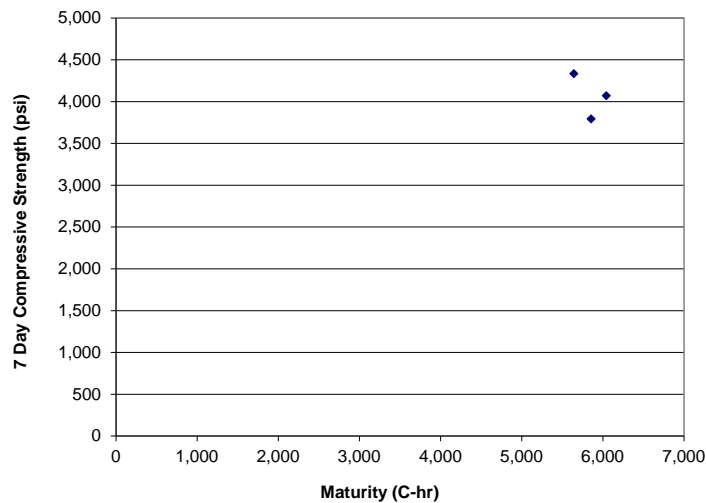
**Figure 10: Maturity curve – MN 7, near Montevideo, MN (2009).**



**Figure 11: Maturity curve – I-90, near Alden, MN (2009).**

One lesson learned in this first construction season was that the form of regression used (a linearized form of a logarithmic curve) does not represent the physical characteristics of the true concrete strength development. Chapter 5 of this report addresses the advantages and disadvantages of the logarithmic models as well as those of the hyperbolic and exponential models for representing concrete maturity-strength relationship. The exponential form of the model was selected for the reasons described in that chapter, and the remainder of this report presents the data in terms of the exponential model.

Another type of testing that was conducted was to evaluate the concrete by testing compressive strength of cylinders made each day on site. These cylinders were cast on site, and cured for 24 hours prior to being transported to the lab at MSU with the beams. Since the cylinders were not expected to become part of the final recommendations for construction implementation, the standard maturity meters described in the previous chapter were not used. Rather, an iButton sensor was placed in one of the cylinders each day to enable the calculation of the maturity index when the cylinders were tested at seven days of age. These cylinders were used to observe the “consistency” of the concrete mix being placed each day the project team was on site. The results of the consistency tests were plotted on a Maturity Index – Compressive Strength plot to show the level of consistency from one day to the next, as shown in Figure 12.



**Figure 12: Daily consistency test results – MN 7, Montevideo, MN (2009).**

**2010**

For the second construction season, a total of six sites, as listed in Table 1, were visited and instrumented. While this was the original plan, to make up for the missing site in 2009, all temperature data in the beams were lost on the I-90 (near Winona) site, resulting in only five viable sets of data from these six sites.

**2011**

As in 2009 and 2010, the project team again worked closely with the MnDOT Concrete Office to identify several concrete paving projects from which to select field sites for the 2011



construction season. The original plan for the project was to instrument five paving sites per year for three years. Since only four were visited in the first year, and only five were successful in the second year, a total of six were planned for the 2011 construction season. By the end of the season, with some additional data collection problems and one site added to the schedule, eight sites, listed in Table 1, were instrumented at various levels, as identified at the beginning of this chapter. The small addition was the MnROAD Cell 6 construction, which was only instrumented for one day, during which the flexural beams were also cast.

***Three-Year Summary of Site Visits***

This section presents a summary of the site visits during the three construction seasons (2009 – 2011). As discussed above, 18 sites were instrumented throughout the project. Although the original plan was to have 15 sites, the project team was not able to collect all of the data at all sites. Sites with critical missing data were omitted and additional sites were instrumented instead. The summary in Table 3 shows the specific information missing for each site. With 18 sites, a planned 4-day stay at each site, and 24 temperature sensors anticipated at each site, it is reasonable to expect that not all the data will be obtained, and that not all of the sensors will work correctly. For the 18 sites instrumented, 16 had complete maturity curve data, with the exception of I-90 EB near Winona (2010) and CSAH 22 in Rochester (2011). For both of these sites, the temperature data for the maturity curve beams was lost.

**Table 3: Summary of site visit data collection over three years.**

<b>Construction Season</b>	<b>Site Location</b>	<b>Status</b>
<b>2009</b>	MN 7 – Montevideo (Chippewa County)	Complete
	MN 23 – Marshall (Lyon County)	Complete
	I-90 – Albert Lea (Freeborn County)	1 of 24 sensors failed
	I-90 – Alden (Freeborn County)	3 days, 8 sensor locations
<b>2010</b>	MN 61 – Cottage Grove (Washington County)	2 days, 4 sensor locations
	MN 56 – Dodge Center (Dodge County)	3 of 24 sensors failed
	MN 23 – Marshall (Lyon County)	8 of 24 sensors failed
	US 14 – Waseca (Waseca County)	3 of 9 sensor locations w/o data
	I-90 EB – Winona (Winona County)	No temperature data for 15 beams
	I-94 – Woodbury (Washington County)	4 of 7 sensor locations w/o data
<b>2011</b>	CSAH 10 – Dover (Olmsted County)	1 of 12 sensor locations w/o data
	I-94 – Barnesville (Clay County)	Complete (11 sensor locations)
	I-35 – Moose Lake (Carlton County)	6 of 11 sensor locations w/o data
	CSAH 22 – Rochester (Olmsted County)	No temperature data for 15 beams
	CSAH 25 – Hutchinson (McLeod County)	4 of 7 sensor locations w/o data
	I-90 – Centerville (Winona County)	1 of 6 sensor locations w/o data
	MN 23 – Granite Falls (Renville County)	Sensor batteries depleted
	I-94 – MnROAD Cell 6	Sensor batteries depleted

The information contained in Table 4 shows the basic mix proportions for each mix evaluated from the site visits. This information, combined with the final maturity-strength curves, is available in the concrete pavement maturity database, which is discussed in Chapter 6. This information is useful when comparing two maturity curves to identify reasons for differences in the mixes. The underlying theory of the maturity method is that two mixes of the same materials and proportions should exhibit the same strength gain characteristics when plotted against the maturity time-temperature factor.

**Table 4: Summary of batch proportions.**

Project	Highway	Date	w/c	Mix Proportions, lb/cy			
				Cement	Fly Ash	Coarse Aggregate	Fine Aggregate
Montevideo	MN 7	Jun. 2009	0.404	401	170	1,721	1,424
Marshall	MN 23	Jul. 2009	0.380	408	178	1,575	1,207
Albert Lea	I-90	Aug. 2009	0.390	420	178	1,820	1,377
Alden	I-90	Sep. 2009	0.338	794	0	1,744	1,119
Marshall (2)	MN 23	Jun. 2010	*	405	178	1,756	1,369
Woodbury	I-94	Jun. 2010	0.360	397	171	1,571	1,606
Dodge Center	MN 56	Jul. 2010	0.348	413	178	1,706	1,425
Winona	I-90	Jul. 2010	0.380	402	175	1,831	1,401
Cottage Grove	MN 61	Aug. 2010	0.347	483	130	1,641	1,524
Waseca	US 14	Aug. 2010	0.393	419	176	1,695	1,391
Dover	Olmsted CSAH 10	May 2011	0.375	402	175	1,784	1,435
Barnesville	I-94	Jun. 2011	0.350	401	137	1,996	1,265
Moose Lake	I-35	Jun. 2011	0.400	409	170	2,135	1,191
Rochester	Olmsted CSAH 22	Jul. 2011	0.355	400	161	1,946	1,304
Hutchinson	McLeod CSAH 25	Jul. 2011	0.344	419	170	1,875	1,244
Centerville	I-90	Aug. 2011	0.384	401	173	1,892	1,304
Granite Falls	MN 23	Aug. 2011	0.420	520	92	1,792	1,228
MnROAD	Cell 6	Aug. 2011	0.354	396	140	1,827	1,258

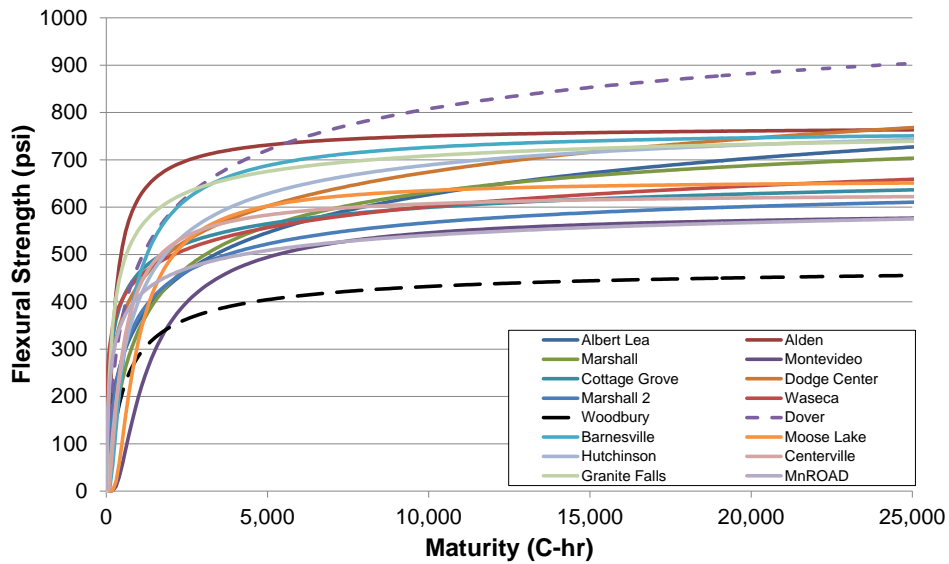
\* This data was not provided in the batch tickets, and calculations from other information indicate a w/c of 0.26 which is likely incorrect.

### *Compilation of Maturity Curves*

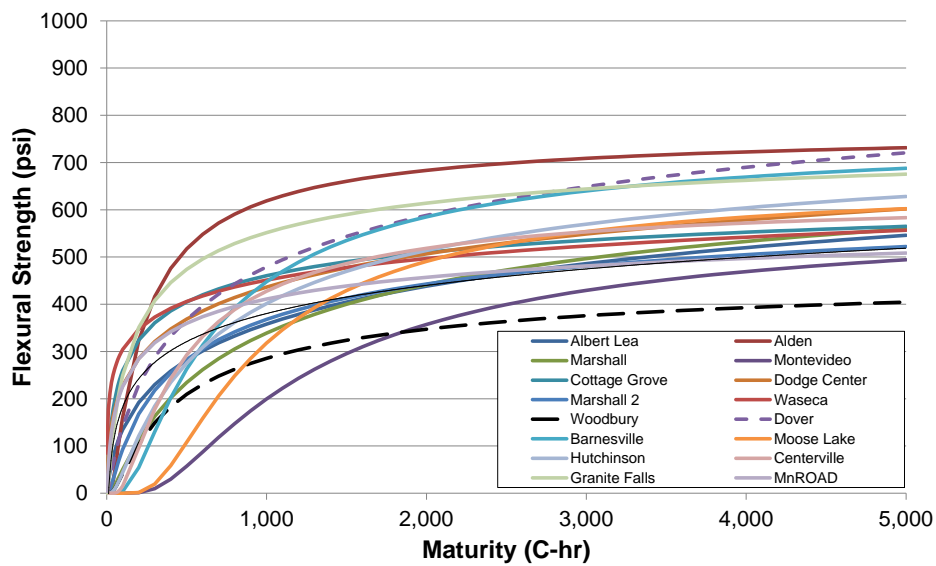
The remainder of this chapter focuses on the initial maturity curves developed for the concrete mixes during this project. The plotted lines shown in Figure 13 are the maturity curves developed for all of the project locations visited throughout the project, except for the two sites without this information, mentioned previously. Figure 14 shows the same data for only the first seven days. These curves use the computed coefficients based on the regression of the data

collected at each of the site visits, and the exponential model, described in more detail in Chapter 5.

In these figures, with 16 maturity curves, it is impossible to distinguish them all in a printed report. However, the curves with the highest and lowest strength after 28 days are indicated with dashed lines (short dashes for the highest strength at 28 days – CSAH 10 in Dover, and long dashes for the lowest strength at 28 days – I-94 in Woodbury).



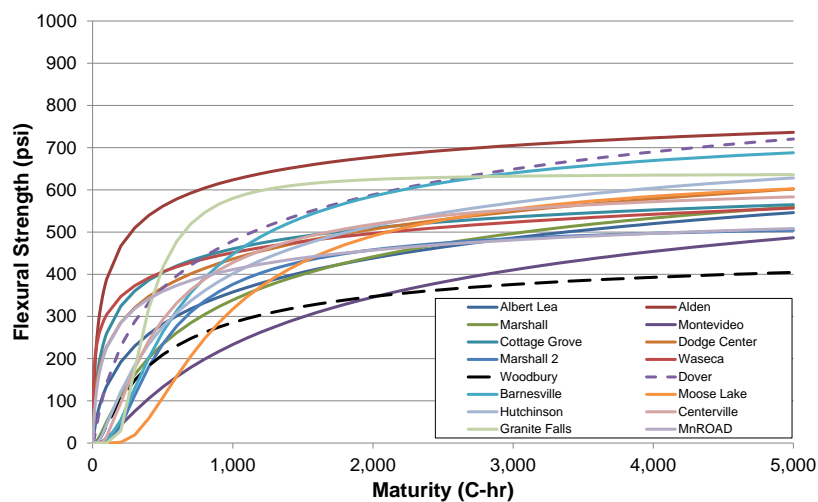
**Figure 13: Flexural strength maturity curves – all sites – approximately 28 days.**



**Figure 14: Flexural strength maturity curves – all sites – approximately seven days.**

In these figures, 25,000 degree-hours is slightly more than the maturity achieved by the time the 28-day testing was conducted, and 5,000 degree-hours represents maturity at about 7 days. Most mixes reached about 23,000 degree-hours by the 28-day testing. This consistency in the maturity at the 28-day testing is primarily due to the consistent curing in MSU's environmental chamber which is set at a constant 73° F.

Since the development of a maturity curve for a particular mix involves the regression of the flexural testing results over a 14- or 28-day period, it was found that for three of the 16 regression curves, the regression fit the data better when the 28-day data was removed from the analysis (leaving data only up to 14 days). The curves in Figure 15 show this adjustment. While there are few differences between the data in Figure 15 and Figure 14, some interesting items to note are discussed below.



**Figure 15: Flexural strength maturity curves – best fit (using up to 14 or 28 days of data).**

Several items are noticeable in the preceding figures.

- *High Early Strength.* The maturity curve which shows the earliest strength gain and among the highest ultimate strength is from the Alden I-90 slab replacement and patching project in 2009 (indicated with a short-dashed line). This project used a high-early strength concrete mix, and the results are evident in the figure.
- *Low Ultimate Strength.* The maturity curve showing the slowest strength gain is from the Woodbury project in 2010 (indicated with a long-dashed line). It is unclear what caused the 28-day strength to be almost 100 psi lower than the next lowest mix. The initial strength gain seems to be similar to others, when viewed in Figure 14.
- *Consistent Maturity Curves.* In Figure 15, the two curves just lower than the highest at 5,000 degree-hours (CSAH 10 near Dover and I-94 near Barnesville) are very similar. This is likely due to the fact that the concrete was produced by the same contractor/supplier using the same mix design. It is interesting to note that two concrete mixes, made in different corners of the state, and about four weeks apart, can display maturity curves so similar.

- *Range of Results.* Excluding the highest and lowest maturity curves shown in Figure 13, the range of 28-day flexural strength is less than 200 psi (from just under 600 psi to just under 800 psi).

Since one of the objectives of using the maturity method in concrete pavement construction is to predict the time that the pavement may be opened to traffic, the information in Table 5 provides both the maturity index (TTF) in C-hr and the chronological age in hours from the time of placement to the predicted time of achieving the minimum required opening strength for each of the sites. The opening to traffic criteria is taken from Table 2301-A in the MnDOT Standard Specifications for Construction [16] and is based on the slab thickness. The maturity when the required strength is achieved is the maturity index (TTF) when the maturity curve predicts that the concrete will exceed the required strength according to Table 2301-A. The corresponding age in hours at ambient conditions when this point occurs is given in the third column of Table 5.

**Table 5: Age when required opening to traffic strength is met.**

<b>Project / Date / Highway</b>	<b>Maturity when Required Strength was Achieved, C-hr (in lab samples)</b>	<b>Corresponding Age at Ambient Conditions, hours (in the field)</b>
Montevideo / Jun 2009 / MN 7	4,777	121-132
Marshall / Jul 2009 / MN 23	2,644	67-79
Albert Lea / Aug 2009 / I-90	1,322	27-31
Alden / Sep 2009 / I-90	Less than 1,000 <sup>1</sup>	Less than 24 <sup>1</sup>
Marshall (2) / Jun 2010 / MN 23	4,355	Partial Data Loss <sup>3</sup>
Woodbury / Jun 2010 / I-94	3,803	110-113
Dodge Center / Jul 2010 / MN 56	1,541	36-40
Winona / Jul 2010 / I-90	Lost Temperature Data <sup>2</sup>	
Cottage Grove / Aug 2010 / MN 61	769	Partial Data Loss <sup>3</sup>
Waseca / Aug 2010 / US 14	1,144	21-25
Dover / May 2011 / Olmsted CSAH 10	889	25-29
Barnesville / Jun 2011 / I-94	1,054	23-30
Moose Lake / Jun 2011 / I-35	1,717	46-49
Rochester / Jul 2011 / Olmsted CSAH 22	Lost Temperature Data <sup>2</sup>	
Hutchinson / Jul 2011 / McLeod CSAH 25 <sup>4</sup>	1,412 / 1,821	29-31 / 38-40
Centerville / Aug 2011 / I-90	Less than 900 <sup>1</sup>	Less than 24 <sup>1</sup>
Granite Falls / Aug 2011 / MN 23	Less than 600 <sup>1</sup>	Less than 24 <sup>1</sup>
MnROAD / Aug 2011 / Cell 6	4,237	Partial Data Loss <sup>3</sup>

1. High-early strength mixes, and some others not specified as high-early strength, exceed the minimum required opening strength prior to the first strength test at 24 hours. Where possible, the first strength test was conducted at 12 hours for mixes known to be high-early strength. Even some 12-hour tests indicated strength greater than the opening criteria.
2. Temperature data from field sensors was lost.
3. Only partial temperature data was recovered from the field sensors before the rollover of internal memory.
4. Thickness changed from 8 in. to 6 in. and opening criteria was 460 and 500 psi, respectively, making time to opening 1,412 and 1,821 degree-hours and 29-31 and 38-40 hours, respectively

## Chapter 4. Laboratory Testing

The laboratory and testing plan were developed early in the project, so that the field and lab work could be coordinated. This procedure and testing plan describes the formulation of a comparison in concrete maturity using compressive mortar cubes and a smaller program of testing full-size flexural beams. The objective in using mortar for most of this work was to minimize the material quantities that would be required (if full size beams were used) and to greatly increase the number of mixes and replications that could be tested. This plan includes the development of the testing matrix (variables and levels of each variable), the number of samples to be tested, and the procedures and test standards to be used in the testing.

The sensitivity of the maturity curves to changes in mix proportions is evaluated in this chapter. One important limitation of the maturity method is that for any change in the proportion of components in a concrete mixture, the strength gain can be expected to change as well. As the proportion of cement is increased, or as the proportion of fly ash or other pozzolanic materials is decreased, the early strength of the concrete is expected to increase. As will be shown in this chapter, the results of the laboratory testing plan described in the next paragraph indicate a need to control batch proportions during construction, and that deviations from the approved mix design exceeding 5% by weight (or 0.02 w/c) should require a different maturity curve to be developed.

Originally, the laboratory testing plan included up to 8 mixes using full-size concrete flexural beams (6x6x21 inches). It was found that this would require over two cubic yards of concrete materials to be stockpiled in the laboratory and to be mixed in a 2.5-cubic foot laboratory mixer or a larger rented mixer. The change to the testing plan allowed for 15 different mixes and approximately 600 cubes to be tested. Initial results showed similar relative differences in performance with different mixes is similar for 2-inch mortar cubes tested in compression and full size (6x6x21 inch) beams tested in third-point flexure. After the mortar cube testing was completed, a smaller testing plan using full-size beams was conducted on a select few mixes from the cube testing.

### Test Standards

Appropriate test standards were followed, including:

- ASTM C 109 [17] – Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in. Cube Specimens),
- ASTM C 192 [18] – Making and Curing Concrete Test Specimens in the Laboratory,
- ASTM C 778 [19] – Specification for Standard Sand, and
- Others as referenced by the above standards.

Some important differences were introduced when implementing these standards, however, including:

- Rather than the standard mortar mix for the cubes as specified in ASTM C 109, the mass of cementitious materials was determined in proportion to their relative mass in a common MnDOT 3A21 concrete mix.
- Once the relative proportion of cementitious material was determined, fly ash was substituted for cement at various rates according to the testing matrix.
- Appropriate admixtures were introduced in the mixture, at dosages proportional to those found in concrete mixes in the field sites visited in Task 3.
- For cells in the matrix calling for additional cement (high-early strength mixes) fly ash was omitted and additional cement was added at rates proportional to the mixes found in the field.

### **Development of Testing Matrix**

The sensitivity analysis consists of a base mix, with each successive mix being a variation on the base mix. The mixes were prepared randomly, meaning that of all mixes, including replicates, each batch was chosen at random, rather than being mixed in the order they appear in the testing matrix. The only mixes that were chosen semi-randomly are those requiring different curing temperature or humidity. These were completed after all other mixes, since the environmental chamber can only accommodate samples at a single set of curing conditions at a time. The 28-day testing for one set of curing conditions must be completed before a new mix at a different set of curing conditions can be placed in the chamber.

Each mixture tested was subjected to the following testing regime.

1. Mixing day (Day 0): 18 mortar cubes were prepared and set in environmental chamber (at minimum 95% humidity, except as noted), in their molds, to cure for 24 hours.
2. Day 1: cubes were removed from their molds and immersed in lime water inside the environmental chamber. One set of three cubes was tested at Day 1.
3. Days 2, 3, 4, 7, and 28: one set of cubes was tested at each age. Of the 28-day set of three cubes, only two were tested. The third was used as a container for a temperature sensor.

Upon completion of the 28-day testing program for each mix, the maturity curve was completed, and the coefficients and other parameters of the mix were entered into the database from which the sensitivity analysis and some regression analysis were conducted.

#### ***Testing Matrix***

The following represents the base mix, and the basic variations to the base mix. Each of these mixes was produced in duplicate.

### Base Mix (Mix #1)

14.1% cementitious material by mass cementitious (570 lbs/cy including 30% fly ash replacement)

80.7% Ottawa sand by mass, as specified in ASTM C 109

5.2% water by mass (w/cm = 0.37)

Admixtures according to manufacturers dosing recommendations

Curing temperature: 73 ±3 °F

Curing humidity: minimum 95%

### Additional Mixes

1. Base with 530 lbs cementitious
2. Base with 0% fly ash and 601 lbs cement
3. Base with 600 lbs cementitious
4. Base with 0% fly ash and 789 lbs cement
5. Base with 0% fly ash and 690 lbs cement
6. Base with 0% fly ash and 740 lbs cement
7. Base with alternate cement
8. Base with alternate fly ash
9. Base with 10% fly ash replacement
10. Base with 20% fly ash replacement
11. Base with 0.34 w/cm
12. Base with 0.40 w/cm
13. Base with 25% additional AE admixture
14. Base with 25% additional WR admixture
15. Base with high curing temperature
16. Base with low curing temperature
17. Base with low curing humidity

### *Number of Samples*

Based on 18 mix combinations, 2 replicates each for most mixes, and 18 samples for each, a total of more than 600 cubes were planned. After repeating some replicates due to errors, over 700 cubes were cast and tested.

### **Flexural Beam Testing**

Upon completion of the cube-strength testing, five batches of concrete were made, selected from the mixes in the cube testing program, for validation using full-size flexural beams. Similar mixtures and curing conditions were prepared for the beams as for the cubes. Based on 15 beams per set, a total of 75 beams were cast and tested for this portion of the laboratory testing.

### **Discussion of Results**

The first component of this section relates to the cube testing and the analysis of data from mixes with variations from the “Base” mix, as described above. Several comparisons were made using



the results of the cube testing to describe the effects of changes in the mix on the maturity curve. The comparisons include the following.

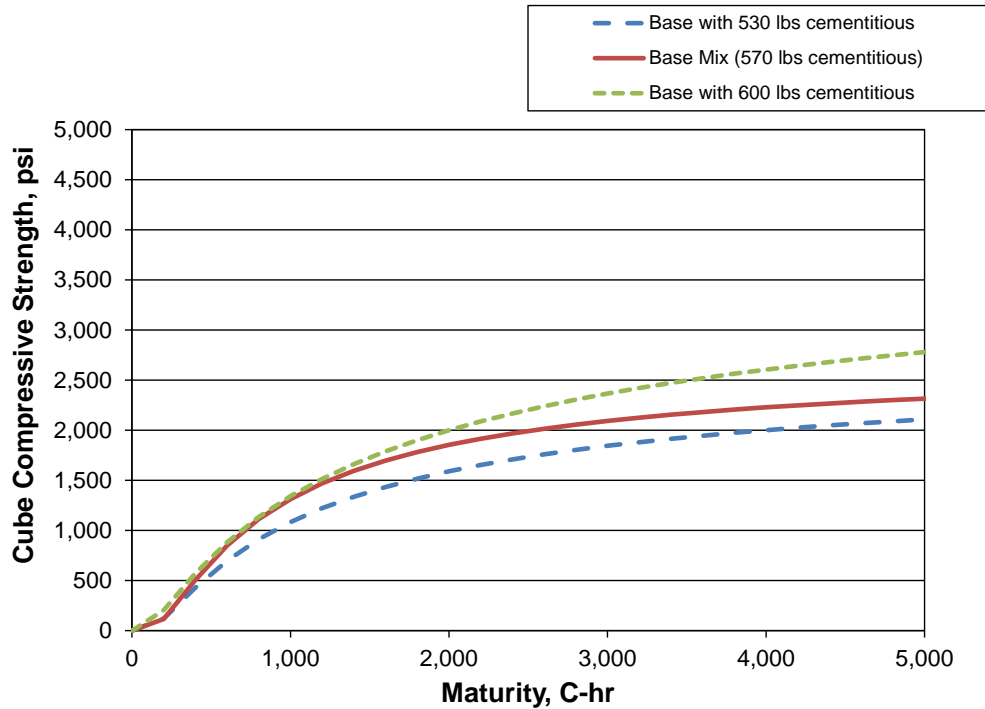
- Quantity of total cementitious material (cement and fly ash)
- Quantity of cement (no fly ash)
- Level of fly ash replacement (with constant cementitious content)
- Water-cement ratio
- Additional air entraining admixture
- Additional water-reducing admixture

In each of the figures below, the Base Mix is shown whether or not it is relevant to the comparison, in order to maintain perspective in the relative levels of the maturity curves. The strength scale on the y-axis of the charts is held constant at 5,000 psi for ease in comparing between figures. Additionally, for the cement and cementitious materials components listed in the charts below, the units listed are in “lbs/cy”.

The purpose of this laboratory study was to identify the sensitivity of maturity curves to changes in mix proportions. For each of the changes indicated in the list above, the following sections will examine the range of effects on the maturity curve and strength development, and the relative effects among the different mixes.

#### ***Quantity of Total Cementitious Material***

Figure 16 shows the relationship between average cube compressive strengths with increasing cementitious material content. Each of the mixes depicted in the chart have 30% fly ash replacement. At the early stages shown in this figure, as the cementitious content increases, so does the compressive strength. The range of strength is from about 2,100 psi to about 2,800 psi at approximately seven days – so that the higher strength mix (with 600 lbs/cy cementitious material) has about 1/3 higher strength than the lower strength mix (with 530 lbs/cy). When compared at about 28 days, the relationship remains, although in this set of laboratory tests the 530-lb and 570-lb mixes are quite close in compressive strength, and the 600-lb mix is significantly higher (a range of 2,600 to 3,700 psi).



**Figure 16: Maturity relationships with varying cementitious content (cement and fly ash).**

***Quantity of Cement (No Fly Ash)***

The curves in Figure 17 show the effect of varying amounts of cement, without fly ash replacement. In general, the three curves displaying the highest strength gains and steepest early-age curves are those with the highest cement contents (690, 740, and 789 lbs). The lower two mixes (not including the Base Mix) were made with 570 and 601 lbs of cement, and also without any fly ash. The Base Mix is shown for comparison. The range of cube compressive strength in this figure (at about seven days) is from about 3,400 psi to over 4,900 psi.

The lowest two curves in the figure (including the Base Mix) have the same amount of cementitious material, and the only difference between them is that one has a 30% fly ash replacement. Without the fly ash, the 570-lb/cy mix has an average seven-day strength of about 3,400 whereas the same mix with 30% fly ash replacement shows about 2,300 psi strength – almost a 50% increase. At about 28 days (25,000 C-hr) the relationship is similar.

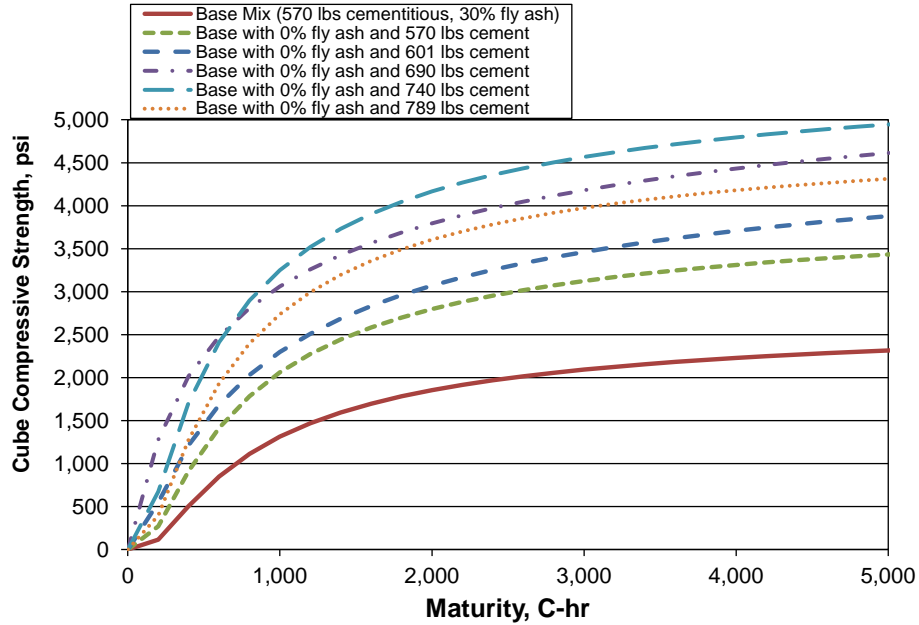


Figure 17: Maturity relationships with varying cement content and 0% fly ash.

### *Fly Ash Replacement*

When the total cementitious content is not changed, but the fly ash replacement level changes from 0% to 30%, as in Figure 18, the overall effect is a decrease in seven-day strength. At approximately 28 days, the maturity curves diverge more than in the other comparisons, as shown in Figure 19. This may be related to the nature of the exponential model at later ages, or to the greater variability in the effects of fly ash on the mixes.

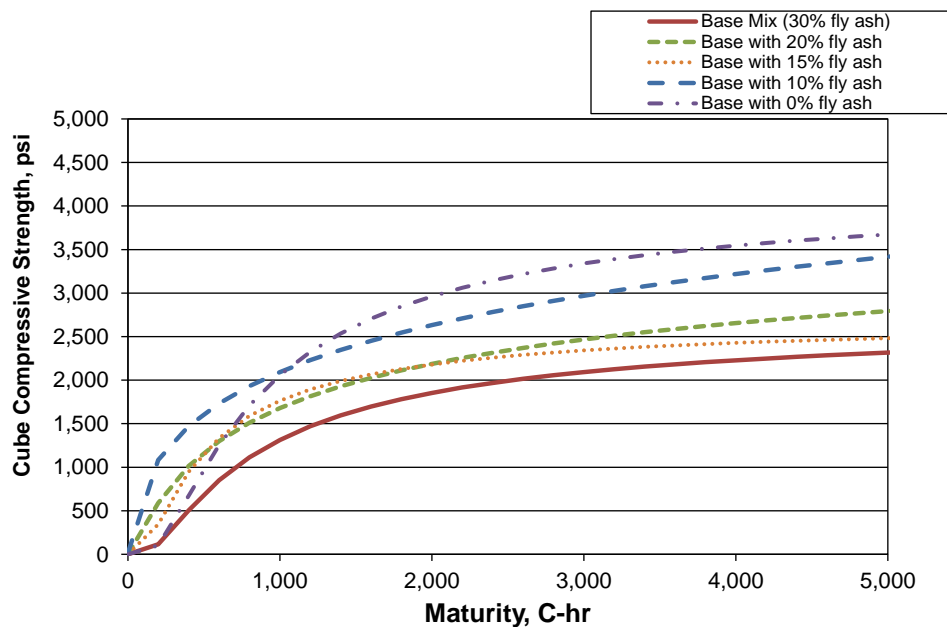
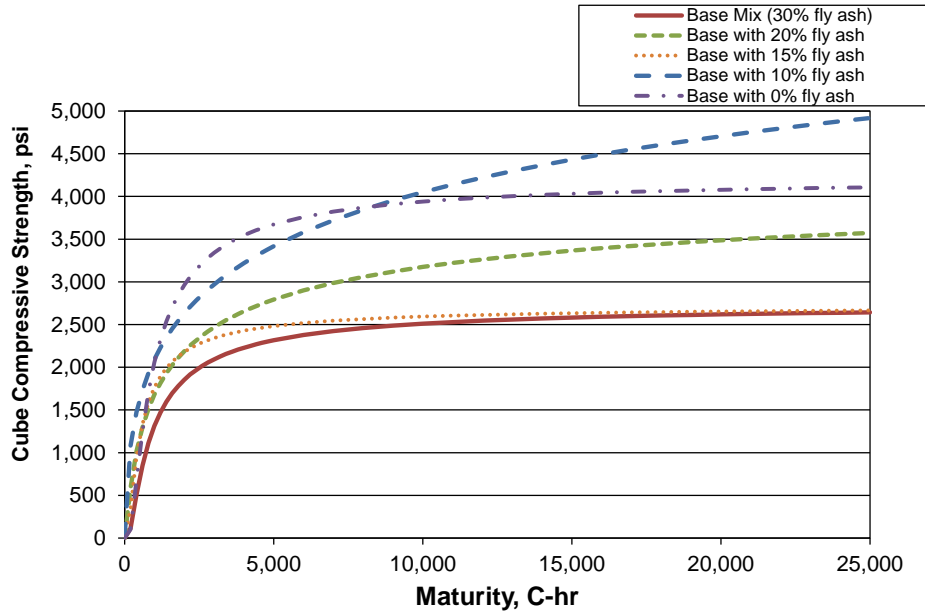


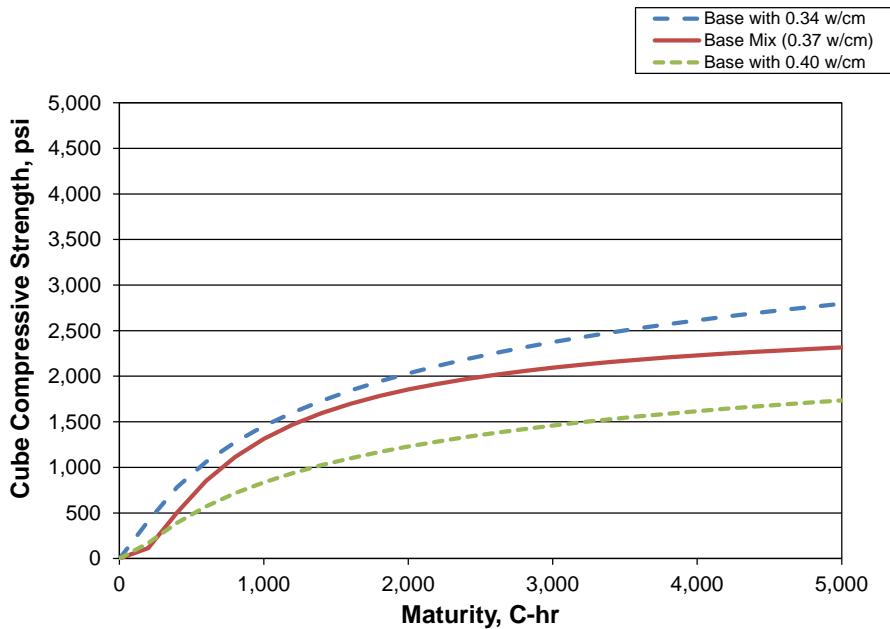
Figure 18: Maturity relationships with varying fly ash replacement, about 7 days.



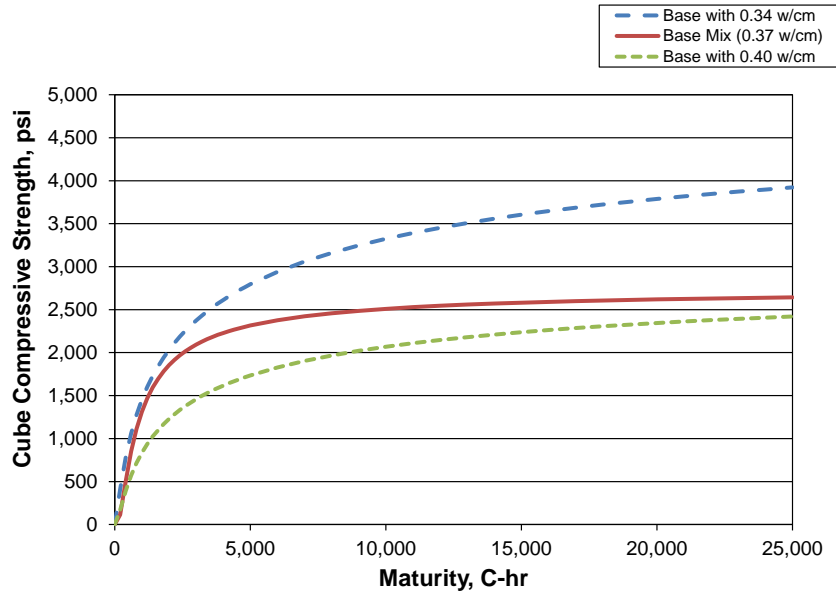
**Figure 19: Maturity relationships with varying fly ash replacement, about 28 days.**

***Water-Cement Ratio***

The curves in Figure 20 show intuitive differences with changes in w/cm. As this ratio increases from 0.34 to 0.40, the compressive strength of the cubes decreases accordingly, at about seven days. At about 28 days, as shown in Figure 21, the 0.40 w/cm mix has increased almost to the level of the base mix (0.37 w/cm).



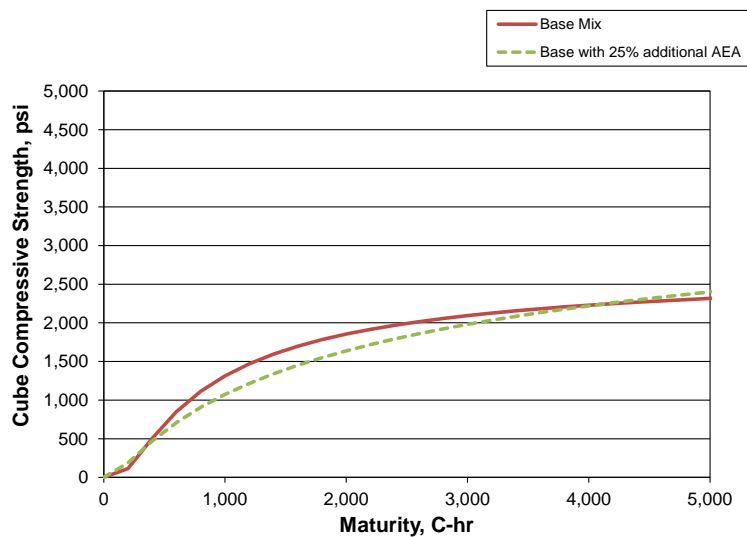
**Figure 20: Maturity relationships with varying w/cm, about 7 days.**



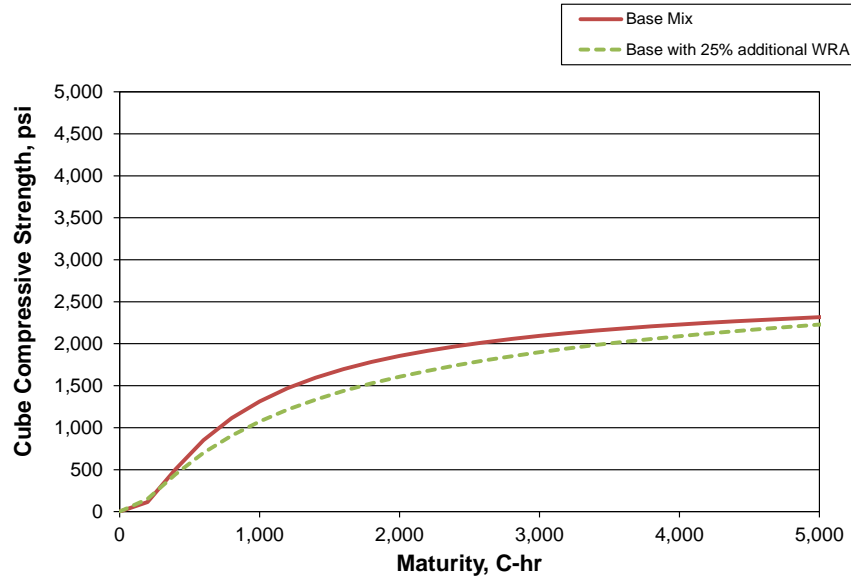
**Figure 21: Maturity relationships with varying w/cm, about 28 days.**

### *Additional Admixtures*

Varying the quantity of air entraining admixture and water reducing admixture did not have a significant effect, as shown in Figures 22 and 23. This would be expected, at the dosage rates included in this study – as specified in the mix design approved by the Concrete Office, and at 25% greater than the approved mix. It might be expected that the air entraining admixture could have a significant effect if it is dosed much higher than specified, if this has the effect of dramatically increasing the air content of the concrete. Likewise, by increasing the water reducing admixture by 25%, a very small (essentially negligible) effect is seen in the maturity curves, as shown in Figure 23.



**Figure 22: Maturity relationships with varying air entraining admixture dosage.**



**Figure 23: Maturity relationships with varying water reducing admixture dosage.**

The next section presents the similar test regime using full-scale flexural beams rather than 2-inch mortar cubes.

### Flexural Beams

Upon completion of the cube testing program, the project team obtained approximately 8,000 lbs of materials to make approximately two cubic yards of concrete for the beam testing program. A total of five mixes was selected and developed based on the original concrete mix proportions used for the cube testing program. The base mix used for the beam testing is as follows.

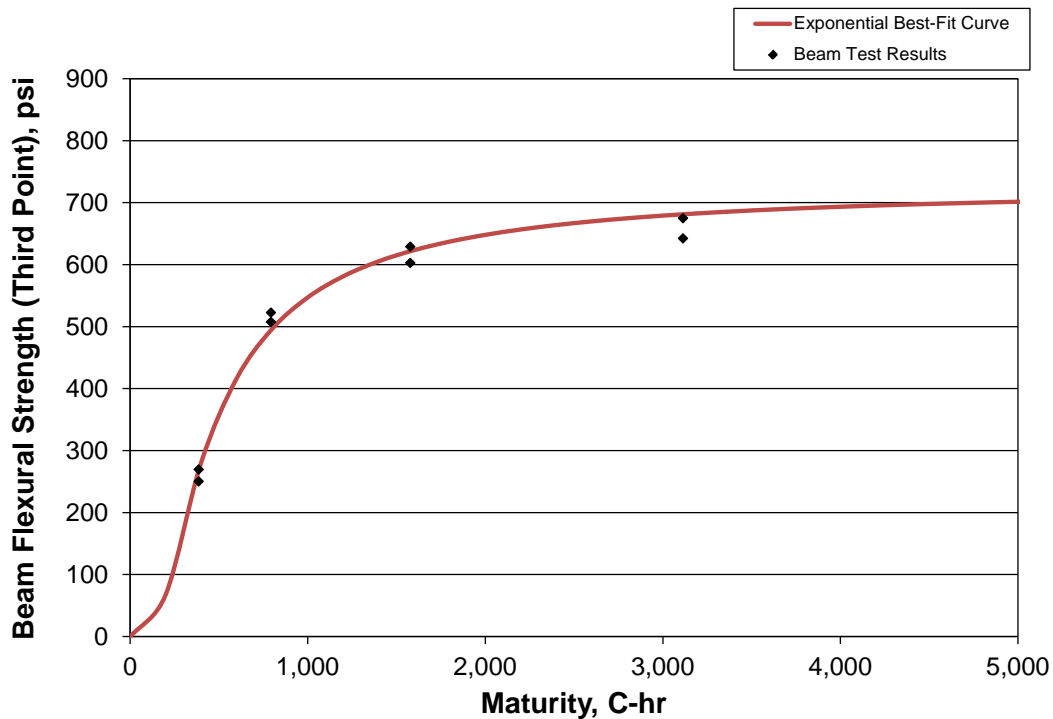
- 400 lb cement, Type I
- 170 lb fly ash, Class C
- 0.37 w/cm
- 1,915 lb coarse aggregate
- 1,235 lb fine aggregate
- 40 oz WRA
- 5 oz AEA

The coarse and fine aggregates were graded to match a typical mix design used in the field sites visited for this project. The beams were cast during the week of 8 – 15 August 2012 in the materials lab at MSU. For each of the five mixes, the materials were weighed, allowed to acclimate in the laboratory for several hours, and were then mixed in a nine cubic foot mixer. Each of the 15 beams was cast within one hour, and temperature sensors (as shown in Figure 2) were placed inside two of them, according to ASTM C 1074. The beams were left in the lab, covered with plastic, for 24 hours. One exception to C 1074 was that one set of beams was tested at an age of 12 hours so that the curve could be defined better in the early ages. After 24 hours, the beams were stripped from the molds and placed inside the environmental chamber, at 72°F and in a condensing fog.

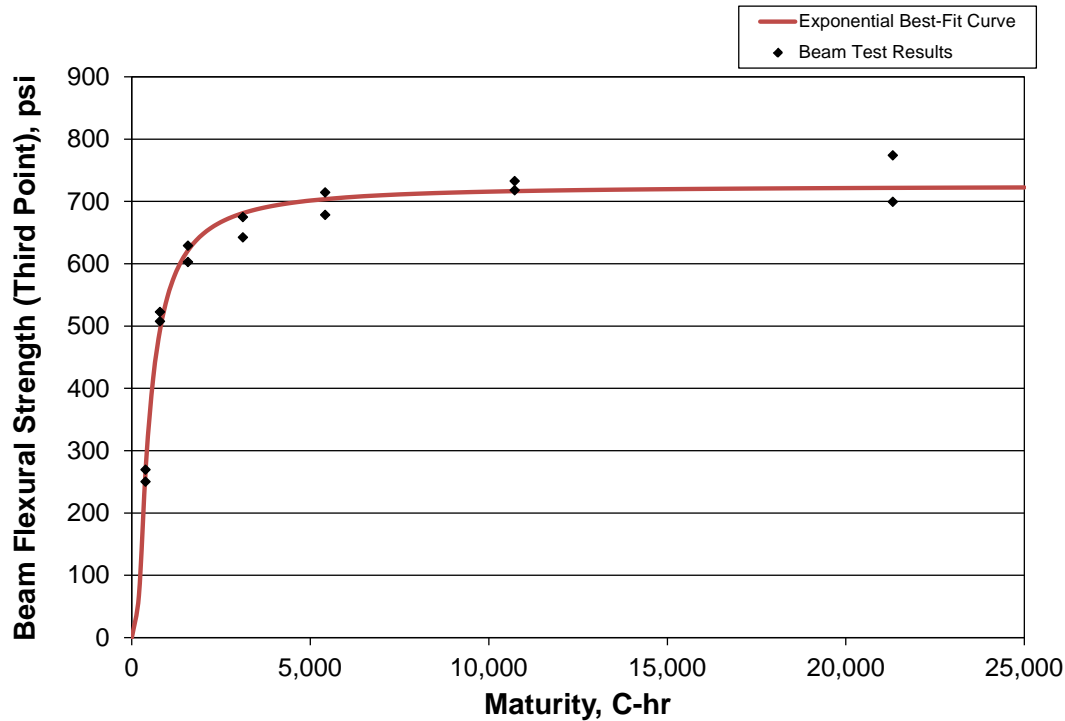
The initial plan for testing the 15 beams was according to ASTM C 1074, which states that two beams are tested at each age, and if the range of the two strength values exceeds 10% of their average, a third beam should be tested and the average of the three is reported. With 15 beams, and with the very good consistency in the test results, the project team was often able to add test ages to the program which enabled the maturity curve to be defined even more.

The concrete beams were tested at five specific ages. If extra beams were available (due to only testing two beams at various ages, additional ages were tested as well. Whereas ASTM C 1074 specifies that the beams be tested at ages of 1, 3, 7, 14, and 28 days, the project team felt that it was important to have a data point at an age of 12 hours, so the five definite ages were 12 h and 1, 2, 7, and 28 days. While preserving adequate specimens for testing at those ages, when additional samples were available testing was also conducted at 4 and 14 days.

Another deviation from the ASTM C 1074 requirements is the type of curve developed from the data. As will be discussed in a later chapter, the exponential curve is used throughout this report because it represents the concrete strength development more completely than the other forms, and especially at early ages. As can be seen in Figure 24, the test results at each age are very close together, and the regression curve fits the early age data very well. The same information is shown in Figure 25, but extended to 25,000 C-hr (about 28 days). At later ages the test results had a bit more variability, but still met the 10% criteria specified in ASTM C 1074.



**Figure 24: Beam test results and exponential regression line, up to about 7 days.**



**Figure 25: Beam test results and exponential regression line, about 28 days.**

In Figure 26, the exponential regression lines of the beam flexural test results are plotted for mixes with varying fly ash content, including 0%, 15%, and 30% replacement of cement. In the very early ages (prior to about 500 C-hr, corresponding to about 12-18 hours) the mix with 0% fly ash has a definite strength advantage over the 15% and 30% mixes. After about 1,000 C-hr, however, the differences are minimal, and as can be seen, by about 5,000 C-hr all three mixes are very close in strength. Approaching 28 days of age, as can be seen in Figure 27, the mix without fly ash again has a small advantage in strength.

It must be emphasized that the results shown in these figures are from a single trial of five mixes, 15 beams each, and with all necessary precautions taken to ensure that the only variation between mixes is the component noted. In addition, while the exponential regression curve models the strength development from a maturity standpoint better than the other forms, it is not perfect. Thus, two randomly chosen beams at a maturity of 1,000 to 2,000 C-hr may have broken a bit high on the base mix, and caused the regression to be pulled higher in that region.



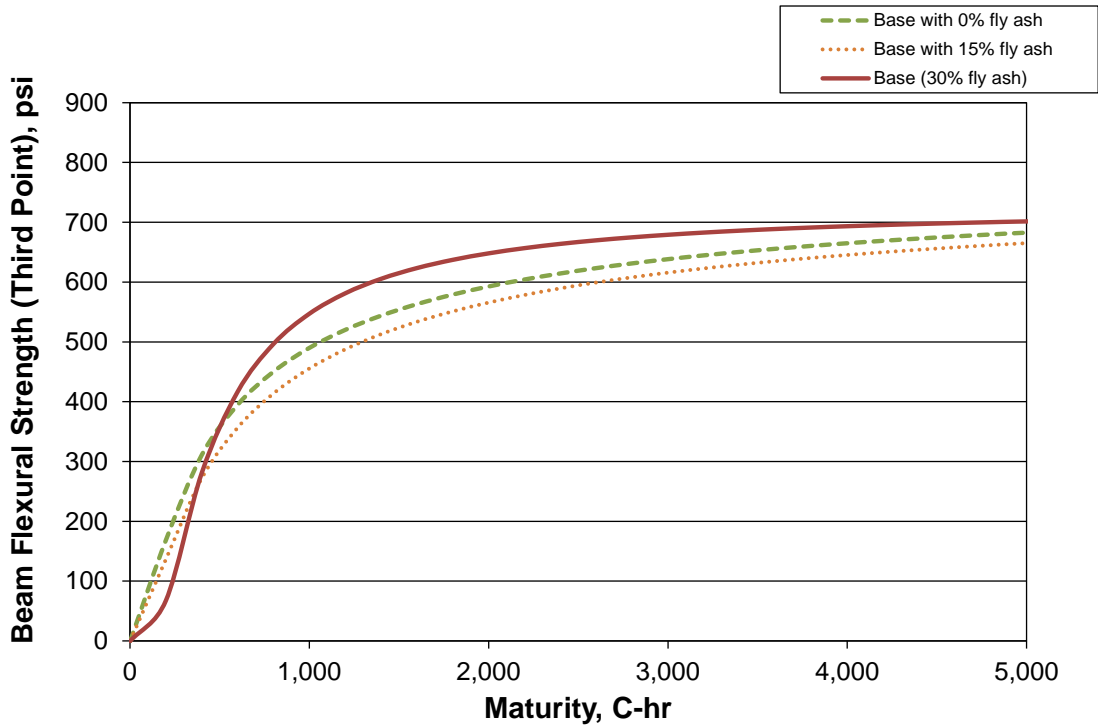


Figure 26: Maturity relationships, varying fly ash content, beams, 7 days.

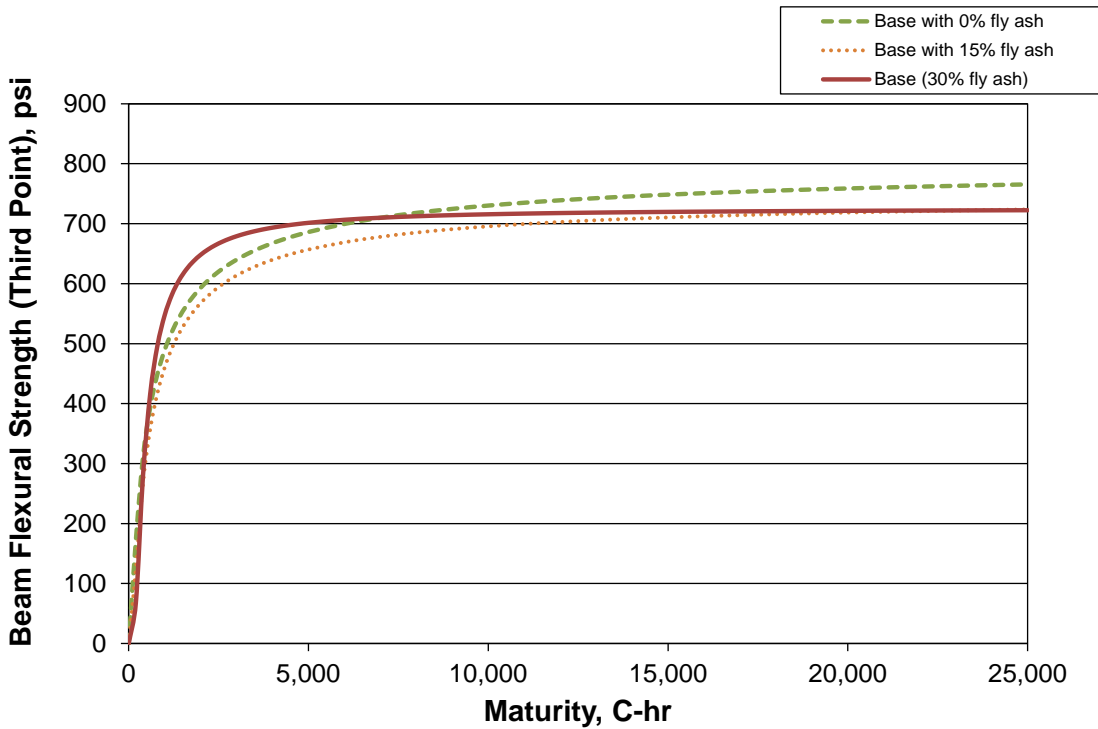
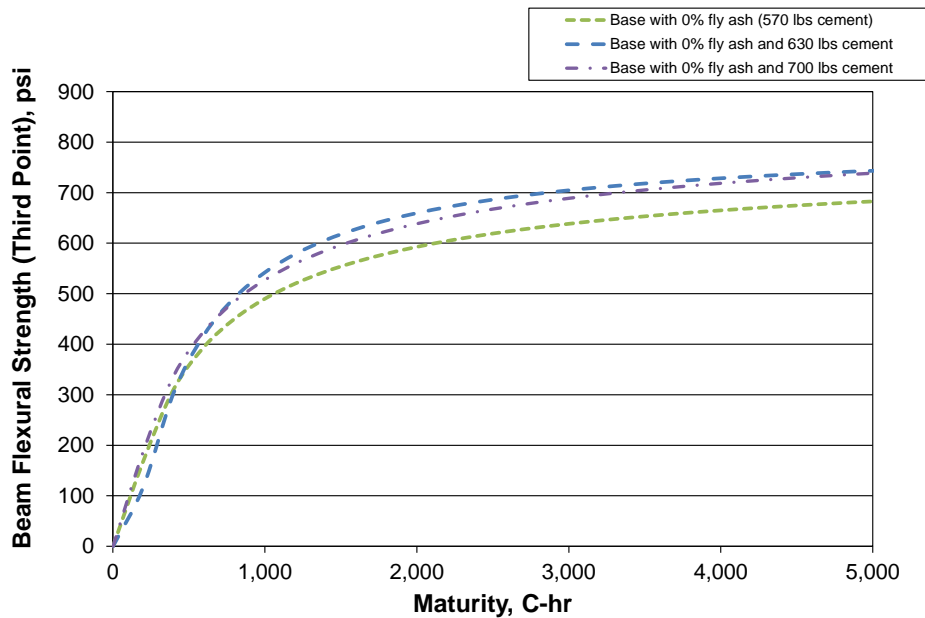
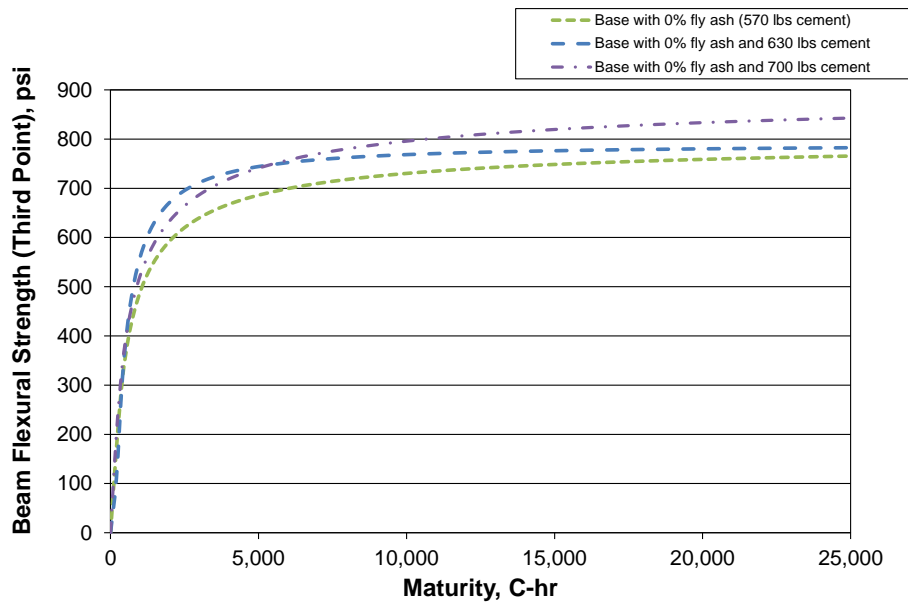


Figure 27: Maturity relationships, varying fly ash content, beams, 28 days.

The curves shown in Figures 28 and 29 contain the maturity curves for three mixes containing no fly ash but varying amounts of cement (570, 630, and 700 lbs, respectively). With these three mixes, during the early ages, the difference in strength is not significant. It is only after about 500 C-hr that the low-cement mix becomes significantly lower in strength than the others. By about 10,000 C-hr, the strengths of the three mixes are visibly in an order expected by the amounts of cement. Even still, at about 28 days the range between the three mixes is only 77 psi, only about 10% greater than the strength of the lower-cement mix.



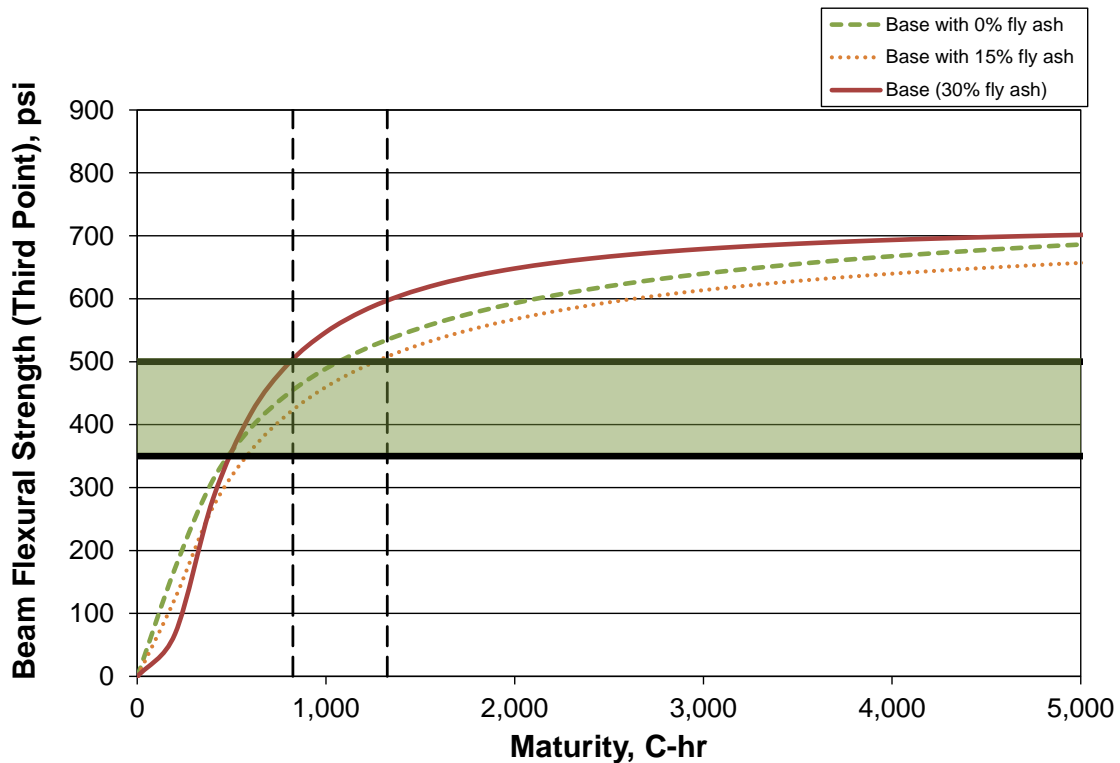
**Figure 28: Maturity relationships, varying cement content (0% fly ash) in beams.**



**Figure 29: Maturity relationships, varying cement content (0% fly ash), beams, 28 days.**

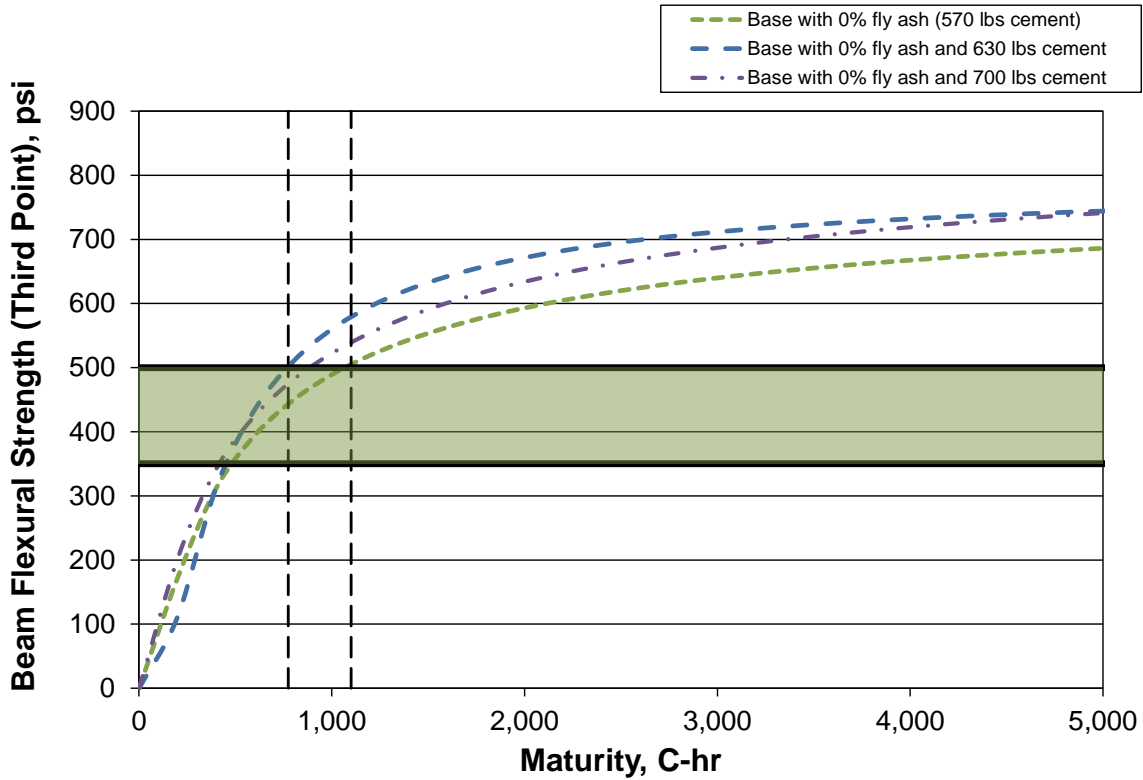
### Opening to Traffic Criteria

Based on the previous discussion about the flexural beam test results, the application of these results is then the relationship of the maturity-strength curves and the time (or the maturity) at which a pavement may be opened to traffic. The green band in Figures 30 and 31 indicate the range of the opening to traffic criterion, based on the slab thickness. This criterion ranges from 350 psi to 500 psi for slabs 10.5 in to 6 in thick, respectively, using information taken from Table 2301-A in the MnDOT Standard Specifications for Construction [16]. Based on the width of this band, the greatest difference in maturity when the mixes with varying fly ash content would have been ready for traffic opening is from 825 to 1,325 C-hr, a range of about 500 C-hr (indicated by the vertical dashed lines). This range of maturity values could represent a time span of 12 to 15 hours, depending on the temperature history of the concrete in question. At the lower end of the range (350 psi) the difference in time to opening is much smaller, both in Figure 30 and in Figure 31.



**Figure 30: Opening to traffic criteria, mixes with varying fly ash content.**

The largest range in maturity values among the mixes with varying cement content and 0% fly ash replacement is lower than that for the varying fly ash content mixes – about 325 C-hr (from 775 to 1,100 C-hr). This can represent a time span of 8 to 10 hours, again depending on the temperature history of the concrete and the conditions at the site.



**Figure 31 Opening to traffic criteria, mixes with varying cement content (0% fly ash).**

***Field Application***

The field sites visited by the project team displayed greater variability in meeting the opening to traffic criterion. Based on the mix proportions given in Table 4, several projects had very similar mix designs, but very different opening to traffic times. Each of the sites in Table 6 had a mix design of approximately 400 lbs cement and 170 lbs fly ash. The information presented in this table is a compilation of data already presented in Tables 4 and 5.

**Table 6 Field sites – Time to meet opening to traffic criterion.**

<b>Project / Highway</b>	<b>Cement / Fly Ash Content, lbs/cy</b>	<b>Opening to Traffic Criterion, psi</b>	<b>Maturity when Met Criterion, C-hr</b>	<b>Time to Meet Criterion after Placement, hrs</b>
Montevideo / MN 7	401 / 170	480	4,777	121-132
Marshall / MN 23	408 / 178	480	2,644	67-79
Dover / CSAH 10	402 / 175	460	889	25-29
Moose Lake / I-35	409 / 170	460	1,717	46-49
Centerville / I-90	401 / 173	390	Less than 900	Less than 24

## Conclusion

As can be seen in Table 6, concrete mixes with similar quantities of cementitious materials and opening to traffic criteria can have very different maturity curves and associated actual time to meet the criteria. This can be due to many variables, including cement fineness, characteristics of the fly ash, aggregate type, gradation and shape, and other factors. This shows the need for individual maturity curves to be developed for specific mixes, and for those curves to be validated at regular intervals throughout a paving project.

Over the course of a paving project, if a particular mix is changed, a new maturity curve should be developed. This may not often be a relevant issue, however, since paving contractors often submit multiple mixes for approval, and it is less often that a mix is modified after having been approved and used on a project. This raises several important questions.

- If a paving contractor submits multiple mixes for approval prior to construction on a project, do all mixes need their own maturity curve?
- May a mix used on a previous project be approved without developing a new maturity curve, if one has already been developed for the same mix?
- May a paving contractor submit some mixes for approval with maturity curves and use them with the maturity method, and submit other mixes without intentions to use the maturity method with them? This could be for mixes intended for small quantities, for example.

Results from the field and laboratory studies seem to indicate that the relationship between maturity and strength gain is sensitive enough to changes in the mix that each submitted mix should have an associated maturity curve. If the MnDOT Concrete Office decides to accept a maturity curve developed for a mix from a previous project, the minimum requirements should be that the mix utilize the same materials, from the same suppliers (and pit, for aggregates), and in the same quantities. In addition, at least one set of verification beams should be tested prior to allowing the mix and its maturity curve to be used on a new project. The question of allowing some mixes to be used with the maturity method and some to be used in the traditional beam testing method should be left to the MnDOT Concrete Office.

## Chapter 5. Maturity Curve Selection

As mentioned in the previous chapters, there are several models with which statistical regression can be performed to develop a maturity curve. Each of these has its own advantages and disadvantages, which will be discussed in this chapter. The three model forms are logarithmic, hyperbolic, and exponential. This chapter describes each of the models and discusses their performance relating to the various stages of concrete strength development, data fitting statistics, and other items. As discussed below, each mathematical model was linearized, at which point a linear regression was performed in order to determine the proper coefficients to fit the model best to the data. From this the curve fit coefficients were determined and the regression statistics were computed. The models were then returned to their original form, and can be used in computations for concrete strength given maturity at any particular time.

### *Statistical Analysis*

For each of the maturity curve methods, a linear regression is performed on transformed equations. This transformation allows the linear regression of the form

$$\hat{Y} = mx + b$$

Where:

$$\begin{aligned} \hat{Y} &= \text{predicted flexural strength at maturity, } x, \\ m &= \text{slope of regression line, and} \\ b &= \text{intercept of regression line.} \end{aligned}$$

The regression line represents the mean value of  $\hat{Y}$  at any value of  $x$  in the regression equation. The confidence interval at any point  $x$  can be estimated using the following statistical methods. The confidence interval represents the limits of the estimated strength value at a confidence level of 95% or 90%, or any other value desired. For this analysis and the figures shown in this report, the t-statistic is determined for a 90% confidence interval, which means that 90% of the expected values would fall between the dashed lines in the figures that follow, or that there is a 5% on either side (high or low) that the actual value would be outside of the dashed lines.

The components of the confidence interval analysis are presented in the remainder of this section. First, the sum of squares of the differences between each  $x$  and the average value of  $x$  is computed, using the actual data.

$$[x^2] = \sum_i (x_i - \bar{x})^2$$

Where:

$$\begin{aligned} x_i &= \text{known } x \text{ value,} \\ \bar{x} &= \text{average of known } x \text{ values, and} \\ [x^2] &= \text{sum of squares of the differences between } x_i \text{ and } \bar{x}. \end{aligned}$$

Next the standard error of the Y values at each x value is computed.

$$s_{y,x}^2 = \sum_i \frac{(Y_i - \hat{Y}_i)^2}{n-2}$$

Where:

- $Y_i$  = known y value at  $x_i$ ,
- $\hat{Y}_i$  = predicted y value at  $x_i$ , and
- $n$  = number of known x values.

Then, the variance of the regression equation at any x is computed.

$$s_2^2 = s_{y,x}^2 \left[ \frac{1}{n} + \frac{(x - \bar{x})^2}{[x^2]} \right]$$

The confidence interval at any point is the standard deviation multiplied by the t-distribution with n-2 degrees of freedom. Thus, the width of the confidence interval is the predicted value at any x plus or minus the standard deviation multiplied by the t-statistic.

$$\hat{Y} \pm s_2 \tau_{n-2}$$

Where:

- $\tau_{n-2}$  = t-distribution statistic with n-2 degrees of freedom.

The following sections describe the transformations and regression results of each of the three methods, using data from three field sites (Albert Lea, Woodbury, and Moose Lake) as examples. For each model discussed, outliers in the data, as defined in ASTM C1074 [1] are removed. In general, the removal of outliers reduces the size of the confidence interval.

### Logarithmic

The natural logarithm model for the maturity-strength relationship is as shown below.

$$MR = m \ln(TTF) + b$$

Where:

- MR = Modulus of Rupture, or flexural strength, psi,
- TTF = Time-temperature factor, using the Nurse-Saul method of modeling concrete maturity, degree-hours, or C-hr,
- m = slope of the linearized logarithmic model, and
- b = y-intercept of the linearized model.

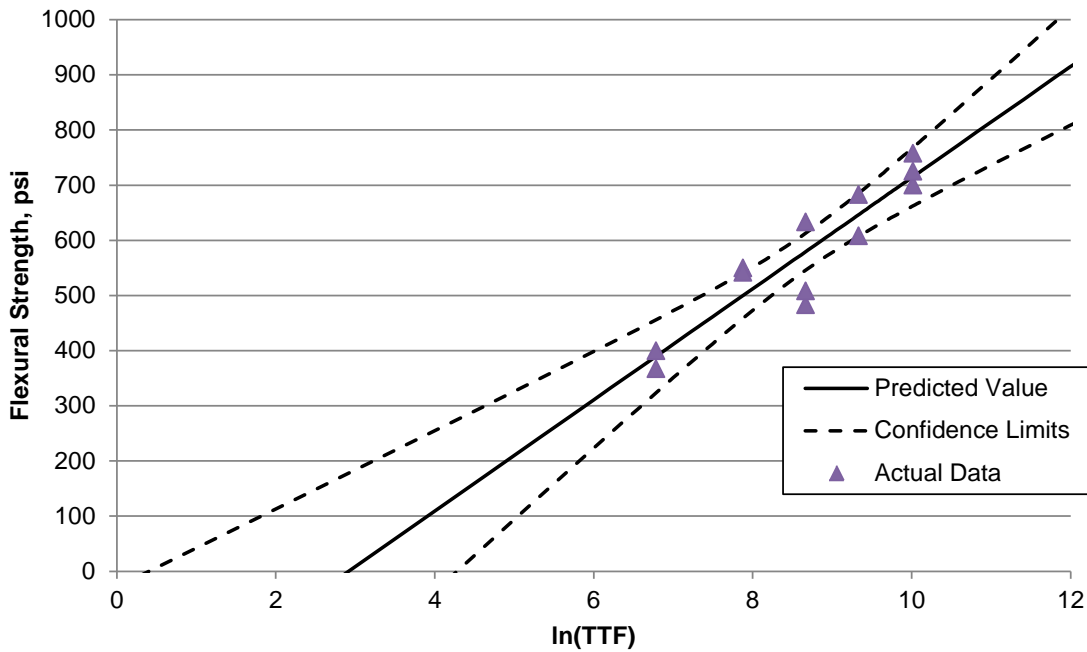
For the regression equation, the model is linearized, using

$$x = \ln(\text{TTF})$$

such that the model is transformed to the familiar

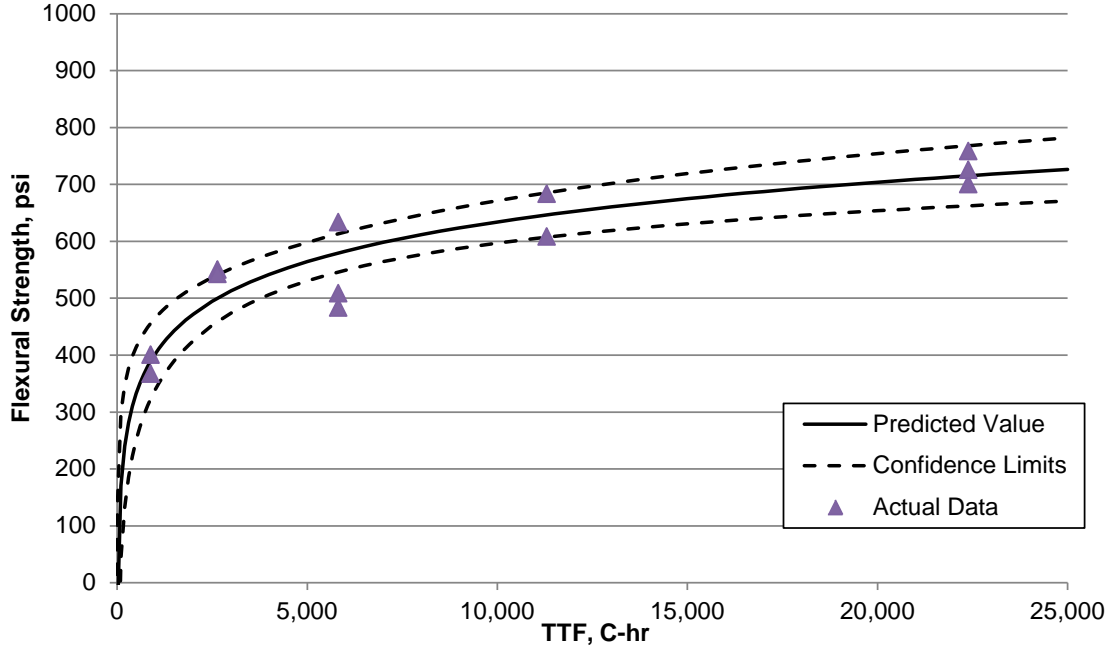
$$MR = mx + b$$

and the regression model is developed normally, solving for the regression coefficients  $m$  and  $b$ . Figure 32 shows the linearized model developed for the data collected at the Albert Lea project site in 2009. The graph shows the actual data, the linear regression model, and the 90% confidence interval. It is important to note that the confidence interval is sensitive to the distance, along the  $x$ -axis, from the mean of actual  $x$  data. Thus, farther from the mean of  $x$ , in either direction, the confidence interval becomes larger.



**Figure 32: Linearized logarithmic regression model, using data from the Albert Lea site.**





**Figure 33: Un-transformed logarithmic model, using data from the Albert Lea site.**

When the x-values are transformed from  $\ln(\text{TTF})$  to TTF, the curve regains its familiar shape, as shown in Figure 33. The confidence interval for the logarithmic model is narrow and stable throughout reasonable maturity values. This is primarily due to the nature of the strength data in the y-axis not needing to be transformed for the regression analysis. As will be seen in the other two methods, this is not always the case.

### Hyperbolic

The hyperbolic model has some advantages over the logarithmic model, but also has some disadvantages. It requires transformation of both the maturity (x-axis) and strength (y-axis) data in order to fit into the linear model for regression and determination of the confidence interval.

$$MR = S_{\infty} \left[ \frac{k_t (\text{TTF} - t_0)}{1 + k_t (\text{TTF} - t_0)} \right]$$

Where:

- $S_{\infty}$  = long-term strength, psi,
- $k_t$  = rate constant, 1/(C-hr), and
- $t_0$  = age at beginning of strength development, C-hr [20, 21].

For the linear regression, the following transformations are made.

$$x = \frac{1}{k_t(TTF - t_0)}$$

$$y = 1/MR$$

The equation then reduces to

$$1/y = S_\infty \left[ \frac{1/x}{1 + 1/x} \right]$$

which transforms to

$$y = \frac{x + 1}{S_\infty}$$

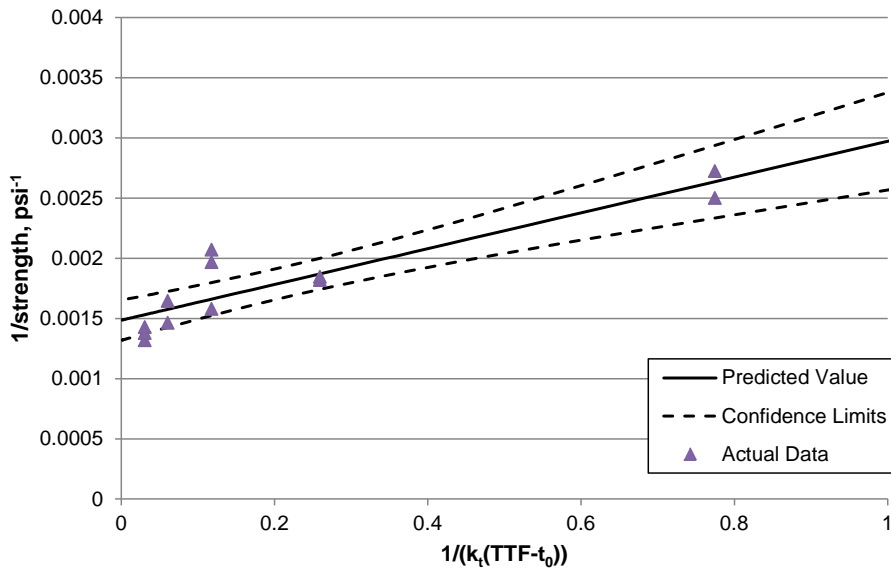
and

$$y = \frac{x}{S_\infty} + \frac{1}{S_\infty}$$

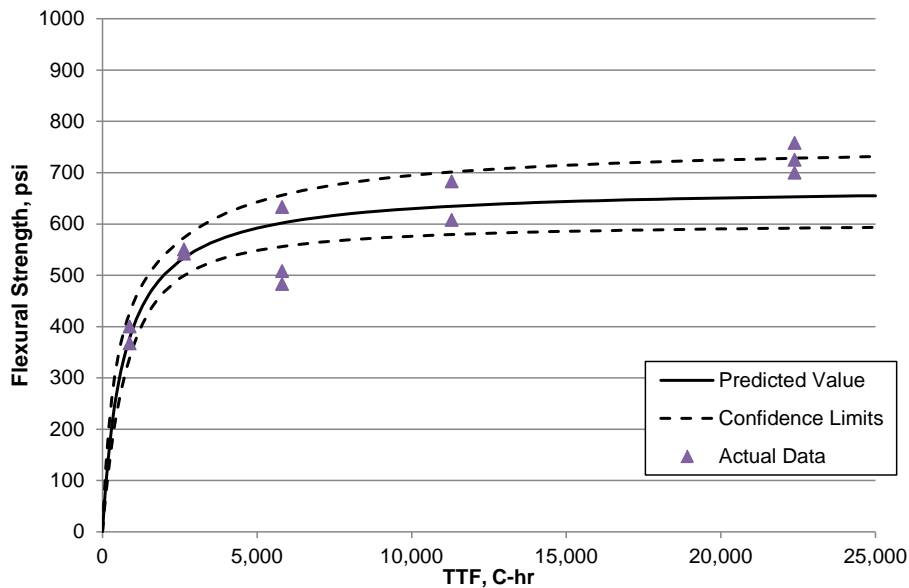
Thus,

$$\begin{aligned} y &= 1/MR \\ x &= 1/(k_t(TTF-t_0)) \\ m &= 1/S_\infty \\ b &= 1/S_\infty \end{aligned}$$

After the confidence interval is computed using linear methods, the predicted values and the interval can be added and then restored by reversing the transformation. As with the logarithmic model, Figure 34 shows the linear model with the confidence interval, and Figure 35 shows the restored axes. As can be seen in Figure 35, the confidence interval is similar to that of the logarithmic model.



**Figure 34: Linearized hyperbolic regression model, using data from the Albert Lea site.**



**Figure 35: Un-Transformed hyperbolic model, using data from the Albert Lea site.**

Exponential

The exponential model is recommended by the Federal Highway Administration, and is used in its HIPERPAV software. It is also recommended in a report by the Innovative Pavement Research Foundation (IPRF) in a report for the Federal Aviation Administration [22]. One of the strengths of this model is in predicting concrete strength at early ages. One drawback, however, to the use of the exponential model can be its confidence interval, as shown in Figures 36 and 37.

The model is given as

$$MR = S_u e^{-\left(\frac{\tau}{TTF}\right)^\alpha}$$

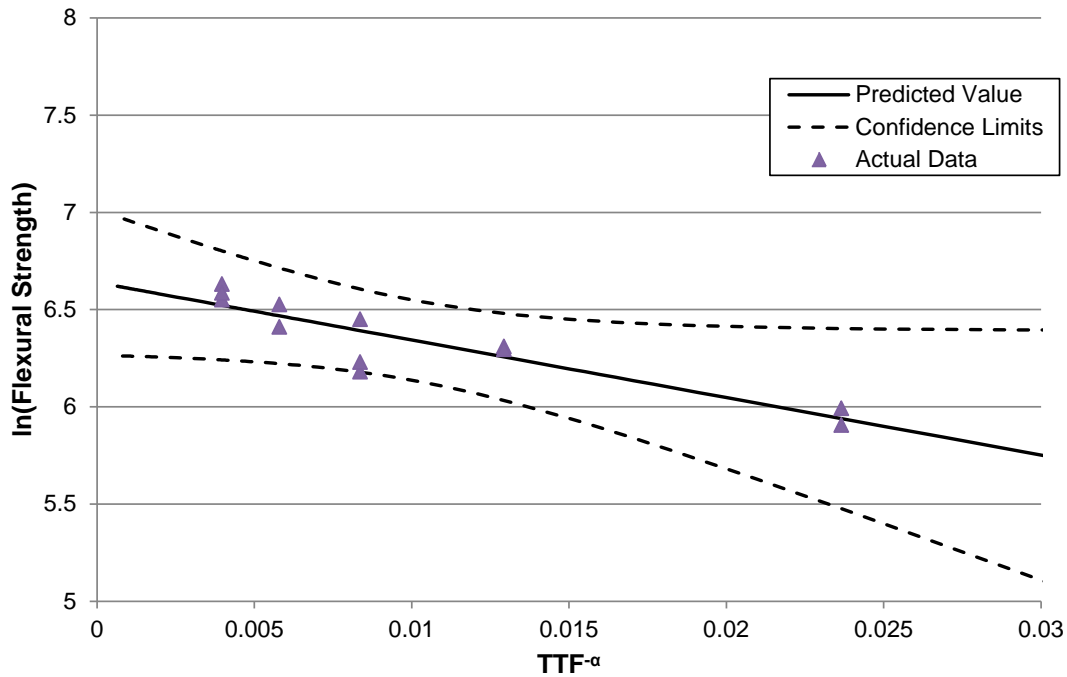
Where:

$S_u$  = ultimate expected flexural strength, psi  
 $\tau, \alpha$  = time and shape coefficients.

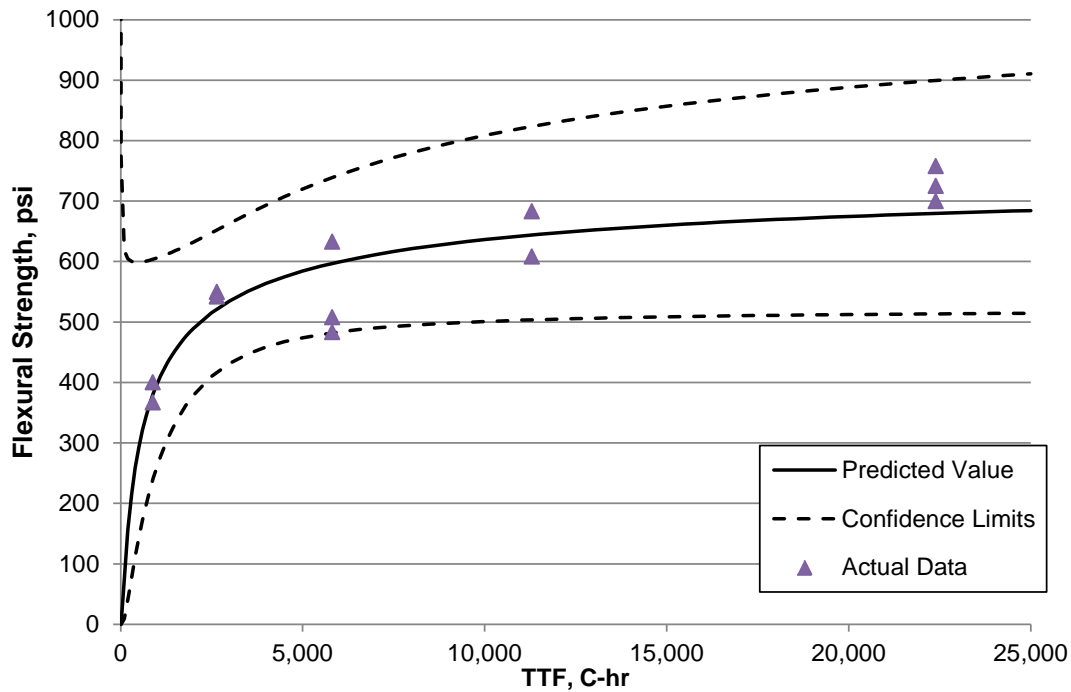
The linearization is given as

$y$  =  $\ln(MR)$   
 $x$  =  $TTF^{-\alpha}$   
 $m$  =  $-\tau^\alpha$   
 $b$  =  $\ln(S_u)$ .

The linearized model, with the actual data, predicted value curve, and 90% confidence interval, is shown in Figure 36. The un-transformed model, after the regression has been performed in the linearized state, is given in Figure 37.



**Figure 36: Linearized exponential regression model, using data from the Albert Lea site.**



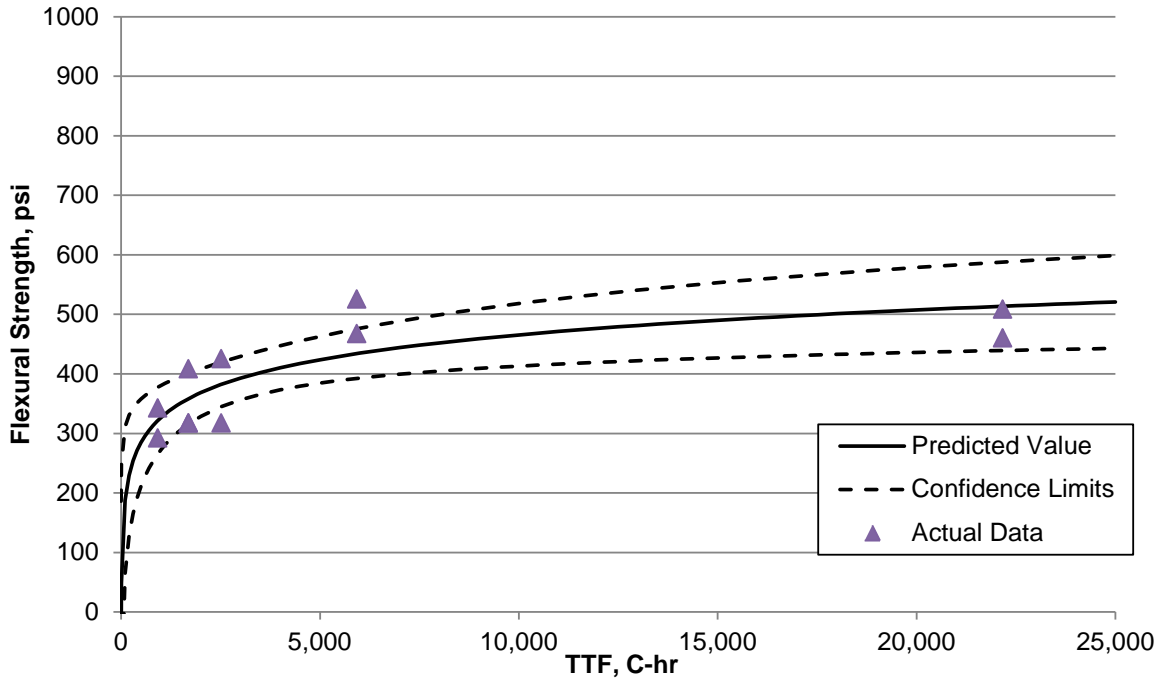
**Figure 37: Un-transformed exponential model, using data from the Albert Lea site.**

***Model Development Discussion***

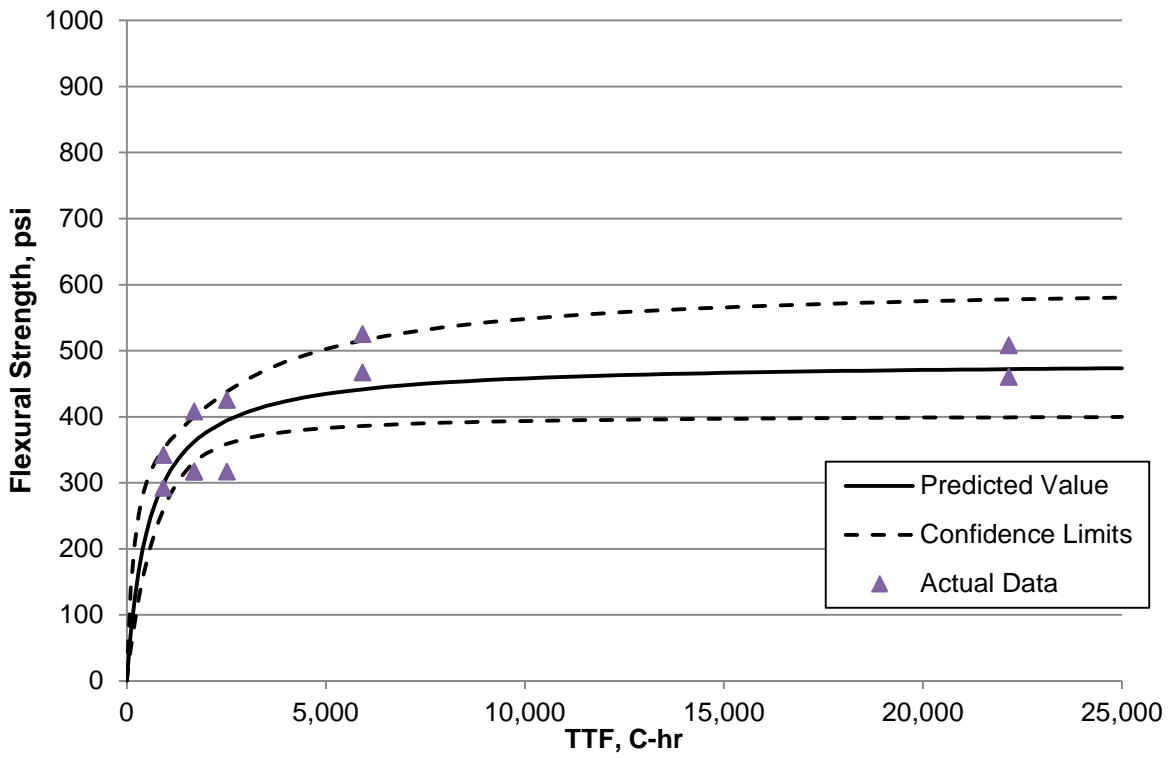
As described above, the data shown in these models and confidence interval calculations is after any outliers have been removed. ASTM C1074 [1] states that of three cylinders cast for testing at each maturity, if the first two tested have a range exceeding 10% of their average, the third is then tested and the average of all three is computed. Although ASTM C1074 references cylinders and compressive strength, the same procedures were followed with the beams and flexural strength testing. Based on the simple 10% of average test for strength data, the flexural strengths used in the model developments do not include any test results that exceed 10% of the average of the three tests.

**Variability**

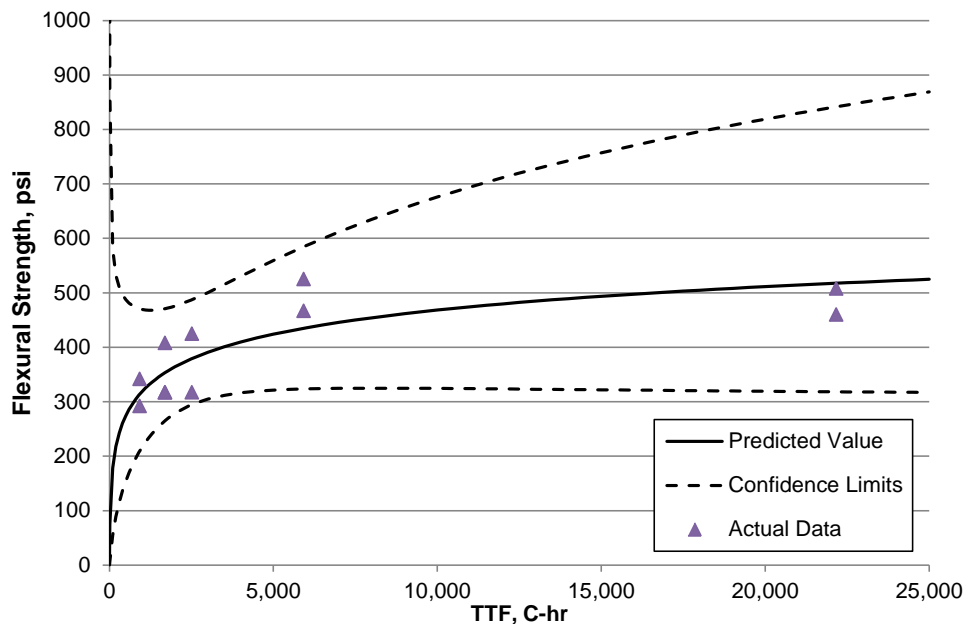
When there is higher variability among the strength test results, some of the models are affected more than others. For example, the samples cast at the Woodbury site, visited by the project team in June 2010, had higher variability in the flexural strength results than those at other sites. For comparison, the three models using the Woodbury data are shown in Figures 38, 39 and 40. In each of these, the confidence interval is greater than for the corresponding model from the Albert Lea project site, although the intervals in the logarithmic and hyperbolic models are not significantly larger. The exponential model, however, displays a large change due to the variability and the lower numbers of test results.



**Figure 38: Logarithmic model, using data from the Woodbury site.**



**Figure 39: Hyperbolic model, using data from the Woodbury site.**



**Figure 40: Exponential model, using data from the Woodbury site.**

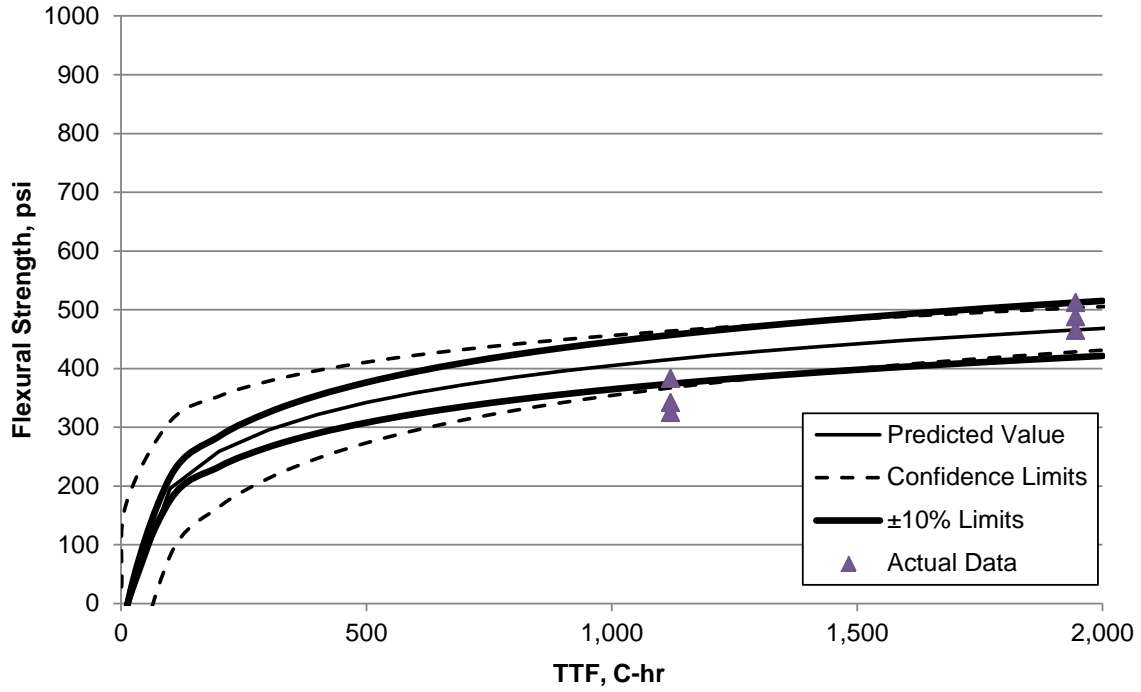
### Early Age Modeling

At early ages, the time of primary concern to this project, it is important that the models reflect reality as closely as possible. Thus, some of the advantages and disadvantages may not apply to this time period, such as the model approaching infinity as maturity increases. Although there are many definitions of “early age”, for the purposes of this project it will be defined as the first seven days while the concrete is developing sufficient strength to be opened to construction and/or public traffic.

In Figures 41 through 43, the performance of the three methods for the Moose Lake project site up to a maturity of 2,000 C-hr is shown. For this mix, 2,000 C-hr is about the maturity where the concrete met the traffic opening criteria. For other mixes studied in this project, the time ranged from about 1,000 to over 5,000 C-hr, representing about 28 hours to almost 7 days.

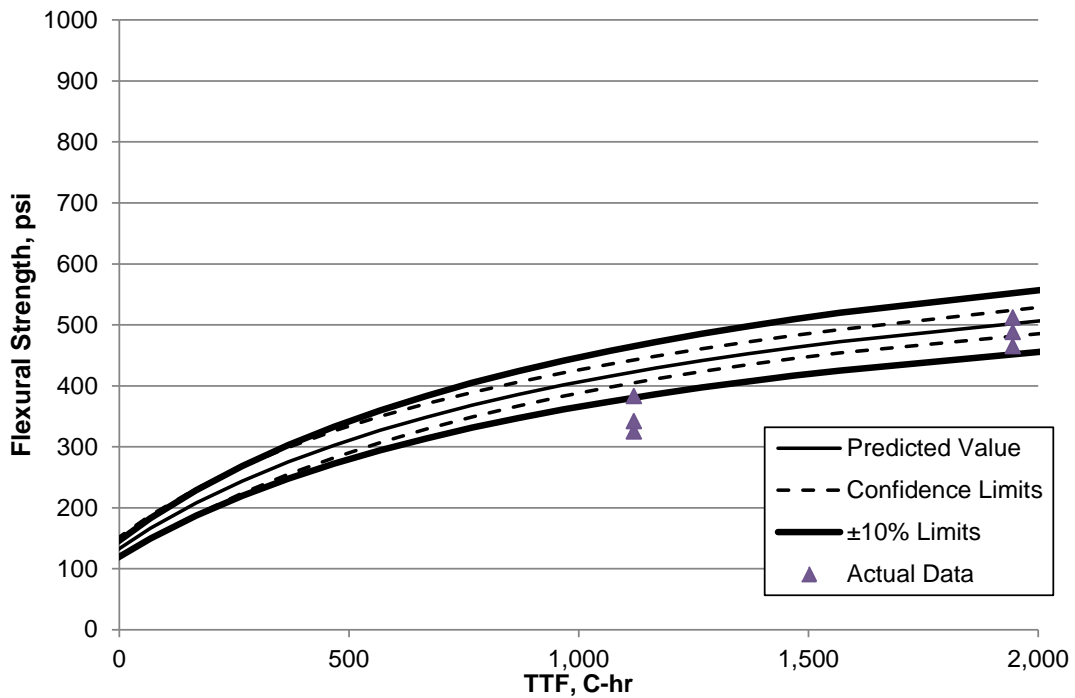
In these figures, it can be seen that the hyperbolic and exponential models fit the actual data better than the logarithmic model at early ages. Of these two, however, the confidence interval (indicated by the dashed lines) of the hyperbolic model is much more narrow, meaning that the 90% confidence interval is a smaller actual strength value in terms of  $\hat{Y} \pm s_2\tau_{n-2}$ , as described in a previous section. For example, with the hyperbolic model, the predicted value and confidence interval at TTF = 2,000 C-hr are 476.3 psi and  $\pm 24.5$  psi, respectively. For the exponential model, at the same maturity, and for the same data, the predicted value and confidence interval are 491.1 psi and  $\pm 69.6$  psi, respectively. In addition, Figure 42 also shows how the hyperbolic model can sometimes begin at a flexural strength greater than zero at very low maturity values.

These figures also show the  $\hat{Y} \pm 10\%$  limits for comparison to the statistical analysis of the individual regression models, shown as heavier solid lines. As can be seen in these figures, the  $\pm 10\%$  limits are most often within a narrower range than the confidence intervals.

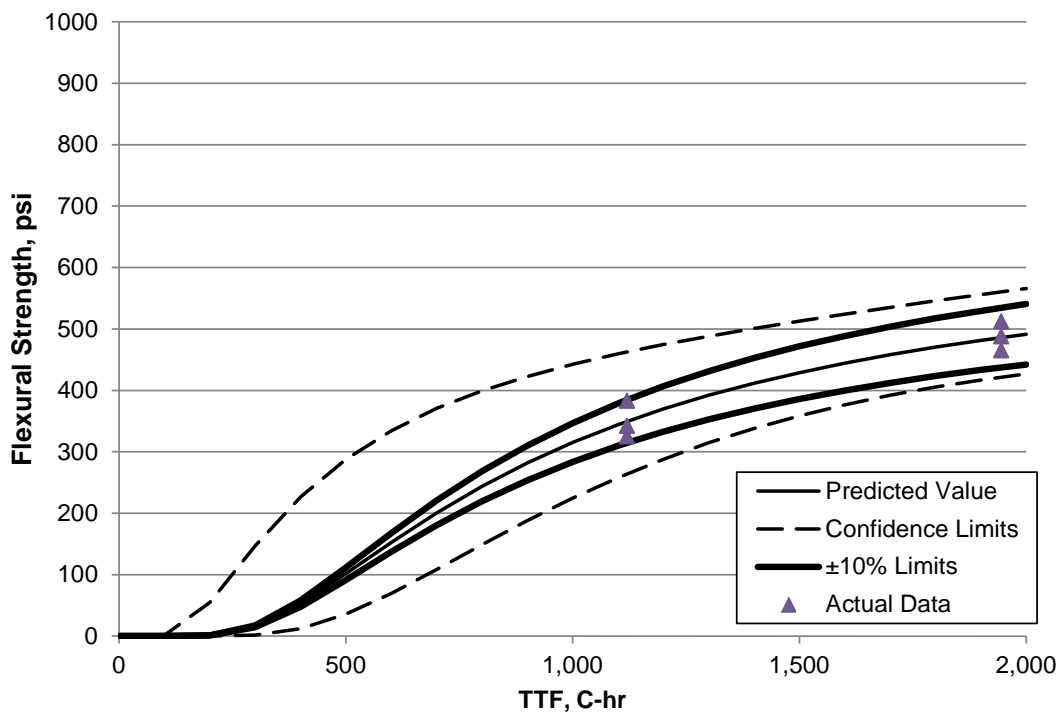


**Figure 41: Logarithmic model, using Moose Lake data, up to 2,000 C-hr.**





**Figure 42: Hyperbolic model, using Moose Lake data, up to 2,000 C-hr.**



*Figure 43. Exponential model, using Moose Lake data, up to 2,000 C-hr.*

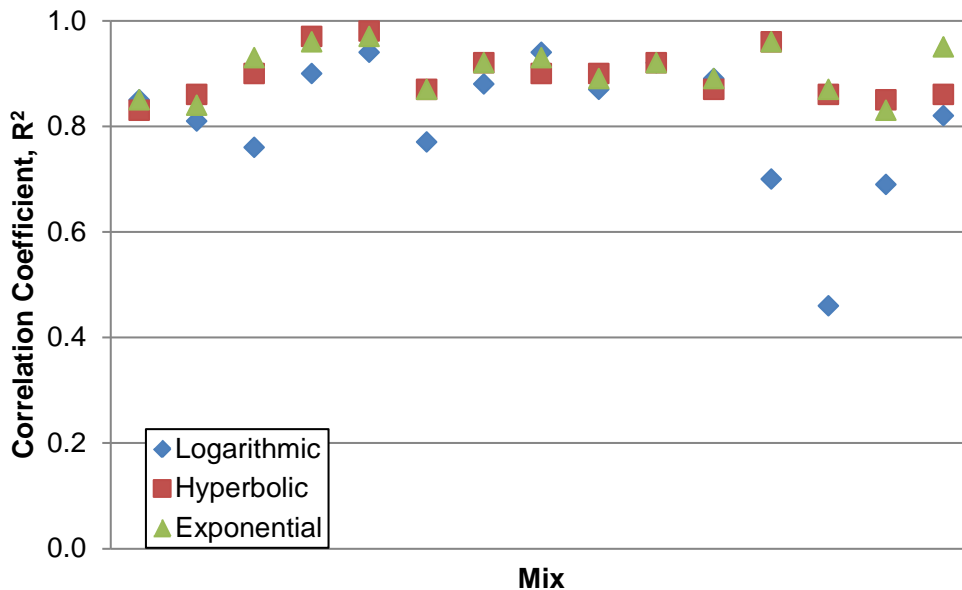
The S-shape of the exponential curve may be beneficial in this case, as was seen in Figure 43. The point where the curve begins to increase dramatically coincides to some degree with the

final set of the concrete, and thus it can be used to estimate strength beginning at that time. The exponential model does not always feature an S-shape coinciding with approximate set of the concrete, however.

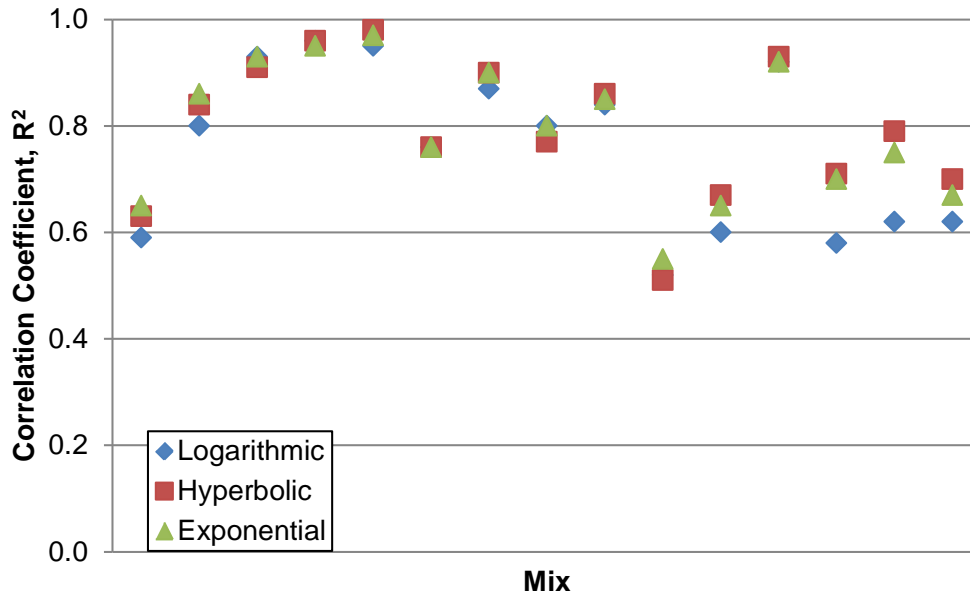
Statistical Correlation

Each of the three models performs at least fairly well in predicting the strength of concrete at various maturities. As a measure of each model’s effectiveness, the correlation coefficient was used. Other methods of comparing the models’ goodness of fit were attempted, but since the linearized version of each model used different units for the x and y values, a direct comparison was not possible. These methods included normalizing the standard estimate of error by dividing it by the average of the known or predicted y values, but these did not seem to represent reality and it is likely that they were not statistically valid methods of comparison.

The data in Figure 44 show that for the field sites visited during this project, the  $R^2$  values are fairly consistent for the hyperbolic and exponential models, and that the logarithmic model is less likely to fit the data as well as the other two when all data (maturity test results from placement through 28 days) are included. If the models are restricted to the first seven days of data as seen in Figure 45, the  $R^2$  values are decreased in general, and the logarithmic model is generally no worse in predicting the flexural strength than the other two models.



**Figure 44:  $R^2$  values for each mix tested in field sites (includes all data).**



**Figure 45: R<sup>2</sup> values for each mix tested in field sites (includes data only up to 7 days).**

Another measure of a model’s effectiveness is the root mean squared error (RMSE). For this analysis, a normalized RMSE was used so that the values could be compared more directly.

The RMSE is defined as a measure of the differences between values predicted by a model and the actual values measured in reality. The RMSE is calculated as the square root of the sum of squares of error of each data point and the model’s predicted value at that point divided by the number of points.

$$RMSE = \sqrt{\frac{\sum_i (Y_i - \hat{Y}_i)^2}{n}}$$

The normalized RMSE (NRMSE) is the RMSE divided by the range of the actual measured values.

$$NRMSE = \frac{RMSE}{Y_{\max} - Y_{\min}}$$

Table 7 shows the NRMSE values for each of the three potential maturity models discussed in this report, using all of the maturity data (up to 28 days, or about 25,000 C-hr). The shaded cells in the table indicate the smallest error for the specific project site. In one case (the Woodbury location) both the hyperbolic and the exponential models had the same NRMSE. Similarly, Table 8 shows the NRMSE for the same models (using the same coefficients) as in Table 7, but only computing the NRMSE for data at less than 10,000 C-hr. This provides an indication of how the models perform at the early ages. Typically, 10,000 C-hr is reached at some time between three and seven days of chronological age.

**Table 7: Summary of NRMSE for maturity models, all data.**

	<b>Logarithmic</b>	<b>Hyperbolic</b>	<b>Exponential</b>
Albert Lea	5.3%	10.1%	8.6%
Alden	14.6%	9.4%	9.5%
Marshall	6.0%	4.4%	4.1%
Montevideo	14.6%	10.3%	10.4%
Cottage Grove	3.7%	1.9%	0.7%
Dodge Center	4.0%	4.3%	4.1%
Marshall 2	7.3%	6.4%	5.3%
Waseca	12.0%	11.6%	13.0%
Woodbury	13.5%	12.3%	12.3%
Dover	5.4%	5.7%	5.0%
Barnesville	13.4%	7.4%	6.9%
Moose Lake	14.1%	6.5%	1.0%
Hutchinson	7.0%	3.6%	3.1%
Centerville	16.4%	9.4%	9.2%
Granite Falls	10.9%	11.0%	10.2%
MnROAD Cell 6	5.0%	9.7%	9.4%
<b>Average</b>	<b>9.6%</b>	<b>7.8%</b>	<b>7.1%</b>

As can be seen in Tables 7 and 8, when computing NRMSE with all the data, the exponential model has an average value over all 16 test sites slightly lower than the next best (hyperbolic) and significantly lower than the logarithmic model. In fact, the logarithmic and hyperbolic models have lower NRMSE values in only three each of the 16 cases, while the exponential model is lower in the other 10 cases. When computing NRMSE with only the maturity values less than 10,000 C-hr, however, the exponential model performs much better (6.2%) compared to the hyperbolic (7.4%) and the logarithmic (9.4%). In this analysis, only one case has the lowest NRMSE with the logarithmic model, four with the hyperbolic, and 11 with the exponential. In addition, the NRMSE of the exponential model decreased much more than the other two when comparing the values using all maturity data to those using only up to 10,000 C-hr.

**Table 8: Summary of NRMSE for maturity models, maturity < 10,000 C-hr.**

	<b>Logarithmic</b>	<b>Hyperbolic</b>	<b>Exponential</b>
Albert Lea	6.4%	12.4%	10.4%
Alden	8.6%	4.2%	3.3%
Marshall	5.0%	5.0%	4.0%
Montevideo	10.5%	2.9%	3.2%
Cottage Grove	3.7%	2.1%	0.8%
Dodge Center	4.1%	4.8%	4.0%
Marshall 2	8.0%	6.7%	5.7%
Waseca	13.3%	12.9%	14.5%
Woodbury	13.9%	10.2%	10.7%

Dover	6.0%	6.3%	5.6%
Barnesville	14.2%	8.3%	7.5%
Moose Lake	14.6%	6.9%	1.0%
Hutchinson	7.3%	3.9%	3.5%
Centerville	17.0%	10.3%	10.2%
Granite Falls	12.1%	10.5%	10.9%
MnROAD Cell 6	5.1%	10.8%	3.2%
<b>Average</b>	<b>9.4%</b>	<b>7.4%</b>	<b>6.2%</b>

Based on the discussion in the previous sections, Table 9 contains a summary of the advantages and disadvantages of each model.

From the figures and discussion in this chapter, it is suggested that the exponential model be utilized for the maturity method for MnDOT's concrete paving operations. In addition, to reduce some of the complexity (both in computation and comprehension) it is recommended that the  $\pm 10\%$  limits be implemented, rather than a statistically computed confidence interval. This is primarily due to the potential size of the confidence interval for the exponential model and the additional complexity of its computation, and to limit one possibility of data manipulation described in the next section. If other reasons are deemed more important, the hyperbolic model (with or without the  $\pm 10\%$  limit method) could be an acceptable substitute.

**Table 9: Summary of advantages and disadvantages of each model.**

<b>Model</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Logarithmic</b>	<ul style="list-style-type: none"> <li>• Good stability for computing statistical confidence interval.</li> </ul>	<ul style="list-style-type: none"> <li>• At early ages the model is the least capable of accurately predicting the actual data.</li> <li>• Sometimes gives negative strength values at low maturity levels.</li> <li>• Strength increases infinitely as maturity increases.</li> </ul>
<b>Hyperbolic</b>	<ul style="list-style-type: none"> <li>• Consistently high <math>R^2</math> when using all tested data.</li> <li>• 90% confidence interval matches <math>\pm 10\%</math> range well in most cases.</li> <li>• Ultimate strength is bounded within reason.</li> <li>• Recommended by Maryland State Highway Agency [23]</li> </ul>	<ul style="list-style-type: none"> <li>• Sometimes gives high strength values at zero maturity.</li> </ul>
<b>Exponential</b>	<ul style="list-style-type: none"> <li>• Fits early age strength data well.</li> <li>• Consistently high <math>R^2</math> when using all tested data.</li> <li>• Best performance when comparing NRMSE</li> <li>• Ultimate strength is bounded within reason.</li> <li>• Currently used in FHWA's HIPERPAV program.</li> <li>• Better for interpolating and extrapolating data points, according to IPRF [22]</li> </ul>	<ul style="list-style-type: none"> <li>• Prone to large confidence intervals, that often do not match well with <math>\pm 10\%</math> range.</li> <li>• Can be unstable in determining coefficients for optimum fit (although better curve fitting methods can help).</li> </ul>

*Flexibility in Data Analysis*

With the maturity method in general and the exponential or hyperbolic models in particular, it is important to be aware of several possible ways the data can be used to imply different results. In addition, this section contains several suggestions for avoiding problems of this nature. As with any activities related to construction, it is important for the field engineer or inspector to observe the contractor's activities, and to take companion samples as often as deemed necessary. The data collection from the temperature sensors or maturity meters utilized both during curve development and verification should be simple, easily recordable, and should be observed by MnDOT's representatives.

1. Intentionally high variability at the time of curve development.

Artificially increasing the variability of the strength test results during the initial development of the maturity curve for a particular mix can allow for a wider band of acceptable test results during the curve verification testing. This could be achieved by lower quality preparation of samples in terms of consolidation or non-random concrete sampling.

2. Intentionally lower strength at the time of curve development.

By artificially causing lower strength results at the time of curve development, beams tested at the time of curve verification are more likely to be above the -10% line.

3. Mis-placement of maturity sensors in pavement

During construction, maturity meters which record temperature history and should be placed at the mid-depth of the concrete pavement. This ensures adequate concrete cover, and provides an average temperature during the critical first few days of curing.

Depending on the weather conditions, a temperature sensor placed closer to the surface or to the bottom of the slab may record higher or lower temperatures. Higher temperature readings will falsely indicate that the strength criteria has been met at an earlier time than if the temperature is accurately measured.

## **Chapter 6. Development of a Maturity Database**

This chapter describes the development and population of a maturity database for MnDOT's future use in correlating the mix design and proportioning with the maturity curve for a particular mix. This chapter also describes the data analysis and efforts to assess the various maturity models and to determine which is of most use to MnDOT in the implementation of the maturity method for portland cement concrete pavements. Future use of this maturity database will depend on its use and the entry of data by the MnDOT Concrete Office as new maturity curves are created by contractors, MnDOT and others. The maturity database and tool developed for this project use the exponential mathematical model described previously in this report.

### **Population of Maturity Database**

In its current state, the maturity database includes three components, described later in this section. The first is the maturity curve information created by the research team at each of the field sites visited over the past three construction seasons. The second is the laboratory work conducted at Minnesota State University, Mankato, which includes data from over 600 two-inch cubes and five full sets of 15 beams made according to ASTM C1074 for the maturity method. The third component of the maturity database is where future data will be entered. It currently includes the data from the curves developed from the research field sites, which were at actual concrete paving projects. This is intended to be a starting point for the database which is intended to grow in the future as additional maturity curves are entered into the database.

### **Maturity Curve Viewer Development**

The maturity curve viewer and database is a macro-enabled spreadsheet written in Microsoft Excel. There are three tabs in the spreadsheet. The first is set aside for use as a database into which new data can be entered and plotted. Comparisons between various maturity curves can be made in a graph as well as by the tabulated mix design information. The second and third sheets are for viewing the data that was collected during the project both in the field and in the lab. In the beginning, the field sheet is contains the same information as the database sheet since those maturity curves were developed from concrete mixes used in actual concrete pavements in Minnesota. However, this tab does not have the capability of adding more data. The third tab contains compressive strength data from the various mixes tested in the form of the approximately 600 two-inch cubes produced for this project. The data contained in this tab are intended to be used for comparisons between different mix characteristics, such as total cementitious content, fly ash replacement, etc.

Each tab contains a maturity curve graph capable of displaying up to five maturity curves, and five pull-down selectors to choose the maturity curves to be displayed. An example of the maturity database sheet is shown in Figure 46.



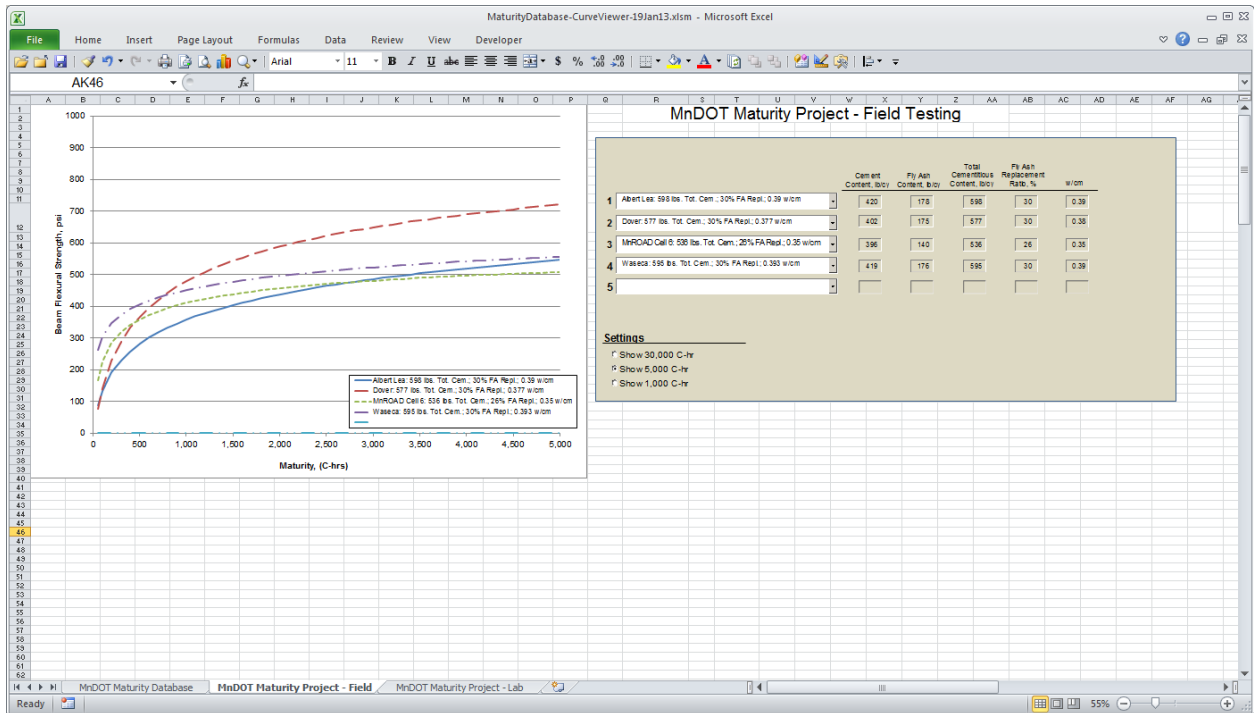


Figure 46: Maturity database sheet.

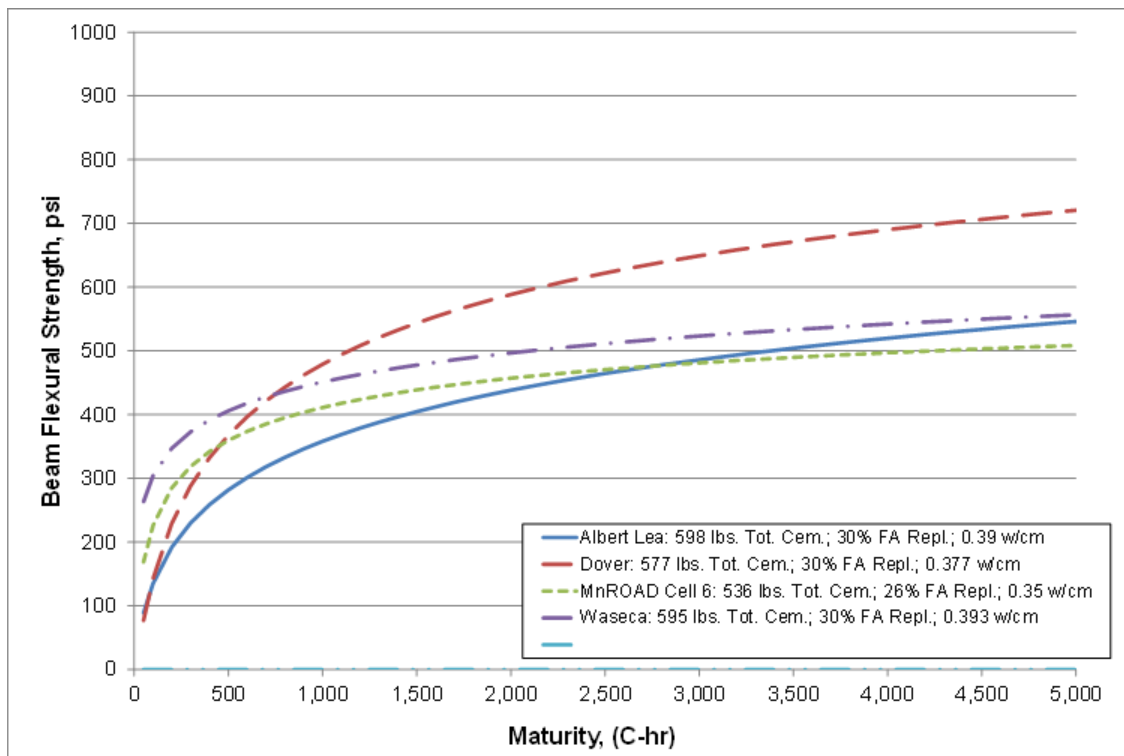


Figure 47: Close-up of maturity database graph.

**MnDOT Maturity Project - Field Testing**

		Cement Content, lb/cy	Fly Ash Content, lb/cy	Total Cementitious Content, lb/cv	Fly Ash Replacement Ratio, %	w/cm
1	Albert Lea: 598 lbs. Tot. Cem.; 30% FA Repl.; 0.39 w/cm	420	178	598	30	0.39
2	Dover: 577 lbs. Tot. Cem.; 30% FA Repl.; 0.377 w/cm	402	175	577	30	0.38
3	MnROAD Cell 6: 536 lbs. Tot. Cem.; 26% FA Repl.; 0.35 w/cm	396	140	536	26	0.35
4	Waseca: 595 lbs. Tot. Cem.; 30% FA Repl.; 0.393 w/cm	419	176	595	30	0.39
5						

**Settings**

- Show 30,000 C-hr
- Show 5,000 C-hr
- Show 1,000 C-hr

**Figure 48: Close-up of maturity database selection pane.**

The Maturity Database tab also allows the user to enter new maturity curve information including test results for flexural strength tests and associated maturity values, and mix proportioning information. The data entry form is shown in Figure 49. After the maturity curve and mix information are entered into this form, the curve is available through the pull-down selectors in the spreadsheet.

**Add New Maturity Data**

**Project / Mix Name** US-14

**MnDOT Project / SP Number** 8101-44

**Mix Designation** 3A21-5

**Beam Casting Date** 8 /16/2010

**Mix Data**

**Cement Content, lb/cy** 417

**Cement Type / Manufacturer** Holcim

**Fly Ash Content, lb/cy** 179

**Fly Ash Type / Manufacturer** CCREEK

**w/cm** 0.39

**Concrete Maturity Data**

Approx. Age, days	Maturity at Time of Testing, C-hrs	Beam Flexural Strength, psi
1	944	444
2	1747	494
3	2571	510
7	5952	564
28	22351	653

Cancel OK

**Figure 49: Maturity database information entry form.**

## Chapter 7. Recommendations for Specification Development

This chapter describes recommendations for the development and revision of construction specifications to incorporate the use of the maturity method for portland cement concrete pavements. Since the maturity method has been in use for structural concrete construction for many years, only minor modifications may be needed to accommodate this method for pavement construction. The chapter begins with characteristics of specifications used by other states in the upper Midwest and nearby areas for use of the maturity method in concrete pavement construction. A discussion of relevant revisions that could be made to MnDOT specifications then follows. Finally, possible tools for developing and verifying maturity curves in the laboratory and in the field are presented. A proposed draft specification is included in Appendix A to this report.

### Concrete Pavement Maturity in other States

This section describes some of the common and unique practices in use by other states for estimating concrete strength by the maturity method. The states evaluated include those in the upper Midwest and some other states known for their use of innovative technology and ideas.

Some of the common characteristics of concrete maturity programs found among the other states include the following.

- Three steps
  - Developing the initial maturity curve
  - Estimating concrete strength in the field (during construction)
  - Validating maturity curve periodically
- Maturity curve characteristics
  - -10 C datum temperature
- Use of beams or cylinders
  - Some states specify beams or cylinders only, and some allow either
  - Minimum 10 samples (Nebraska), maximum 20 (Texas), made from a batch of at least 3cy
- Minimum probe placement during construction
  - Generally 2 sets per day, with at least one near the end of the paving day
- Maturity curve validation schedule
  - Every 30 calendar days
  - Every 4-6 weeks
  - Every month
  - After 1<sup>st</sup> day of use, then every 10 days of production
  - Every 7<sup>th</sup> day of paving
- Maturity curve validation limits
  - $\pm 50$  psi flexural strength deviation from established curve
  - $\pm 350$  psi compressive strength deviation from established curve
  - $\pm 10\%$  from curve
  - $\pm 10\%$  or  $\pm 200$  psi compressive strength deviation from curve, whichever is less

Some unique items specified by individual states include the following.

- Iowa
  - Can use the maturity method in construction while the curve is being developed
  - Between Oct 16 and Mar 15, supplementary cementitious materials can only be used if the maturity method is used
  - Keep maturity curve development specimens above 50°F
  - Curve development testing ages and strength must span expected opening criteria, with at least two testing sets below opening strength
  - Maturity curve development mix uses highest w/c expected during construction for that mix
  - New curve required if w/c exceeds curve development mix by 0.02
- Kansas
  - Mix proportions during construction may deviate up to 5% from curve development mix proportions
- Missouri
  - Curve must be developed in the field, with project equipment and materials
  - One probe placed every 3750 sy of pavement, with one in the last 50 linear feet
  - Mix proportions during construction may deviate up to 5% from curve development mix proportions
  - Mix w/c may deviate up to 0.02 from curve development w/c
- Texas
  - Regression equation for curve development must have  $R^2$  greater than 0.90
  - Must use qualified personnel
  - Discard maturity curve development samples with test results deviating more than 10% of the average of three samples

## **Recommendations**

Based on the common and unique practices found in other states relating to the use of the maturity method for concrete pavements, the following basic recommendations are made for the development of a standard or provisional specification for MnDOT's concrete maturity program.

### ***Maturity Curve Development***

- Use the -10 C (or 14°F) temperature as a datum.
- Specify the use of 15 beams for developing the maturity curve for a particular mix.
- Specify that the 15 beams must be made from a batch of at least 3 cy
- Specify ages for maturity curve development at
  - 1, 2, 3, 7, 28 days for normal strength mixes
  - 0.5, 1, 2, 7, and 28 days for high-early strength mixes
- Maintain beams above 50°F during the curve development period
- Use a standard maturity curve development spreadsheet, such as the one found in Appendix B
- Require the contractor to develop the maturity curve

### ***Maturity Curve Usage in Construction***

- Develop a different maturity curve for any mixes where w/c is different by more than 0.02, and where all other proportions remained unchanged, or where any other component is different by more than 5% by weight.
- Specify a maturity sensor every 1,400 linear feet (approximately equivalent to Missouri's 3,750 sy, for a two-lane paving width). This value could be modified to coincide with other regular testing intervals to avoid confusion and sensor omissions less likely). A minimum of two maturity sensors per paving day should be required, including at least one in the last 50 ft of the day's paving.

### ***Maturity Curve Validation***

- Validation schedule: every 7th paving day or portion thereof
- Test validation beams at approximately the maturity index expected for opening to traffic
- Use a standard maturity curve validation spreadsheet, similar to the one found in Appendix B
- Validation limits:  $\pm 10\%$  from curve
- If validation test falls  $>10\%$  above the curve, proceed with caution
- If validation test falls  $>10\%$  below the curve, make field beam specimens and test under non-maturity specifications
- Require the contractor to conduct maturity curve validation for quality control. The agency should conduct regular quality assurance testing for maturity curve validation, using some method of split samples.

### **Suggestions for Consideration**

- Provide a laboratory manual in addition to a standard specification for using the maturity method in concrete pavement construction, similar to the draft contained in Appendix C.
- If a validation test falls below the limit, revert to the "worst case" maturity curve until a problem can be identified. This will allow the contractor to continue to use the maturity method during this phase, and may result in more consistent operations. If a second validation test in a row fails to fall within the  $\pm 10\%$  range, consider reverting to the non-maturity method of testing and require the contractor to determine the reason(s) the concrete no longer matches the developed maturity curve.
- Allow paving operations to begin at the same time a maturity curve is being developed. Pavement would not be allowed to be opened until the developing maturity curve is meets the opening criteria and until the pavement concrete meets the maturity index required for opening. This will also alleviate schedule problems and requirements to wait for 28 days to use a maturity curve. For example, if a validation test fails and a new maturity curve is required, the paving operations can continue with the newly placed concrete following the new maturity curve that had just begun. Another benefit to this method is that the concrete used in the curve development would most likely be the same concrete that is currently being used in the paving operations.

## Chapter 8. Conclusions

As a summary of the activities performed under this project, this chapter describes the field testing, laboratory testing, selection of the recommended mathematical form for the maturity curve model, development of the maturity curve database, and the recommendations for construction specifications for using the maturity method in standard practice.

The project team spent three construction seasons visiting 18 concrete paving projects on interstate, state and county highways as well as some county roads establishing the viability of using the maturity method in Minnesota using flexural beams as specimens. On each of the projects, maturity sensors were installed in up to 12 locations, simulating three sensor installations per day over four days on each project. In addition to the field installation of maturity sensors, the project team cast 270 flexural strength specimens and tested them in the field and at the lab on the MSU campus.

The laboratory testing program included over 700 mortar cubes for compression testing and an additional 75 flexural strength beams to further establish the maturity method and to quantify the variability in the materials testing. It was found that the flexural strength test has a relatively low variability and lends itself well to the regression conducted to describe the strength-maturity curve. The laboratory testing program was also used to verify the ability of maturity curves to distinguish between different mixes with variations in materials and proportions greater than about 10 percent.

The data produced in the field and laboratory testing was used to select the mathematical form of the model recommended for use in Minnesota's concrete paving maturity program. The selection was based on the ability of the three candidate models (logarithmic, hyperbolic, and exponential) to adequately predict the flexural strength of concrete at early ages, and standard error in the three regression models using the same maturity and strength data. The exponential model was selected due to its shape and ability to model the very early age strength development of concrete in most cases. This model was used from the beginning of this report, but the reasons for its selection were described more fully in Chapter 5.

One of the primary deliverables for this project is the maturity curve database, where different mixes and their associated maturity curves can be entered and stored for future reference. Up to five curves can be viewed simultaneously in the database's charts to facilitate comparison of maturity curves with similar mixes.

Another major deliverable of this project is the recommendation for construction specifications for the future use of the maturity method in concrete paving in Minnesota. In Chapter 7 several recommendations are made regarding potential features of a maturity specification. These include recommendations for the three major functions of the maturity method – maturity curve development, usage during construction, and curve validation. The current specifications for the maturity method in concrete paving in other states, and particularly those in the Upper Midwest were evaluated to find best practices and to incorporate those into the recommended specification in this report.

The maturity method is recommended for use in concrete paving operations in Minnesota, as it has a demonstrated ability to predict the strength of portland cement concrete with good accuracy and has been used successfully in many other states. It is recommended that further analysis be conducted by the MnDOT Concrete Office during initial implementation of this method to ensure that the specifications and other expectations progress as expected.

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# **Appendix A: Draft Construction Specification**

## 2XXX

### Estimating Concrete Flexural Strength by the Maturity Method

#### 2XXX.1 DESCRIPTION

The maturity method may be used to determine development of adequate concrete strength for opening to traffic. Use of this method requires the establishment of a relationship between concrete strength (third-point flexural method) and the computed maturity index (using the Nurse-Saul method) for a specific concrete mixture prior to construction. The Contractor may use this method, in accordance with this specification and Section 5-694.50X of the MnDOT Concrete Manual to estimate the in-place strength of the concrete pavement.

#### 2XXX.2 EQUIPMENT

Utilization of the maturity method requires the following equipment, at a minimum.

- a) maturity meter or temperature sensor and data logger with a secure means of collecting data that is unalterable, and conforms to the requirements in ASTM C 1074.
- b) beam testing apparatus for conducting third-point flexural strength tests in the field.
- c) beam molds and other concrete making and testing equipment.

#### 2XXX.3 PROCEDURE

The in-place concrete strength shall be estimated using the maturity method as described in ASTM C 1074, except as noted in this specification, using 15 flexural strength beams, the Nurse-Saul method of computing maturity and a datum temperature of -10 C (14° F).

The computed maturity results from each sensor will only apply to concrete placed under the following conditions:

- a) of the same mix designation and the same project as the test location,
- b) placed on the same day and on, before, or within 50 feet after the time the sensor was placed,
- c) cured under conditions similar to those of the test location.

#### **A. *Development of Maturity-Strength Relationship***

Prior to any concrete paving, the Contractor shall develop a strength-maturity relationship (maturity curve) for any mixture for which the maturity method will be used. The Contractor shall notify the Engineer prior to developing the maturity curve. The maturity curve may be developed in the laboratory or in the field, provided the precautions for field curing and testing are followed, as described in Concrete Manual. Specimens shall be kept at temperatures greater than 50° F for the duration of the maturity curve development.

Beam specimens shall be tested at chronological ages of 1, 2, 3, 7, and 28 days for normal strength concrete mixes, and at ages of 0.5, 1, 2, 7, and 28 days for high-early strength concrete mixes. Until an acceptable strength-maturity relationship is established, concrete beams shall be used to verify strength.

**B. Documentation**

The Contractor shall submit a completed *Concrete Maturity-Strength Development* form to the Concrete Engineering Unit and to the Engineer in the field for each concrete mixture to be placed with the maturity method, prior to placing any concrete pavement using the maturity method.

At intervals specified in Section 2XXX.3.E, the Contractor shall submit completed *Concrete Maturity-Strength Verification* forms to the Engineer.

Electronic data from the maturity meters or temperature loggers shall be submitted in the form of a text file or a spreadsheet.

**C. Placement of Temperature Sensors**

For concrete paving, temperature sensors shall be embedded at approximately mid-depth and approximately 18 (but no less than 12) inches from the edge of the pavement. Any wires protruding from the pavement surface or edge shall be protected from finishing and/or shouldering equipment until the maturity index is reached indicating that the strength has exceeded opening strength requirements. The surface of the concrete pavement shall be finished as with any other location on the surface.

**D. Frequency**

Maturity meters or temperature sensors shall be placed in the pavement at a rate of at least one for every 1,400 linear feet of paving, including one in the last 50 feet of each day's paving.

**E. Verification**

Once every 7 calendar days during paving operations, a verification test shall be conducted by the Contractor to ensure that the in-place concrete strength is accurately estimated by the maturity-strength relationship. The verification test shall be conducted according to the Concrete Manual. The Engineer shall be notified at least 24 hours in advance of the time and location of both the verification specimen's casting and strength testing.

Once the maturity index for the verification sample indicates that the concrete specimen will meet or exceed the opening to traffic criteria specified in Table 2301-A (MnDOT Standard Specifications for Construction) the sample shall be tested according to the Concrete Manual. The results of this test shall be entered into the verification form and an updated copy with the newest test result shall be submitted to the Engineer the day that the verification test is completed.

If the actual flexural strength measured in the verification test is within 10% of the strength predicted by the maturity-strength relationship, the relationship may continue to be used.

If the actual flexural strength measured is more than 10% greater than the predicted strength, the relationship will not be considered verified, but will be considered acceptable for further use. A new maturity-strength relationship may be developed at the discretion of the Contractor.

If the actual flexural strength measured is more than 10% lower than the predicted strength, the relationship will no longer be acceptable and a second verification test may be conducted, or a new maturity-strength relationship may be developed, at the Contractor's discretion. If the second verification test does not fall within 10% of the maturity curve, a new maturity-strength relationship must be developed. The maturity method may not be utilized until a new relationship is developed.

Proper operation of maturity meters and temperature sensors is required to be verified every 30 days during paving operations. Verification is done by comparing the temperature recorded by the maturity meter or temperature sensor to a known temperature, as provided by a calibrated thermometer. At least three temperature points (e.g. 40°F, 75°F, and 110°F [5°C, 25°C and 45°C]) must be used in the sensor verification.

#### **2XXX.4 CHANGES IN CONCRETE MIXTURE**

Changes in the concrete mixture may require a new maturity-strength relationship to be developed. If any of the following conditions occur, a new maturity-strength relationship must be developed, and no additional concrete pavement may be placed using the maturity method until a new relationship is developed.

- a) changes greater than 5% by weight in the concrete proportions,
- b) change in the water-cementitious ratio greater than 0.02,
- c) changes to the curing method or conditions of the pavement,
- d) change in average daily ambient temperatures greater than 30°F from the conditions under which the original relationship was developed,
- e) changes in concrete mixing or placing equipment (concrete plant, paver, etc.), or
- f) changes in concrete mixing or placing methods (plant-mixed vs. ready-mixed, formed vs. slip-formed, etc.)

At the Contractor's discretion, if any of these conditions occur, a verification test may be conducted in lieu of a new maturity-strength relationship. If the verification test indicates that the relationship remains acceptable, a new relationship is not required.

# **Appendix B: Maturity Curve Development and Validation Spreadsheets**



# Concrete Maturity - Strength Development

Using Flexural Beam Strength

State Proj. No. \_\_\_\_\_  
 Project Location \_\_\_\_\_  
 District \_\_\_\_\_

Performed by \_\_\_\_\_  
 Contractor \_\_\_\_\_  
 Inspector \_\_\_\_\_

Report Date \_\_\_\_\_  
 Casting Date \_\_\_\_\_  
 Casting Time \_\_\_\_\_  
 Slab Thickness 8

Beam No.	Age at Break (days)	Ave. Width "B" (in)	Ave. Depth "D" (in)	Total Test Load (lbs)	Broken in Center Third? (Y/N)	Mod. of Rupture (psi)	TTF Sensor 1 (C-Hours)	TTF Sensor 2 (C-Hours)	Ave. TTF (C Hours)
1		5.98	6.01	4000	Y	370			
2	1	6.00	6.02	3800	y	350	881	887	885
3		6.00	6.00	4600	Y	425			
4		5.98	6.00	6600	Y	615			
5	2	6.00	6.01	6500	Y	600	2644	2638	2640
6		6.00	6.02	6000	Y	550			
7		5.98	6.00	7100	y	660			
8	4	5.98	6.00	7600	Y	705	5812	5816	5815
9		5.98	6.01	7200	Y	665			
10		6.00	6.02	8200	Y	755			
11	7	6.00	6.00	8100	Y	760	11295	11299	11295
12		6.00	6.01	8300	Y	765			
13		6.00	6.02	8400	Y	775			
14	28	5.98	6.00	9100	Y	845	22385	22391	22390
15		5.98	6.00	8700	Y	810			

Mix Information	
Air, %	_____
Slump, in.	_____
Mix No.	_____
Truck No.	_____
Time	_____

Comments

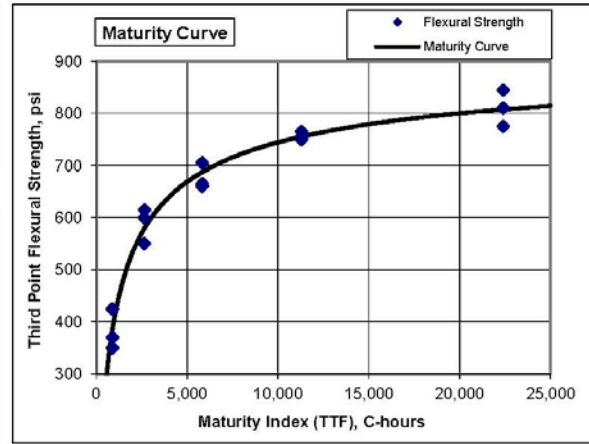
\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_



Curve Coefficients:  $S_u = 927.67$   
 $t = 710.37$   
 $a = 0.573$

**Solve Maturity Curve**

Required Strength for Opening 460 psi  
 Required TTF for Opening 1320 C-hours

cc: Project Engineer  
 Concrete Engineer  
 District Engineer

Signatures

Certified Contractor Rep. \_\_\_\_\_

Maturity Curve Reviewed by: \_\_\_\_\_

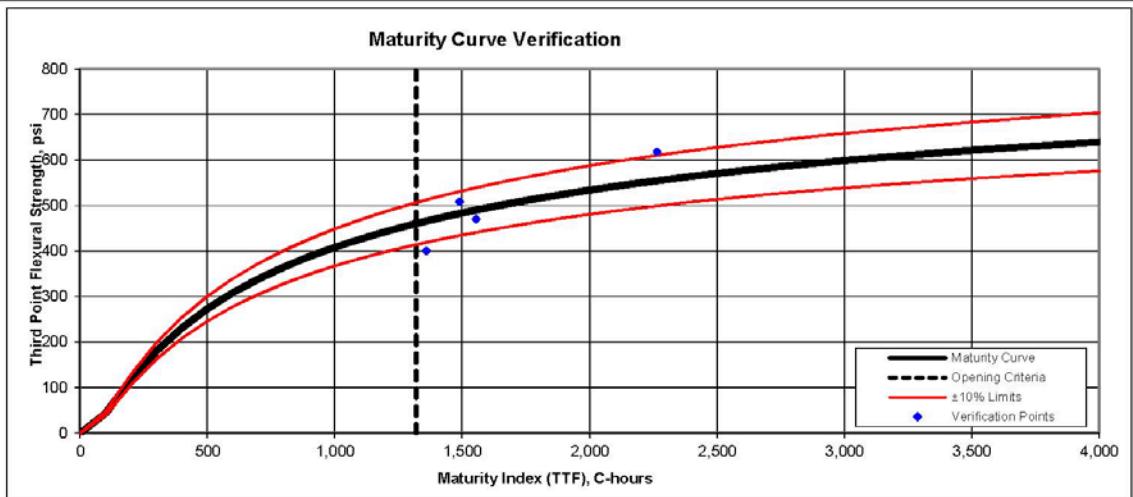


# Concrete Maturity - Strength Verification

Using Flexural Beam Strength

State Proj. No. _____	Performed by _____	Report Date _____
Project Location _____	Contractor _____	Casting Date _____
District _____	Inspector _____	Casting Time _____
Curve Coefficients	Maturity-Strength Report Date _____	Air, % _____
(from Maturity-Strength	Slab Thickness _____	Slump, in. _____
Development Report)	Required Strength for Opening _____ psi	Mix No. _____
$S_u = 927.67$	Required TTF for Opening _____ C-hours	
$t = 710.37$		
$a = 0.573$		

Test No.	Beam No.	Age at Break (days)	Ave. Width "B" (in)	Ave. Depth "D" (in)	Total Test Load (lbs)	Broken in Center Third? (Y/N)	Mod. of Rupture (psi)	TTF Sensor 1 (C-Hours)	TTF Sensor 2 (C-Hours)	Ave. TTF (C-Hours)	Verification Test Result
1	1		5.98	6.01	5200	Y	480				PASS
	2	2	6.00	6.02	5000	Y	460	1560	1550	1555	
	3										
2	1		5.98	6.01	4400	Y	405				FAIL
	2	2	6.00	6.02	4000	Y	370	1350	1370	1360	
	3		6.00	6.00	4600	Y	425				
3	1		5.98	6.01	5600	Y	520				PASS
	2	2	6.00	6.02	5400	Y	495	1490		1490	
	3										
4	1		5.98	6.01	6600	Y	610				ACCEPTABLE
	2	3	6.00	6.02	6800	Y	625	2260	2270	2265	
	3										
5	1										
	2										
	3										
6	1										
	2										
	3										



Signatures

Certified Contractor Rep. _____
Verification Test Reviewed by: _____

cc: Project Engineer  
Concrete Engineer  
District Engineer



## **Appendix C: Draft laboratory Manual**

## 5-694.50X DEVELOPING STRENGTH-MATURITY RELATIONSHIP

### A. GENERAL

This test method describes the procedure for developing maturity-strength relationships to estimate concrete flexural (or compressive) strength using the maturity method. This method uses either beams for flexural strength (pavement) or cylinders for compressive strength (structures). While the majority of this procedure is described using dual units, all temperatures relating to the computation of maturity shall be measured and recorded in degrees centigrade (°C).

### B. DEFINITIONS

#### 1. Temperature Sensor

The device on a maturity meter or data logger that is inserted into the concrete and provides a measure of temperature.

#### 2. Data Logger

A commercially available device that record temperature measurements from a temperature sensor at various intervals.

#### 3. Maturity Meter

A commercially available device that includes a temperature sensor, data logger, and conducts maturity calculations automatically.

#### 4. Maturity index

The cumulative area under the time-temperature curve developed as concrete cures. The units of maturity index are in degree-hours (C-hr). For the purposes of this procedure, the maturity index is often called the time-temperature factor (TTF).

#### 5. Maturity Curve

The relationship between the time-temperature factor and the strength of the concrete.

#### 6. Verification Test

At various intervals during construction, the maturity curve is verified by casting additional specimens and comparing the TTF-strength relationship with the original maturity curve for a particular mix.

### C. BACKGROUND

The maturity method utilizes the principle that the strength of concrete is directly related to the cumulative temperature history of the concrete. Using this principle, the strength of concrete in the field can be estimated quickly and reliably, and concrete pavement can be opened to traffic based on the *maturity index* (equivalent age or time-temperature factor) rather than by beam or cylinder tests in the field or the laboratory. The maturity as applied to a concrete mix is specific to that particular mix, and cannot be applied to any other. When the mix design is changed, a new maturity relationship, or *maturity curve*, must be developed and verified.

The development of a maturity-strength relationship requires three steps. These include:

- 1) developing the maturity-strength curve in the laboratory or in the field,

- 2) estimating the in-place strength in the field, and
- 3) verifying the strength-maturity relationship in the field.

This procedure utilizes the Nurse-Saul method for developing strength-maturity curves, as described in ASTM C 1074. The Nurse-Saul method uses a specific datum temperature (usually -10°C, but may be determined experimentally) to calculate the time-temperature factor (TTF) and to relate this to the measured concrete flexural or compressive strength at the particular TTF value. The general form of the Nurse-Saul method is shown in Equation 1.

$$TTF = \sum (T_a - T_0) \Delta t \quad (1)$$

where

- TTF = the time-temperature factor at age t, degree-days or degree-hours,
- $\Delta t$  = time interval, days or hours,
- $T_a$  = average concrete temperature during time interval,  $\Delta t$ , °C, and
- $T_0$  = datum temperature, -10°C.

#### D. APPARATUS

##### 1. Maturity Meter or Temperature Sensor and Data Logger

A maturity meter, for the sole purpose of recording concrete maturity, or a temperature sensor and data logger combination, accurate to  $\pm 1^\circ\text{C}$ , and capable of recording data at a time interval of 1 hour or less. For high-early strength or accelerated opening mixes, the devices must be capable of recording data at a time interval of 15 minutes or less.

##### 2. Beam Specimen Molds

For pavements, developing a maturity relationship with beams, a minimum of 15 beam specimen molds is required. The beam molds must be 6 in. x 6 in. (150 mm x 150 mm) in cross section, and with an overall length allowing for a span length in the testing apparatus of at least 3 times the depth.

##### 3. Cylinder Specimen Molds

For structures, developing a maturity relationship with cylinders, a minimum of 15 cylinders specimen molds is required. The cylinder molds must be 4x8 in (100 x 200 mm). If the aggregate has a maximum size greater than 1¼ in (31.5 mm), use 6x12 in. (150 x 300 mm) molds.

##### 4. Flexural Strength Test Apparatus

The apparatus for testing beam strength in flexure shall conform to the requirements in Section 5-694.522 (Testing Beams for Flexural Strength) of the MnDOT Concrete Manual.

##### 5. Compressive Strength Test Apparatus

The apparatus for testing compressive strength shall conform to the requirements in Section 5-694.510 (Compressive Strength Tests) of the MnDOT Concrete Manual and AASHTO T-22 (Compressive Strength of Cylindrical Concrete Specimens).

#### E. PREPARATION OF SPECIMENS

- A. Specimens must be prepared according to Section 5-694.511 (cylinders) or Section 5-694.521 (beams). It is preferred that specimens be cast, cured, stored, and tested in the

field. Ensure that concrete temperatures do not drop below 50°F (10°C). If air temperatures are expected to drop below 40°F (4°C), place the specimens on foam board or plywood to insulate them from the cold ground. Insulation may be placed on and around the specimens. If prepared in the laboratory, ensure that concrete used in making the specimens is identical in mixture proportions, quantities, and material manufacturers to those specified in the Mix Design Approval form.

- B. Prepare a total of 15 specimens according to the appropriate standard listed in part A above. For beams, the specimens should be made from a batch of at least 3 cy. For cylinders, a batch of at least 1 cy should be prepared.

Embed temperature sensors in at least two of the specimens. Ensure that all sensors are placed so that they are approximately 3 in. (75 mm) from any surface. For beams, place the sensor in one of the outside thirds (i.e. within 6 in. (150 mm) from the end of the beam). The specimens with the temperature sensors are to be the last specimens tested (at an age of 28 days). For cylinders, cast two additional cylinders that will not be tested, and place the sensors in the center of each cylinder.

- C. Test and record air content, temperature, and slump of the fresh concrete on the *Concrete Maturity-Strength Development* form.
- D. Protect the concrete specimens according to Section 5-694.511 (cylinders) or Section 5-694.521 (beams).

## F. PROCEDURE

### 1. Develop Strength-Maturity Relationship

Perform strength tests according to Section 5-694.522 (beams) or AASHTO T-22 (compressive) at ages of 1, 2, 3, 7, and 28 days (for high-early strength mixes, test at ages of 0.5, 1, 2, 7, and 28 days). Test two specimens at each age and compute the average strength. If the range of the two test results exceeds 10% of the average strength, test a third specimen and average the three strength test results. If a low test is the result of an obviously defective specimen, discard the result from the average but record its value and the reason for discarding it in the data entry form.

At each test age, determine the average maturity index (TTF) at the time the specimens are tested, by averaging the values obtained from the two maturity meters or data loggers. If using a maturity meter, the maturity index can be read directly from the meter. If using a temperature sensor and data logger, the maturity index must be calculated using the time-temperature history from the logger, and equation 1 in Section 1 of this procedure. Average the two maturity index values and report this in the appropriate location on the *Concrete Maturity-Strength Development* spreadsheet.

The *Concrete Maturity-Strength Development* form is a Microsoft Excel® spreadsheet that plots the average flexural strength vs. the average maturity index for each test age, and determines the best-fit exponential curve using the form

$$S = S_u e^{-\left(\frac{\tau}{TTF}\right)^\alpha}$$

where

- S = flexural strength (modulus of rupture) or compressive strength, psi
- TTF = the time-temperature factor at age t, degree-hours,
- S<sub>u</sub> = ultimate expected flexural strength, psi
- τ, α = time and shape coefficients.

The resulting fitted curve is the maturity-strength relationship to be used for estimating the in-place strength of concrete cured under any conditions including those in the lab or in the field. The *Concrete Maturity-Strength Development* spreadsheet for these calculations may be obtained from the Office of Materials.

For pavements, determine the opening strength criteria for concrete pavements from Table 2301-A in the MnDOT Standard Specifications for Construction.

For structures, determine the criteria for form removal or loading from Table %%%.

Enter all data, as it is collected, in the *Concrete Maturity-Strength Development* spreadsheet.

## 2. Estimate In-Place Concrete Strength

To estimate the in-place concrete strength in the field, place a temperature sensor in the concrete at a rate specified in MnDOT Standard Specification 2XXX.

Record the identification number(s) of the maturity meters or data loggers and protect any protruding wires from construction equipment. Initiate data collection and recording according to the manufacturer's instructions. If asked for a datum temperature, use a value of -10°C.

At regular intervals, check the recorded maturity index (or temperature history and compute the maturity index) and calculate the estimated strength of the in-place concrete using the equation determined in Section F.1, above. Report the time at which the concrete reached required opening strength criteria (for pavements) or form removal criteria (for structures) on the data form %%%.

## 3. Verify Strength-Maturity Relationship

At intervals specified in Standard Specification 2XXX, cast and cure three specimens and insert a temperature sensor in at least one of them (or in an additional specimen if using cylinders) as described above. Test all three specimens as described in this standard as close to the maturity index (TTF) for the pavement opening or form removal criteria as possible. Compute the average strength as described in Section F.1.

Plot the average strength and maturity index on the *Concrete Maturity-Strength Verification* spreadsheet and check that it falls on or near the curve. Take appropriate actions according to Standard Specification 2XXX.

Report the results of the validation testing on the *Concrete Maturity-Strength Verification* spreadsheet and submit the form to the Engineer in the field.

#### **4. Factors Requiring a new Curve**

When any of the following occurs, the development of a new maturity curve may be required.

1. Change in mixture proportions greater than 5% by weight
2. Change in the water-cementitious materials ratio greater than 0.02
3. Change in the source of any material in the approved mix design
4. Changes to the curing method or conditions of the pavement
5. Change in average daily ambient temperatures greater than 30° F (17°C)
6. Change in concrete mixing or placing equipment (concrete plant or slip-form paver)
7. Change in methods of mixing or placement (plant-mixed vs. ready-mixed, hand placement vs. slip-form placement)

If any of these changes occur, but a verification test, according to Section F.3, indicates no change in the maturity relationship has occurred, a new curve is not required.

#### **G. EXAMPLE WORKSHEET**

An example of the spreadsheet that is used to develop the maturity curve is shown below. The data collected in the testing procedure is entered in the yellow cells. The maturity-strength relationship is automatically computed.

#### **H. REPORT**

Report the fully-developed maturity curve relationship by entering the collected data in the *Concrete Maturity-Strength Development* spreadsheet. Report each verification test in the *Concrete Maturity-Strength Verification* spreadsheet. Submit all printed or electronic forms to the Concrete Engineering Unit and the Engineer in the field.

#### **I. CALIBRATION OF SENSORS**

Maturity meters must be calibrated yearly to ensure proper operation and temperature sensing.