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THE INFLUENCE OF CURING CONDITIONS ON STRENGTH PROPERTIES AND MATURITY DEVELOPMENT OF CONCRETE

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INDOT Research

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

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The Influence of Curing Conditions on Strength Properties and Maturity Development of Concrete

Introduction

The main objectives of this project were to establish a correlation between maturity development and degree of hydration of cement and to establish equivalent curing methods for concrete specimens that can accurately represent the curing conditions of concrete in pavement. To achieve these objectives, the following tasks were performed.

1. The maturity development of cement in relation to cement hydration was evaluated.
2. The influences of different specimen curing conditions and specimen types on the flexural strength, compressive strength, and maturity development of pavement concrete were evaluated.

Findings

Based on the research results presented in this document, the following conclusions were drawn from the study.

1. There existed a good correlation between maturity development of cement paste and the degree of hydration of cement. This correlation was valid only if sufficient moisture was available for continuous hydration of the specimens. The maturity-degree of hydration correlation could also be extended to concrete since the maturity development in cement paste and concrete was found to be similar.
2. With respect to flexural strength of the specimens, curing specimens in the lime bath or in the sandpit produced specimens with equivalent flexural strengths. Air curing of specimens did not produce specimens with a strength equivalent to the strength of specimens cured in either the lime bath or sandpit.
3. The temperature-matched curing technique was able to produce specimens with strengths within 10 percent of the flexural strength required for opening the pavement to traffic. This result was repeated in the field based on maturity values.
4. With respect to compressive strength, the specimens cured in the sandpit and the specimens cured in air were the most similar. The strengths of the specimens cured in the lime bath were different than the strengths of the specimens cured in the other two curing conditions.
5. The ambient temperature in which the concrete was cured had a significant influence on the maturity development of the concrete. The sandpit-cured specimens most accurately matched the maturity development of the pavement in the field study (within 6 percent). The lime-bath, sandpit and air-cured specimens all matched the maturity of the pavement to within 14 percent. The temperature-match cured specimens matched the maturity development in the pavement to within 1 percent in laboratory studies.

6. It appears that there was no difference between the maturity development in beam specimens and cylinder specimens. Air curing of specimens has a greater effect on the maturity-strength relationship of beam specimens than on cylinder specimens. Also, the temperature match-cured specimens validated the maturity curve for the concrete.

Implementation

Currently INDOT specifies two different types of field curing: lime bath and sandpit curing. Lime bath curing is used for QC/QA pavement construction for specimens made to determine the 7 day flexural strength of the concrete. Sandpit curing is used for estimating opening-to-traffic strengths of the pavement concrete. The constant temperature of the lime bath provides a uniform curing environment that should provide repeatable results (based on maturity) from batch to batch. However, due to the inability of the lime-bath-cured specimens to adjust to environmental conditions these specimens may not always provide an accurate representation of the strength of the pavement concrete. Thus, it is not recommended that the lime-bath-cured specimens be used for opening-to-traffic purposes. Specimens cured in the sandpit have the ability to adjust to the temperature of the environment, as does the concrete in the pavement. Therefore, these specimens are more appropriate for opening-to-traffic purposes. Thus, current INDOT specifications are appropriate.

Temperature match curing has the ability to provide specimens with an accurate representation of the maturity of the pavement. However, most commercial systems are costly. Less expensive in-house systems can be developed that would provide satisfactory results, however, the TMCB system developed in this study needs more development before it could be implemented. Further, sandpit curing provides results that are statistically equivalent to the maturity of the pavement. Thus, INDOT needs to determine if the extra expense of TMC systems is worth the increase in accuracy when current methods provide satisfactory results.

A method for converting between the strength of specimens cured in a given curing condition to the strength of the pavement is needed. An attempt was made to perform a regression analysis of the maturity data obtained in this study to develop such a relationship. However, the ANOVA results indicated that the trial (field trials T1-T3) was a significant factor. Since it was significant, the trial would have to have been included in the regression equation. Thus the use of the equation would have been limited to these three field studies.

To develop an equation with a broader range of uses, a greater number of trials need to be conducted. This experimental setup would remove the effect of the trial on the maturity development. Thus, the equation developed would be based only on the different curing conditions. Also, to base this equation on the strength of the pavement, cores of the pavement concrete should be taken and evaluated. The proposed form of the equation is shown in the following equation.

$$\ln(MOR) = a_0 + a_1C1 + a_2C2 + a_3C3$$

MOR = Modulus of Rupture
C1 = Curing Condition 1 Indicator Variable
C2 = Curing Condition 2 Indicator Variable
C3 = Curing Condition 3 Indicator Variable
a_n = Constant

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16. Abstract

In this study, the results of both laboratory studies and a field study, conducted to evaluate the effects of different curing conditions on the strength properties and maturity development of pavement concrete, are presented. Further, a laboratory study was performed to evaluate the maturity concept in relation to the degree of hydration of cement.

Concrete specimens, beams and cylinders, were prepared in the field study. The specimens in the field were cured in one of four curing conditions: lime bath, sandpit, air, or by temperature match curing. Specimens were tested for flexural strength and compressive strength, respectively. The temperature of the specimens was recorded and maturity calculated for specimens as well as for the pavement in the field study. The results indicate that there is no difference between the maturity development of beam and cylinder specimens. Also, Curing of specimens in lime bath and in the sandpit produced specimens with similar flexural strengths. Further, specimens cured in the sandpit most closely match the maturity development in the pavement.

Beams and cylinders were also made in the laboratory studies. Specimens were cured using temperature match curing. The technique was able to accurately replicate the maturity development in the pavement.

Paste cubes were prepared and samples of hardened paste were taken to determine the degree of hydration at different ages (by determination of non-evaporable water). While the specimens were cured (in either lime bath, sandpit, or air) the temperature of the specimens was recorded and the maturity of the specimens was subsequently determined. The study indicated that a good correlation exists between the maturity development of cement paste and the degree of hydration of cement. This correlation was valid only if sufficient moisture was available for continuous hydration of the specimens. The maturity development of the cement paste was also found to be similar to the maturity development of the concrete.

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1 INTRODUCTION

This section provides a brief background for the research project, presents the problem statement, specifies the research objective, and covers the scope of the research.

1.1 Background

The opening of pavements to traffic at the earliest possible time is a goal that is shared by both contractors and Departments of Transportation (DOTs). Contractors desire to proceed quickly with their work to minimize construction costs. The DOTs want the construction to be completed in a timely manner to minimize construction-related delays to the travelling public. However, early opening-to-traffic of portland cement concrete pavements requires an accurate method of determining the strength of the concrete in the pavement.

The Indiana Department of Transportation (INDOT) uses a method commonly used by other DOTs for determining the strength of concrete for opening-to-traffic purposes. Beam specimens are prepared from a representative sample of concrete used in construction of the pavement. These specimens are cured in a sandpit constructed on the job site. INDOT requires the sandpit to be kept in a moist condition to provide water necessary for the continued hydration of the cement in the specimens. The specimens are then tested for flexural strength, which is assumed to represent the flexural strength of the

in-situ concrete pavement. The age at which the specimens are tested is based on the judgment of the project personnel.

A different technique for determining opening-to-traffic times has recently been adopted by INDOT. The maturity method correlates the integral sum of the temperature of the concrete over the duration of time at which the concrete is that temperature, known as "maturity," to the flexural strength of the concrete. Thus, the temperature of the pavement concrete is monitored over the time the concrete is being cured, the maturity is calculated, and the strength of the pavement is predicted based on a previously established relationship between maturity and strength.

For Quality Control/Quality Assurance (QC/QA) portland cement concrete pavement construction projects, INDOT requires a second method of curing beam specimens to be tested for flexural strength. The specimens are cured in a bath of lime saturated water which is kept at a constant temperature (23°C).

Another curing method being considered by INDOT is known as Temperature Match-Curing (TMC). This curing method uses an external heating system to keep the temperature of a concrete specimen at the same level as the concrete in the pavement, at any given time. Thus, based on the maturity concept, the specimens would then have the same strength as the in situ concrete at any given time.

INDOT is currently developing a Performance Related Specification (PRS) for portland cement concrete pavement. In this specification, the amount of money the contractor will be paid for the pavement concrete will be adjusted with pay factors. Pay factors will be determined based on the life cycle cost of the pavement. The life-cycle cost is dependent on the results of flexural strength tests of the concrete (amongst other parameters). Since contractor payment is based on the results of flexural testing, a specimen curing condition that best represents the curing process of the pavement is desired.

1.2 Problem Statement

The problems addressed in this study can be broken into two categories: a) maturity development and hydration of cement, and b) effect of specimen curing condition and type on maturity development.

1.2.1 Maturity Development and Cement Hydration

Strength development in concrete is the result of a chemical reaction between cement and water known as hydration. Although this reaction is affected by many factors, only time, temperature, and availability of water are discussed here.

Time affects hydration as follows: the longer the period of time for which the reaction continues, the greater the amount of hydration products, and thus the greater the strength of the concrete. Temperature affects the rate of the hydration of cement as it does any chemical process: the greater the temperature, the quicker the reaction rate, and thus the

quicker the concrete strength gain. Finally, as long as a sufficient amount of water is provided, the hydration of the cement and concrete strength gain will continue.

Maturity methods account for the effects of time and temperature on the strength gain of concrete. It is presumed that two concrete specimens having the same maturity will have the same strength, provided they are made from the same concrete mix. However, as was previously stated, the strength gain depends on the hydration of the cement in the concrete. This reaction also depends on the availability of moisture. Maturity methods do not account for this factor. As such, there remains a question as to whether or not maturity accurately represents the hydration of the cement in the concrete.

1.2.2 Influence of Specimen Curing Condition and Type on Maturity Development

Specimens are made on the job site to determine the properties of the concrete in the pavement. Due to the specimen's smaller size and mass it will not be able to retain heat as well as the concrete pavement system. The curing conditions in which the specimens are placed compensate for this difference by providing insulation, and in the case of lime bath curing and TMC, heat. However, the degree to which each curing condition compensates for this difference is unknown.

The temperature of the pavement is subject to daily ambient temperature cycles. These cycles will effect the strength gain of the pavement. Since specimens placed in a lime-bath are held at a constant temperature they can not compensate for this factor. The temperature of specimens placed in a sandpit on the job site will follow the ambient

temperature cycles. The degree to which either the lime-bath-cured specimens or the sandpit-cured specimens represent the thermal history of the pavement is unknown.

By its nature TMC is expected to more accurately replicate the thermal history of the pavement than the traditional curing methods. Little testing has been done to evaluate the effectiveness of TMC. The results of the tests indicated the method is accurate. However, TMC systems are expensive while the other curing methods are inexpensive. The justification of the added cost of the TMC system based on its accuracy has not been established. As TMC is a simple concept, a less costly TMC system might be developed.

As previously stated the smaller size and mass of concrete specimens will effect the maturity development of the specimen. The maturity development of a beam specimen would be different than maturity development of the pavement. The maturity development of a cylinder specimen would be different from the maturity development of a beam specimen. The degree to which the maturity development of each differs from each other is unknown.

1.3 Research Objectives

The project seeks to establish a correlation between maturity development and degree of hydration of cement. Also, the project seeks to establish equivalent curing methods for concrete specimens that can accurately represent the curing conditions of concrete in pavement. Thus, the objectives of the experiment are as follows:

1. To evaluate the maturity development of cement in relation to cement hydration, and
2. To evaluate the influence of different specimen curing conditions and specimen types on the flexural strength, compressive strength, and maturity development of pavement concrete.

1.4 Research Scope

This section covers the scope of the project. Charts containing the test plan used to meet the objectives of the project can be found in Figure 1.1, Figure 1.2, and Figure 1.3.

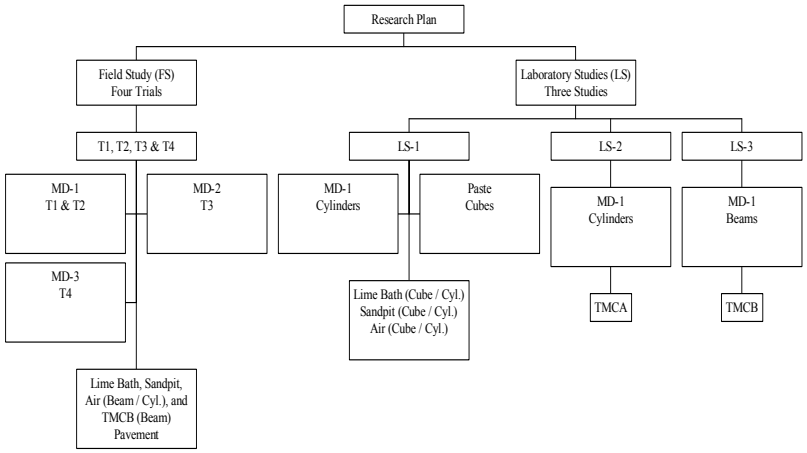


Figure 1.1 Overview of Test Plan

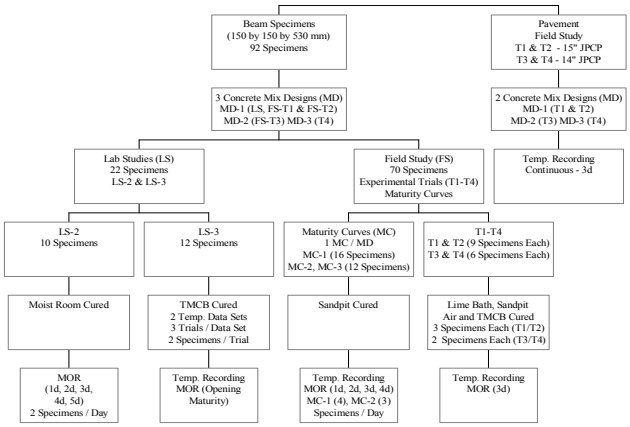


Figure 1.2 Test Plan for Concrete Beam Specimens and Pavement

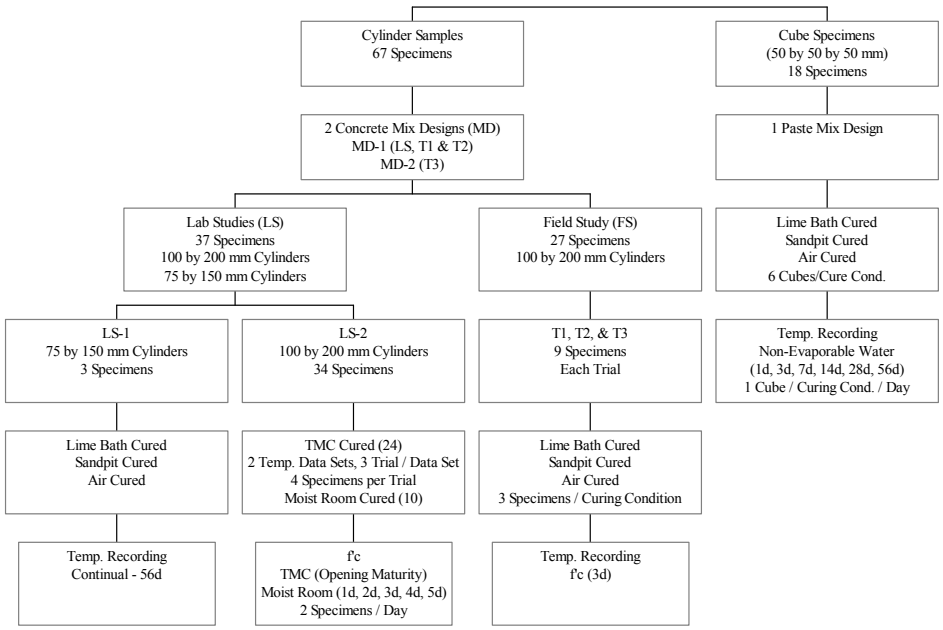


Figure 1.3 Test Plan for Concrete Cylinder and Paste Cube Specimens

To meet the first objective, cement paste cube specimens and concrete companion cylinders were made in the laboratory. One paste and one concrete mix design (MD-1 discussed later in this section) was used (see section 3.1). The 18 paste cubes and three concrete cylinders were cured in three different curing conditions: lime bath, sandpit and air. The first two conditions were chosen because they are currently used by INDOT. The third curing condition, air curing, was used to determine the effect of the lack of moisture on the maturity. See Section 3.2 for a detailed description of each curing condition. The temperature histories of the paste and concrete specimens were recorded for 56 days. The maturity of the paste and concrete specimens was determined. Also, the percent of non-evaporable water of one cement paste cube from each curing condition was determined at 1, 3, 7, 14, 28, and 56 days. This study was designated as Laboratory Study 1 (LS-1).

To meet the second objective, concrete beam specimens and cylinder specimens were made in one field study (FS) and two different laboratory studies (LS-2 and LS-3). Concrete pavement was also placed during the field study. The field study was repeated in four separate trials (T1, T2, T3, and T4). The location and description of the construction projects on which the trials were conducted can be found in Table 1.1. The field study can be divided into two parts: maturity curve development and experimental evaluation of mechanical properties and maturity.

Table 1.1 Location and Description of Construction Projects Used in Field Study Trials

Trial	Location	Description
T1	I-70 Rest Areas near Greenfield, IN	15 Inch, Jointed Plain Concrete Pavement (JPCP), Reconstruction Project
T2	I-70 Rest Areas near Greenfield, IN	15 Inch, Jointed Plain Concrete Pavement (JPCP), Reconstruction Project
T3	US-231 By-pass in Lafayette, IN	14 Inch, Jointed Plain Concrete Pavement (JPCP), New Construction
T4	I-465/I-74 Interchange in Indianapolis	14 Inch, Jointed Plain Concrete Pavement (JPCP), Reconstruction Project

In order to establish a relationship between maturity and the flexural strength of the concrete maturity curves were developed. In the field study, two concrete mix designs were used. Mix Design 1 (MD-1) was used in field trials T1 and T2. Mix Design 2

(MD-2) was used in field trial T3. A maturity curve was developed for each mix design. To develop the maturity curve for mix designs MD-1 and MD-3, the contractor of the construction project on which field trials T1, T2, and T4 were conducted, made 16 and 12 beam specimens, respectively for MC-1 and MC-3. To develop the maturity curve for mix design MD-2, the contractor on which field trial T3 was conducted, made 12 beam specimens. The beam specimens were cured in the sandpit. The temperature histories of the beams were recorded for 4 days and the maturity values of the specimens were calculated. Also, the specimens were tested for flexural strength at 1, 2, 3, and 4 days (four specimens per day for mix design MD-1 and three specimens per day for mix designs MD-2 and MD-3). From this information a relationship was developed between the maturity and the flexural strength. Using this relationship the maturity corresponding to the minimum flexural strength required for opening the pavement to traffic was determined.

In order to evaluate the effect of specimen type and curing condition on maturity development in the field, nine beam specimens and nine cylinder specimens were made in field trials T1 and T2. Six beam specimens and nine cylinder specimens were made in field trials T3 and T4. The specimens were cured in four curing conditions: lime bath, sandpit, air, and temperature match curing. The temperature histories of the in situ pavement concrete pavements placed during each trial and the specimens made for each trial were recorded for 3 days. The maturity values of the pavements and the specimens were calculated. The beam specimens were tested for flexural strength and the cylinder

specimens were tested for compressive strength at 3 days. The ambient temperature near the pavement was also recorded over the same period.

In order to evaluate the effect of TMC on maturity development of specimens (laboratory study LS-2), six sets of four cylinder specimens were made using mix design MD-1. The specimens were cured with a commercial TMC system, the "Sure Cure" system, using pavement temperature data sets obtained in field trials T1 and T2 (three specimen sets per data set). Curing with this system is designated as TMCA curing. The specimens were cured until the opening maturity was attained, and the specimens were tested for compressive strength. In order to compare these results to flexural strength data (the criteria used for opening the pavement to traffic) obtained in the field study, a relationship between the compressive strength of the concrete and the flexural strength of the concrete was needed.

In order to establish this relationship, 10 beam specimens and 10 cylinder specimens were made using mix design MD-1. The specimens were cured in a moist room at 100 percent humidity. Two beam specimens were tested for flexural strength and two cylinder specimens were tested for compressive strength at 1, 2, 3, 4, and 5 days. These data were combined with the flexural and compressive strength data from field trials T1 and T2 to produce a compressive-flexural strength relationship.

As an alternative to the commercial TMC system a system was developed and constructed to match cure beam specimens. This system was called the TMCB system.

The development and evaluation of the TMCB system was done in laboratory study LS-3.

In order to calibrate the TMCB system, four beam specimens were made using mix design MD-1. The specimens were cured with the TMCB system using pavement temperature data sets obtained in field trial T1. The temperature histories of the beams were recorded and the maturity of the beams were calculated. The specimens were not tested for flexural strength.

The TMCB system was also used to evaluate the effect of TMC on maturity development of specimens. Six sets of two beam specimens were made using mix design MD-1. The specimens were cured with the TMCB system using pavement temperature data sets obtained in field trials T1 and T2 (three specimen sets per data set). The specimens were cured until the opening maturity was attained, and the specimens were tested for flexural strength.

The effectiveness of the TMCB system to match the temperature of an actual pavement in the field was evaluated in an additional trial (T4) of the Field Study. A similar test plan as was used in the other Field Study Trials was conducted: the maturity curve was developed, six beam specimens were made from Mix Design 3 MD-3, monitoring of the specimen, pavement, and ambient temperatures was done, and the specimens were tested for flexural strength at 3 days.

2 LITERATURE REVIEW

Specimens of concrete in many shapes and sizes can be made and tested to determine various strength properties. These techniques are useful to determine the potential strength of a particular concrete mix. However, it is common practice to use these specimens to predict the strength of the concrete placed in a larger unit. Due to the greater size, different curing conditions, and variable proportions of the concrete mass, the reliability of these specimens in predicting the actual in-place strength of the concrete is sometimes questionable. Cores can be taken to determine the actual strength of the concrete however this practice is rarely used due to its destructive nature.

The maturity method has been proposed as a valid, nondestructive way to estimate in place concrete strength. Based on the maturity method, Temperature-Matched Curing (TMC) is a technique that holds promise for accurate estimation of in-situ strength using concrete specimens. The hydration of cement, and thus concrete strength gain, is also dependent upon sufficient moisture being supplied to the system. The literature review contained in this section reviews these topics.

2.1 Maturity Concepts

Described in this section is a brief history on the development of the maturity method and its implementation in pavement construction projects.

2.1.1 Development of the Maturity Method

The maturity concept was first studied in connection with the development of steam-cured concrete in the 1950s. As is with any chemical reaction, the rate of hydration of cement in concrete is related to the temperature at which the reaction takes place: the higher the temperature, the quicker the reaction. It is also commonly known that concrete will continue to gain strength with time. The maturity concept combines these ideas, and states that the development of concrete strength is related to the temperature of the concrete and the length of the curing time. With these two factors known, one can develop a correlation between the maturity value and the concrete strength at any given time. Since both the temperature of the concrete and the curing time can be determined nondestructively, the maturity method becomes an attractive tool for in-situ strength prediction.

The ability to predict the strength of concrete at any time has allowed the method to be adapted to many current construction practices. Hossain and Wojakowski [1988] noted the use of the maturity method in fast-track pavement construction. The use of the method in rapid pavement patching applications was noted by Whiting et al. [1994]. Also, ASTM [1995] cites use of the method for prestressed concrete production, and cold weather concreting. Projects that implemented the maturity method will be discussed later in this report. This section summarizes the history of the maturity method.

The maturity method is based on the premise that the product of time and temperature can be used to predict the strength of the concrete. As reported by Carino [1991], the

beginnings of the maturity method can be found in a series of papers dealing with accelerated curing methods for concrete. The first to propose that the product of the concrete temperature and time over a specified datum temperature (the lowest temperature at which concrete would develop strength) be used to predict concrete strength was McIntosh [1949]. This product was called the "basic age." However, McIntosh was unable to establish a clear relationship between the basic age and concrete strength development.

The same year, in his work on steam curing, Nurse [1949] also suggested the product of temperature and time could describe strength development. However, his work did not suggest the use of a datum temperature. Further, the temperature he used in the product was that of the curing environment, not that of the concrete. Nevertheless, Nurse's work was the first to verify the relationship between the temperature-time product and strength development.

Based on research conducted at the Cement and Concrete Association in England, Saul [1951] summarized research performed on steam-cured concrete. In his work, Saul coined the term "maturity" to describe the product of temperature and time. He also suggested that a datum temperature could be used. The maturity is described by the Equation 2.1.

$$M = \Sigma\ (T - T_o)\ \Delta t \qquad (2.1)$$

M = maturity,
T = average concrete temperature during Δt, and
Δt = time increment, and
T_o = datum temperature.

This relationship has become known as the Nurse-Saul function. When the temperature of the concrete is plotted against the curing time, the maturity, as described by the Nurse-Saul equation, is simply the area under the temperature-time curve above the specified datum temperature (see Figure 2.1). Saul suggested the datum temperature used in this equation should be -10°C. In his work, Saul also put forth what is now termed the "maturity rule." This rule states 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".

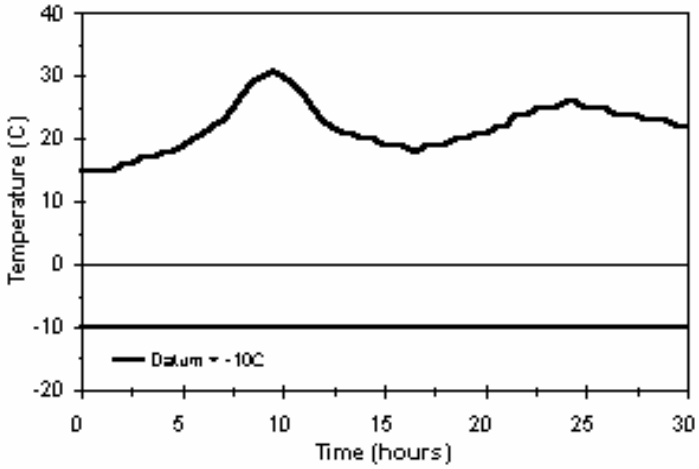


Figure 2.1 Nurse-Saul Concept of Maturity

The Nurse-Saul function can also be expressed in terms of "equivalent age." This quantity, shown in Equation 2.2, represents the amount of time required at the reference temperature to reach the same maturity at other temperatures.

$$t_e = \Sigma\ (T - T_o)\ \Delta t\ /\ (T_r - T_o) \qquad (2.2)$$

t_e = equivalent age at the reference temperature,
T_r = reference temperature,
T = average concrete temperature during Δt,
Δt = time increment, and
T_o = datum temperature.

Rastrup [1954] was the first to suggest the concept of equivalent age. His concept was based on the idea that a chemical reaction rate is doubled if the temperature is increased by 10°C. However, a later study by Wastlund [1956] reported that Rastrup's equation was not as accurate as the Nurse-Saul relationship.

Verbeck [1960] suggested that the Arrhenius equation could be adapted to describe the effects of temperature on the hydration rate of cement. However, it was not until 17 years later that Freiesleben Hansen and Pederson [1977] suggested the following relationship based on the Arrhenius equation (Equation 2.3).

$$t_e = \Sigma\ e^{-[E/R][1/(273+T) - 1/(273+Tr)]}\ \Delta t \qquad (2.3)$$

t_e = equivalent age at the reference temperature,
T_r = reference temperature, °C,
T = average concrete temperature during Δt, °C,
Δt = time increment
E = activation energy, J/mol, and
R = universal gas constant, 8.3144 J/mol(°K).

In a comparison of the equivalent age equations, Byfors [1980] and Naik [1985] independently confirmed that the Arrhenius equation best described the combined effects of temperature and time on concrete strength development.

2.2 Implementation of Maturity Method in Field Applications

Field studies of the maturity method were done in Canada as early as the 1970s. Bickley [1975] reported on the use of the maturity method in the construction of the Canadian National Tower. The tower had a slip formed concrete superstructure. The last three months of construction of the tower was done in the winter from December of 1973 to February of 1974. The maturity method was used to check that as the slip forms were moved, the concrete exposed to the winter conditions had achieved an adequate strength.

Mukherjee [1975] reported use of the maturity method in the construction of a building at the University of Waterloo. The strengths of the in situ concrete slabs were predicted to determine form removal times. Specimens of the in situ concrete were taken to determine the adequacy of the predictions. The report concluded that the maturity method provided satisfactory results.

2.2.1 SHRP Experience

Whiting et al. [1994-1] evaluated the maturity method for use in the field as part of the Strategic Highway Research Program (SHRP). The study focused on the rapid repair of full-depth concrete pavement repairs. Two sites were chosen to evaluate the method for this application. The first project was located on I-20 west of Augusta, Georgia. A total of 60 repair sections were tested. The second site was on State Route 2 near Vermilion, Ohio. A total of 80 repair sections were tested at this site. Nine mix designs were evaluated. In several cases, either Type III cement and/or accelerators were used in the mixes. The depth of the pavement was 9 inches in both projects.

Also, field studies were done using the maturity method to determine the opening-to-traffic time for concrete bridge overlays. Four sites were chosen to evaluate the maturity method. Two sites were in Ohio: US-52 in New Richmond and I-270 in Columbus. And two sites were in Kentucky: I-265 in Jefferson County and US-41 in Henderson. Two different mix designs were used. The first mix design was a latex modified concrete containing Type III cement. The second mix design was a silica fume concrete.

In both the rapid repair study and the bridge overlay study the maturity was determined using ASTM C 1074. Both the Nurse-Saul function and the Arrhenius equation were used to calculate the maturity. Excellent correlations were found between maturity and strength using both techniques.

In the rapid pavement repair study, cores of the pavement concrete were taken and tested at ages earlier than 8 hours. In the bridge deck overlay study, cylinders were made and cured under the burlap used to cure the concrete. These specimens were tested at 24 hours. The strengths of these specimens were used in a comparison with the maturity-predicted strengths. In both cases the maturity gave a safe estimation of the concrete strength.

Since the validity of the maturity method as an effective nondestructive field test was verified by SHRP, many states have implemented the maturity method for opening concrete pavements to traffic. The following section reviews the implementation of the maturity method in the states of Iowa and Indiana.

2.2.2 Iowa Experience

The state of Iowa was one of the first states to implement the maturity method. This section provides a summary of the history of these experiences and the conclusions regarding maturity methods that were drawn from these experiences.

2.2.2.1 History of Implementation in Iowa

Grove and Cable [1997] report that in 1988 a study involving fast-track concrete paving incorporated the use of nondestructive testing techniques including the maturity method. The FHWA used this project to demonstrate the benefits of nondestructive testing. Through subsequent trials in the late 1980s and early 1990s the study of nondestructive testing techniques was continued in Iowa. These studies found that the maturity method was a reliable test for field estimation of concrete strength.

In 1995, the maturity method was used in a series of field trials encompassing 14 concrete paving projects. The studies utilized three different mix designs and involved various pavement construction applications, e.g. primary highways, county highways, and pavement patching. These projects addressed such factors as: the number of specimens required to develop the maturity curve, the location of temperature probes within the pavement and specimens, and the variability of concrete mixes allowed for the maturity curve to remain valid.

In 1996, six projects were selected to utilize the maturity method to determine opening-to-traffic strengths. Results were positive and pavements were open to traffic in 18 hours in spite of projects not being designated as "fast-track" projects.

In 1997, Iowa allowed the contractor the option to choose to use the maturity method for opening the pavement to traffic. One of the first projects was done in May under cool

weather conditions (high temperatures of 15°C were noted). Opening strengths were attained in 3 days.

2.2.2.2 Conclusions from Iowa Studies

Given the results of the field studies of 1996 and 1997, Grove and Cable [1997] concluded that weather conditions had the greatest effect on the pavement opening strength. To reach the opening strength only 18 hours were needed in the summer, while as long as 3 days were needed in the early spring. The ambient temperature was found to have a much greater effect on strength development than pavement thickness.

In their review, Grove and Cable [1997] noted benefits of the maturity method to be reduced construction time and shortened traffic delays. This second benefit was noted to improve public relations during construction. Recommendations were made to use the maturity method to determine saw-cut times.

Grove and Cable [1997] also emphasized that the time of concrete placement and the temperature at which the concrete was placed should be noted when using the maturity method. It was recommended that probes should be placed in both the morning and afternoon to account for temperature variability and a back-up temperature sensor should be provided. The authors also stated that unique maturity curves should be developed for each mix.

The number of beams used to develop the maturity curves in the 1995 trials was 16 (three per time interval, five time intervals, and one to monitor temperatures). Many people thought that 16 beams was excessive. Thus, the number of beams was reduced to nine beams (two per time interval, four time intervals, and one to monitor temperatures) in 1996. This number of specimens provided a 95 percent confidence interval of ±70 psi (483 kPa) from the target flexural strength. To reduce this variability to ±50 psi (345 kPa) from the target flexural it was recommended to increase the total number of beams to 12 (three per time interval, and four time intervals).

In 1997, this number of specimens was used in selected projects. To provide a greater level of confidence, a procedure to validate the maturity curve was developed, Iowa Department of Transportation [1997-1]. Three beams were produced and monitored to determine their maturity. The flexural strength of the beams was determined at the required opening maturity. The average strength value was to be within ±50 psi (345 kPa) of the required opening strength. The Iowa Department of Transportation [1997-2] required this validation to be conducted once a month.

The Iowa Department of Transportation [1997-1] also noted that a project in which a section of pavement placed on August 19th was opened on August 21st. Loaded trucks were allowed on the pavement the same morning the pavement was opened. At the time of the report no visible cracks were noted.

The studies performed in Iowa recommended extending the use of the maturity method to structural and precast concrete. Cautions were again made regarding mix variability and recommended that changes in the w/c ratio should be limited to ±0.030. Also, warnings were made regarding the changing of the datum temperature. This change could allow pavement openings to occur too early.

2.2.3 Indiana Experience

Encouraged by the success of the Iowa studies the Indiana Department of Transportation (INDOT) decided to study the maturity method's usefulness in determining opening-to-traffic strengths. Nantung [1997] summarized the implementation efforts. The project selected to demonstrate the maturity method was a fast-track project, located at an interstate highway interchange. A bonus for early completion, a penalty for late completion, and lane rental fees were included to expedite completion.

The methods used to develop and validate the maturity curve were adopted from the Iowa studies. Twelve beams were used to develop the maturity curve and three specimens were made to validate the curve.

Initial results indicated the maturity curve had an R^2 value of 0.95. As the process became more refined, new maturity curves had R^2 values of 0.97. Thus, as the project progressed, the accuracy of the pavement strength predictions increased.

Among the benefits of the maturity method noted were increased motorist safety, reduced labor costs (due to minimizing number of specimens cast), and increased testing accuracy (due to fewer variables). The findings also suggested the maturity method could be used to determine times for form removal, pavement sawing, and concrete sealing.

INDOT currently allows contractors the option to use the maturity method. INDOT has developed its own test method, ITM 402-99T, based on the Nurse-Saul function, for use of the maturity method. A copy of this test method can be found in Appendix A.

2.3 Review of Temperature-Matched Curing (TMC) Concept

The effects of temperature history on concrete strength development as stated in the "maturity rule" have been extended to the temperature-matched curing (TMC) of specimens. Specimens cured using this technique are placed into a curing chamber. This chamber automatically adjusts the temperature of the specimen to match the temperature of a concrete reference, e.g. an in-place slab or structure. Since the specimens have the same thermal history as the reference, the specimens should also have the same strength at any point in time (if made from the same mix). Specimens can be match-cured simultaneously with the mass concrete. Alternatively, a thermal history of the reference can be recorded and the specimens can be match-cured to the reference at a later time.

In field studies done on rapid concrete repairs, Whiting, et al. [1994-1,2] reported that match-cured specimens exceeded pavement core strengths by over 20 percent. It was noted that the cause of this "over-estimation" of strength might have been the highly

insulated molds. The insulation did not allow as much heat loss as allowed by the slab. Thus the temperature of the specimens was kept too high. This study focussed on rapid early strength concrete and the strengths used in the comparison were determined 8 hours after the concrete was placed. Type-III cement and accelerating agents were used in several of the concrete mixes. No additional studies were found to confirm these observations. No additional studies were found that evaluated TMC over longer curing periods, either.

2.4 Influence of Moisture on the Degree of Hydration of Cement

The effects of sufficient moisture on strength development are well established. Neville [1997] notes that a moist curing environment will promote continued cement hydration and, thus, continued strength gain. Kosmatka and Panarese [1988] state this idea another way. If the amount of moisture required for continued hydration is not provided, strength gain will cease.

Powers and Brownyard [1948] note that as the hydration of cement proceeds, water becomes chemically bound in the hydration products. This water has been called "non-evaporable" to distinguish it from the evaporable water (adsorbed water and capillary water) within the system that is lost upon drying. The amount of non-evaporable water depends principally on the degree of hydration. In other words, the amount of non-evaporable water increases as the degree of hydration increases. Thus, the amount of non-evaporable water can be used to gage the degree of hydration of the cement.

3 EXPERIMENTAL PROCEDURE

In this section, elements of the experimental procedure are described. The first topics discussed are the materials and mix designs used to prepare the concrete and paste specimens used in all studies. Next, the equipment that was used for temperature data acquisition, TMCA evaluation, and TMCB development and evaluation are presented. The final topics discussed are the testing procedures that were used to test specimens in all studies.

3.1 Mix Designs and Materials

This section discusses the mix designs and materials used to produce both concrete and cement paste.

3.1.1 Concrete Mix Designs and Materials

Two separate concrete mix designs were adopted from the field study for use in both the field study and the laboratory studies. The contractor from the construction project on which field trials T1, T2 and T4 were conducted designed Mix Design 1 (MD-1) and Mix Design 3 (MD-3). The contractor from the construction project on which field trial T3 was conducted designed Mix Design 2 (MD-2). Table 3.1. contains a list of the materials used in mix design MD-1, their respective proportions, and their respective sources. Similar data for mix designs MD-2 and MD-3 can be found in Tables 3.2 and 3.3, respectively. The specifications regarding the requirements for #23 fine aggregate and #8

coarse aggregate can be found in the INDOT Standard Specifications Sections 904.01 and 904.02, respectively.

Mix design MD-1 was used in field trials T1 and T2 to produce concrete from which beam specimens, cylinder specimens, and pavements were made. Mix design MD-1 was also used in all laboratory studies to produce concrete from which beam and cylinder specimens were made. Mix design MD-2 was used in field trial T3 to produce concrete from which beam specimens, cylinder specimens, and pavements were made. Mix design MD-3 was used in field trial T4 to produce concrete from which beam specimens, and pavements were made.

Table 3.1 Materials for Mix Design 1 (MD-1)

Material	Type	Source	Proportion*
Cement	Type 1	Lonestar Cement	512 lbs/cyd
Fine Aggregate	#23 Natural Sand	Connersville	1466 lbs/cyd
Coarse Aggregate	#8 Limestone	Stony Creek	1685 lbs/cyd
Water Reducer	WRDA 82	W.R. Grace	3 oz/100 lbs
Air Entrainment	Daravair 1400	W.R. Grace	0.4 oz/100 lbs
Water (w/cm = 0.42 ± 0.03)†	N/A	N/A	215 lbs/cyd

*Proportions based on saturated surface dry condition of aggregate
† The w/cm used for field study was 0.42, w/cm used for laboratory study was 0.45
Note: 1 kg/m^3 = 1.66 lbs/cyd

Table 3.2 Materials for Mix Design 2 (MD-2)

Material	Type	Source	Proportion*
Cement	Type 1	Lonestar Cement	480 lbs/cyd
Fly Ash	Class C	Mineral Solutions	106 lbs/cyd
Fine Aggregate	#23 Natural Sand	Vulcan Materials	1208 lbs/cyd
Coarse Aggregate	#8 Limestone	Vulcan Materials	1818 lbs/cyd
Water Reducer	WRDA 82	W.R. Grace	4 oz/100 lbs
Air Entrainment	Daravair 1400	W.R. Grace	3 oz/100 lbs
Water (w/cm = 0.41 ± 0.03)	N/A	N/A	240 lbs/cyd

*Proportions based on saturated surface dry condition of aggregate

Note: 1 kg/m^3 = 1.66 lbs/cyd

Table 3.3 Materials for Mix Design 3 (MD-3)

Material	Type	Source	Proportion*
Cement	Type 1	Lonestar Cement	444 lbs/cyd
Fly Ash	Class C	Mineral Solutions	71 lbs/cyd
Fine Aggregate	#23 Natural Sand	Connersville	1553 lbs/cyd
Coarse Aggregate	#8 Limestone	Stony Creek	1657 lbs/cyd
Water Reducer	WRDA 82	W.R. Grace	3 oz/100 lbs
Air Entrainment	Daravair 1400	W.R. Grace	0.4 oz/100 lbs
Water (w/cm = 0.42 ± 0.03)	N/A	N/A	153 lbs/cyd

*Proportions based on saturated surface dry condition of aggregate
Note: 1 kg/m^3 = 1.66 lbs/cyd

The mix designs (MD-1, MD-2 and MD-3) are similar in that the same cement and admixtures (type and source) are used. The same sizes of aggregates (fine and coarse) are used by both mix designs. Also, the difference between the target w/cm ratio between the two mix designs is only 0.01. Finally, the target air contents of the two mix designs only differed by 0.5 percent.

The first notable difference between mix designs MD-1, MD-2 and MD-3 is that mix designs MD-2 and MD-3 contained fly ash. Field trials T1 and T2 were conducted in late

October and early November, respectively. INDOT does not approve the use of fly ash in concrete mix designs used on their projects after October 15th. Thus, the contractor could not use fly ash in the mix design. Field trials T3 and T4 were conducted in September, before the cutoff date. Thus, the contractor could use fly ash in the mix design. Another difference between the mix designs is that the aggregate sources are different.

3.1.2 Cement Paste Mix Design and Materials

One cement paste mix design was used to produce cement paste cube specimens for laboratory study LS-1. The paste mix design was based on the w/cm ratio used for mix design MD-1 in the laboratory. A w/cm ratio of 0.45 was used. The same cement type and source as used to produce concrete from mix design MD-1 was also used to produce the cement paste.

3.2 Specimen Preparation and Curing

As discussed earlier, two series of concrete specimens were used in this study. The first series was prepared in the field and the second series was prepared in the laboratory. This section describes the techniques used for preparing these specimens in both environments.

3.2.1 Field Specimens

This section describes the techniques used to prepare and cure the concrete specimens in the field study.

3.2.1.1 Concrete Specimen Preparation and Initial Curing

Table 3.4 contains a summary of the type, size, and number of specimens prepared for the maturity curve development and for each trial of the field study.

Table 3.4 Summary of Field Study Specimens

Trial	Number of Beams (150 by 150 by 530 mm)	Number of Cylinders (100 by 200 mm)
MC-1*	16	N/A
MC-2*	12	N/A
MC-3*	12	N/A
T1	9	9
T2	9	9
T3	6	9
T4	6	0

*Prepared by the contractor

The field study was broken into two different parts: maturity curve development and experimental evaluation. Mix Design 1 (MD-1) was used in trials T1 and T2 of the field study. Mix Design 2 (MD-2) was used in trial T3 of the field study. Mix Design 3 (MD-

3) was used in trial T4 of the field study. A maturity curve was developed for each mix design. Maturity curve MC-1 corresponds to mix design MD-1, maturity curve MC-2 corresponds to mix design MD-2, and maturity curve MC-3 corresponds to mix design MD-3. The technique used to develop the maturity curve was as outlined in Indiana Department of Transportation Test Method, ITM 402-99T (see Appendix A). To develop maturity curve MC-1, the contractor made 16 beam specimens. To develop maturity curves MC-2 and MD-3, the contractors made 12 beam specimens. ITM 402-99T required 12 beams to be made for the development of a maturity curve. The contractor opted to use a greater number of beams to develop maturity curve MC-1 in order to reduce the amount of variability associated with the maturity curve.

In order to evaluate the effect of different curing conditions and specimen types on maturity development a total of 30 beam specimens and 27 cylinder specimens were prepared in the field study.

The concrete used in the Field Study was produced in portable ready-mix concrete plants located on the site of the pavement construction projects. A front-end loader was used to obtain the material discharged from the plant mixer. The loader transferred the material to a designated testing area. The concrete was shoveled from the bucket of the loader into a wheelbarrow. Samples of the concrete from the wheelbarrow were used to cast specimens. All experimental specimens were prepared in accordance with ASTM C 31. Steel beam forms and plastic cylinder moulds were used to form the specimens. The specimens were consolidated by internal vibration.

All specimens were immediately placed in a laboratory trailer (kept at 23°C) on the job site for an initial curing period of 24 hours with the following exception. The trial T4 specimens cured in the TMCB system were placed in their molds in the curing box and covered with wet burlap for the first 24 hours. To monitor concrete temperatures, thermocouples, prepared as described in Section 3.3, were taped to a wooden dowel (6.4 mm diameter) and inserted into three each beam and cylinder specimens as shown in Figure 3.1. Cylinder specimens were capped with plastic lids (holes were made in the lids to accommodate the thermocouple wire) and beam specimens were covered with wet burlap to prevent moisture loss.

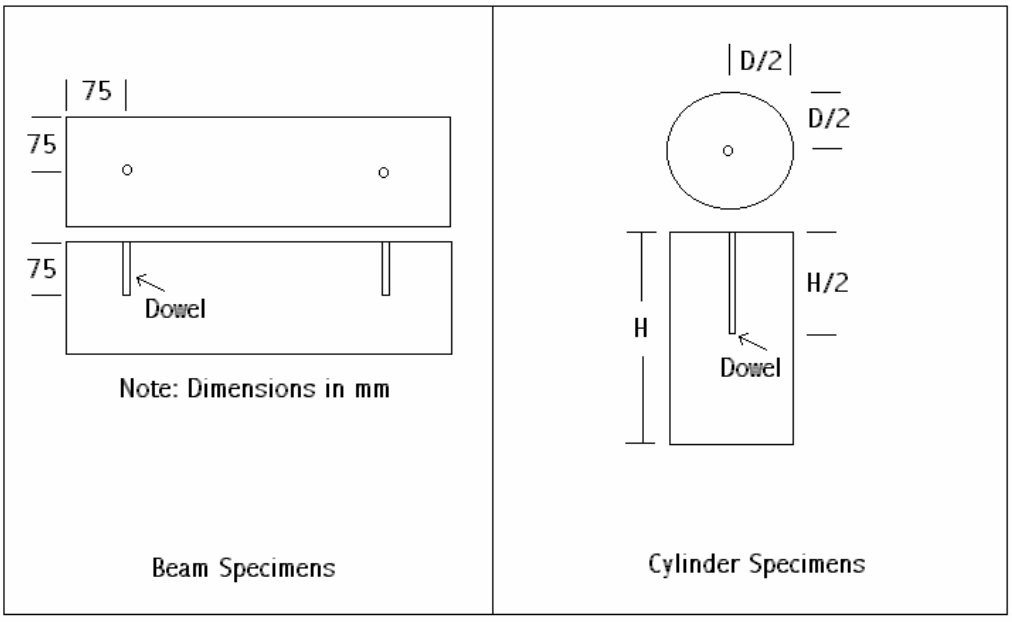


Figure 3.1 Location of Thermocouples in Specimens

For gathering temperature data from the pavement, thermocouples, prepared as described in Section 3.3, were taped to a wooden dowel and inserted into the pavement. The thermocouples were placed at mid-depth within the slab in accordance with ITM 402-99T.

To evaluate the maturity development of the specimens prepared for the development of the maturity curves, the thermocouples inserted into the specimens were connected to a Humbolt Model H-2680 maturity meter. To evaluate the maturity development of the specimens prepared for the experimental evaluation of maturity during the initial curing period, the thermocouples were connected to two different devices. In field trial T1, the Sure Cure system (see Section 3.4) was programmed to record the temperature data of the specimens. In field trials T2, T3, and T4 the TMCB control unit (see Section 3.4) was used to record the temperature data of the specimens. The control unit was used to record the pavement temperature data in all trials of the field study.

3.2.1.2 Experimental Concrete Specimen Final Curing

After the initial 24 hour curing period, the experimental specimens from trials T1, T2, and T3 were removed from the moulds and exposed to three different curing conditions. One each of the thermocouple-instrumented cylinders and beams were placed in each curing condition. The first curing condition, lime bath curing (see Figure 3.2), was achieved by immersing the specimens in lime saturated water as described in ASTM C 31.

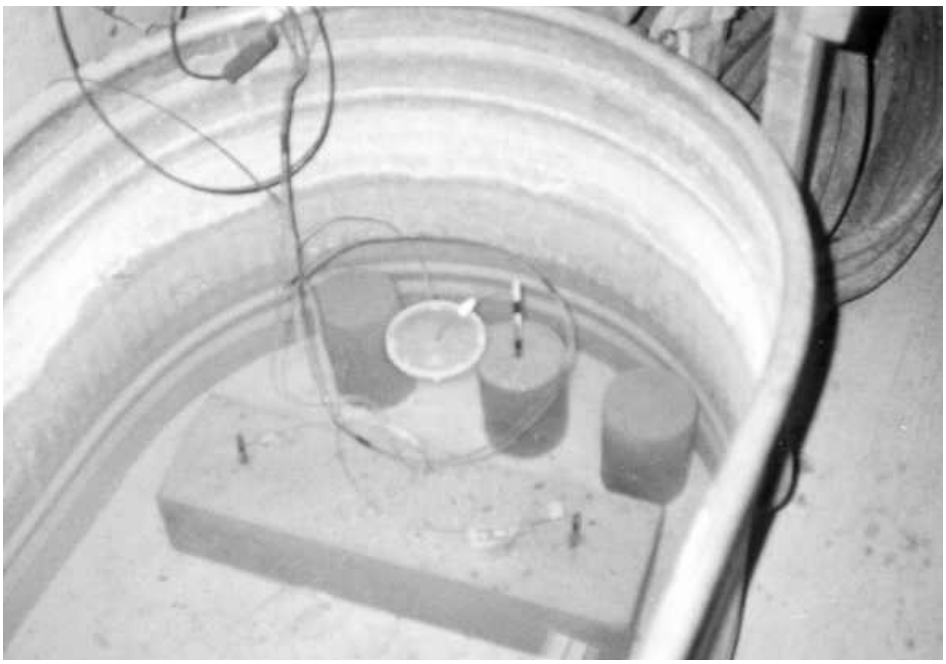


Figure 3.2 Lime Bath Curing

The second curing condition, sandpit curing (see Figure 3.3), was achieved by burying the specimens in moist sand as described in INDOT Standard Specifications 501.03.

Figure 3.3 Sandpit Curing

The third curing condition, air curing (see Figure 3.4), was achieved by placing the specimens on the surface of the existing pavement adjacent to the newly constructed pavement. No special arrangements were made to provide the specimens with moisture or insulation in this condition.

For field trial T4, the beam specimens were placed in the lime bath and sandpit as described above. The beam specimens cured by the TMCB system remained in the curing box.

The specimens remained in these curing conditions for 48 ± 2 hours at which time they were transported to the testing laboratory at Purdue University for determination of compressive and flexural strengths. All specimens were buried in wet sand and placed in plastic containers for transportation to the laboratory.

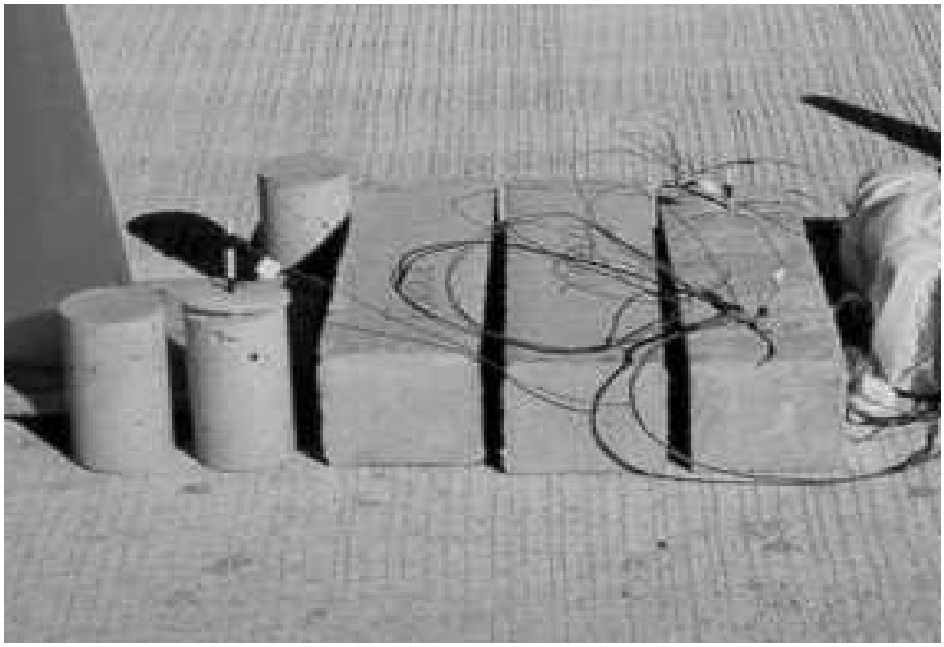


Figure 3.4 Air Curing

3.2.1.3 Maturity Curve Concrete Specimen Final Curing

After the initial 24 hour curing period, the specimens prepared for the maturity curve development were removed from their forms. One set of specimens (four specimens for the development of maturity curve MC-1 and three specimens for the development of maturity curves MC-2 and MC-3) were tested to determine their flexural strength at that time. The remaining beam specimens were cured in the sandpit until they were tested for flexural strength at 2, 3, and 4 days (four specimens per day for maturity curve MC-1 and three specimens per day for maturity curves MC-2 and MC-3).

3.2.2 Laboratory Specimens

This section describes the techniques used to prepare and cure the concrete specimens used in the laboratory studies.

3.2.2.1 Concrete Specimen Preparation

A list of all the concrete specimens used in the laboratory studies is provided below in Table 3.5.

Table 3.5 Summary of Laboratory Study Specimens

Laboratory Study	Beam Specimens (150 by 150 by 530 mm)	Cylinder Specimens (100 by 200 mm)	Cylinder Specimens (75 by 150 mm)
LS-1	0	0	3
LS-2	10	22	0
LS-3	16	0	0

In laboratory study LS-1, three concrete cylinders were made. These cylinders were used as companion cylinders to the paste cube specimens to compare the maturity development in cement paste to the maturity development in concrete.

In laboratory study LS-2, six sets of four cylinder specimens were prepared to evaluate the effect of TMCA on maturity development and strength. To correlate compressive strength results obtained in this experiment to the flexural strength results attained elsewhere in this study, a relationship between the compressive strength and flexural strength of the concrete was needed. This relationship was established by testing 10 cylinder-beam pairs.

In laboratory study LS-3, two sets of two beam specimens were made to calibrate the TMCB system. For the evaluation of the effect of TMCB on maturity development, six

sets of two beam specimens per set were made. Thus, a total of 16 beam specimens were prepared in laboratory study LS-3.

Materials necessary to replicate mix design MD-1 were obtained from the job site or their respective sources. On the construction project from which this mix design was adopted, the pavement was constructed by the slip-forming method. This method required a stiff concrete mix. However, consolidation and finishing of specimens made with this mix was difficult. Thus, the mix was modified by increasing the water-cement (w/cm) ratio from 0.42 to 0.45. This increase was within the limits allowed for the maturity curve to remain valid (target w/cm ratio ± 0.03).

Mixing of the concrete for the laboratory studies was done in accordance with ASTM C 192. A Lancaster Counter Current Batch Mixer was used to mix the concrete. Aggregates were used in the as-received condition. Prior to mixing, the moisture content of the aggregate was determined and adjustments to the water content were made for each batch, as needed. The value used for the absorption correction was obtained from the job site records.

Concrete specimens were cast according to ASTM C 192. After the first batch, slump and air tests were discontinued. This was done because there was not enough time to perform these tests and prepare the specimens within the time limits stipulated ASTM C 192. Also, there was a desire to begin temperature data collection as soon as possible.

Steel forms were used to form the beam specimens in all studies. Plastic moulds of two sizes (75 by 150 mm and 100 by 200 mm) were used to form the cylinder specimens in laboratory studies LS-1 and LS-2. The Sure Cure cylinder moulds (see Section 3.4) were also used to form specimens in laboratory study LS-2.

The specimens were consolidated by external vibration using a vibrating table except for the Sure Cure cylinder moulds that were consolidated by internal vibration. The specimens cured in the Sure Cure moulds were consolidated in this manner to reduce damage to the moulds.

To monitor concrete temperatures in the laboratory studies, thermocouples, prepared as described in Section 3.3, were taped to a wooden dowel and inserted into the concrete specimens as shown in Figure 3.1. One thermocouple was inserted into each cylinder made for laboratory study LS-1. In laboratory study LS-3, one beam was instrumented with thermocouples for each pair of beams prepared for the TMCB calibration trials. For the same study, one beam was instrumented for each pair of beams prepared for the six evaluation trials of the TMCB system. The thermocouples were connected to the TMCB control unit (see Section 3.4) to record the temperature data. All specimens were then cured as described in the following section.

3.2.2.2 Concrete Specimen Curing

Concrete specimens were cured by one of six curing methods: moist room curing, TMCA, TMCB, lime bath curing, sandpit curing, or air curing.

For laboratory study LS-1, the concrete companion cylinder specimens were capped in their moulds with plastic lids to prevent moisture loss. The specimens were initially cured in the laboratory for the first 24 hours. After the initial curing period, the specimens were removed from their forms and final specimen curing was achieved using three different curing techniques: lime bath, sandpit, and air curing. To prepare lime bath and sandpit curing environments in the laboratory, two plastic containers measuring 300 by 150 by 100 mm were obtained. Water was placed in one of the containers and calcium hydroxide in the amount sufficient to saturate the water was added into the container. This container was used for the lime bath curing. The second container was filled with sand and the sand was saturated with water. This container was used for the sandpit curing. One specimen was placed in each of the containers. These containers were placed on a shelf in the laboratory. The third specimen was air-cured in the ambient conditions of the laboratory by placing the specimen next to the containers on the shelf. No attempt was made to provide insulation to the specimen or to prevent moisture loss from the specimen. Figure 3.5 shows samples being cured under all three curing conditions. The specimens were kept in these curing conditions for a period of 56 days. The temperature of the specimens was monitored for this entire curing period. No further testing of these specimens was done.

Figure 3.5 Lime Bath, Sandpit, and Air Curing of Laboratory Specimens

In laboratory study LS-2, two different curing conditions were used, moist room curing and TMCA curing. The beam and cylinder specimens, used to determine the compressive-flexural strength relationship, were initially cured in their moulds in the laboratory for 24 hours. During this period, the beam specimens were covered with wet burlap and the cylinders were capped with plastic lids to prevent moisture loss from the specimens. After the initial curing period, the specimens were removed from their forms. Two pairs of beam and cylinder specimens were tested to determine flexural and compressive strengths at this time. The remaining specimens were left in the moist room at 100 percent humidity. The specimens remained in this condition until they were tested

to determine flexural and compressive strengths at 2, 3, 4, and 5 days. Two pairs of beam and cylinder specimens were tested at each testing period.

The cylinder specimens used to evaluate TMCA in laboratory study LS-2 were cured using the Sure Cure TMC system (see Section 3.4). The pavement temperature data sets to which the cylinders were match-cured were recorded in late October (field trial T1) and early November (field trial T2). Thus, pavement temperatures as low as 10°C degrees were recorded. In order to achieve these temperatures in the laboratory the Sure Cure moulds were placed in an environmental chamber set to 10°C.

After the specimens were cast, they were immediately transferred to the environmental chamber. In the chamber, the specimens were covered with wet burlap to prevent moisture loss. The cylinder moulds were connected to the Sure Cure system and curing was initiated. The curing continued until the opening-to-traffic maturity was attained (36.5 hours with the temperature data set from field trial T1 and 56.5 hours with the temperature data set from field trial T2). For this study, maturity corresponding to the flexural strength of 550 psi was used as an opening criterion. At this point the specimens were removed from their moulds and tested to determine their compressive strengths.

The beam specimens used to evaluate TMCB in laboratory study LS-3 were cured using the TMCB system (see Section 3.4). The TMCB system controlled the temperature of the curing box, in which the specimens were cured, to an offset temperature. The offset

temperature compensated for the difference in temperature between the specimens and the curing box. The offset temperature was used exclusively with the TMCB system.

As previously mentioned, the pavement temperature data sets to which the beams were match-cured were recorded in late October (field trial T1) and early November (field trial T2). Thus, pavement temperatures as low as 10°C were recorded. In order to achieve these temperatures in the laboratory the TMCB curing box was placed in an environmental chamber. For the series of specimens match-cured to the field trial T1 pavement data the environmental chamber was set to 10°C. The pavement temperatures recorded in field trial T2 were lower than the field trial T1 pavement temperatures. Thus, the offset temperature calculated based on the field trial T2 temperatures was lower than offset temperature calculated based on the field trial T1 temperatures. In order to attain this offset temperature in the lab, the environmental chamber was set to 0°C for the series of specimens match-cured to the field trial T2 pavement data.

After the specimens were cast, they were immediately transferred to the environmental chamber. In the chamber, the specimens were covered with plastic wrap to prevent moisture loss. The curing box and the specimen thermocouples were connected to the Sure Cure system and curing was initiated. The curing continued until the opening-to-traffic maturity was attained (36.5 hours with the temperature data set from field trial T1 and 56.5 hours with the temperature data set from field trial T2). As in laboratory study LS-2, maturity corresponding to the flexural strength of 550 psi was used as an opening

criterion. At this point the specimens were removed from their moulds and tested to determine their flexural strengths.

3.2.2.3 Paste Specimen Preparation and Curing

In order to evaluate the relationship between maturity development and degree of hydration of cement, 18 cement paste cube specimens were made. The paste mix design described in Section 3.1.2 was used to prepare the paste. Cement paste was prepared according to ASTM C 305 with the exception that a 2 minute mixing period on slow speed was used in lieu of a 1 minute mixing period on medium speed. This was done to reduce the amount of splattering of cement paste produced by the mixing process. Cube specimens were prepared according to ASTM C 109 however the flow test was eliminated, as this information was not needed in the experiment. The mixing of the paste was done in two batches. Nine 50 by 50 by 50 mm specimens were made from each batch. To monitor paste temperatures, thermocouples, prepared as described in Section 3.3, were placed in three specimens from the second batch at mid-height, mid-depth, and mid-width of the specimens.

Paste cubes were initially cured in their moulds under wet burlap for 24 hours. At the end of the initial curing period, the specimens were removed from their moulds. At this point three of the specimens were tested to determine the percent of non-evaporable water in the specimens (see Section 3.7). Six specimens were placed along side the companion concrete cylinders in each of the three curing conditions described in Section 3.2.2.2. To avoid localizing any of the batch variability, three specimens from each batch

were placed in each of the three curing conditions. One of the instrumented specimens was placed in each curing condition. Specimens were kept in these curing conditions until tested at 3, 7, 14, 28, and 56 days. One specimen from each curing condition was tested at each day. The specimens were tested to determine the percent of non-evaporable water in the specimens.

3.3 Preparation of Thermocouples

All thermocouples used in this study were prepared in-house following the procedure below.

The preparation of thermocouples used in this study was based on a method developed by Mr. Jon A. Jonsson, a fellow graduate student at Purdue University. The Type T thermocouples used in the experimental portion of the study were prepared in the following manner. About 25 mm of Type T thermocouple wire (24 gage, copper-constantine) was stripped from each end of a workable length (600 to 1200 mm) of wire. A Type T, male connector was attached to one end. In order to create a junction, the two leads at the opposite end of the wire were first twisted together and then soldered. Next, a two-part epoxy was spread over the twisted and soldered end. After the epoxy hardened, a piece of shrink-tube, measuring approximately 25 mm in length, was placed over the epoxy. The tube was shrunk over direct heat from a flame and crimped at each end of the tube with pliers. Next, silicone caulk was spread over the shrink-tube. Another piece of shrink-tube, measuring approximately 30 mm in length, was then placed over the silicone caulk. The tube was again shrunk over direct heat from a flame and

crimped at each end of the tube with pliers. Evaluations of the thermocouples indicated that the layers did not adversely affect the thermocouple's ability to accurately determine temperatures.

3.4 Equipment Used for Match Curing Specimens

This section describes the two match curing systems used in this study. The TMCA system was a commercially available system manufactured by Products Engineering, Inc. suitable for curing cylinder specimens only. The TMCB system was a system developed and built during this study to allow for curing of beam specimens.

3.4.1 TMCA (Sure Cure System)

This section describes the components, programming, and evaluation of the TMCA (Sure Cure) System.

3.4.1.1 TMCA (Sure Cure) System Components

The Sure Cure system was composed of four major parts: a personal computer (PC), a printer, an I/O cabinet, and four specialized cylinder moulds (100 by 200 mm). The computer was used to input test parameters into specialized, Sure Cure software that runs the system. The computer displayed temperature versus time data in a graphical form. These graphs were also printed using the printer. Maturity values were calculated by the PC and displayed on the computer screen.

The I/O cabinet (see Figure 3.6) was connected to the PC and was powered by a 120 Volt AC current. It contained connectors for thermocouples and connectors for heating

devices such as the cylinder moulds. Each thermocouple connector represented a different channel. The I/O cabinet contained an analog to digital converter that translated the temperature signals detected by the thermocouples to numerical data.

The numerical data was processed into temperature data by the software installed on the computer. The PC checked the data every 30 seconds and determined whether to activate or deactivate each channel's output relay. The data from each channel was recorded every 6 minutes. The system recorded the temperature in degrees Fahrenheit. The maturity was calculated using the Nurse-Saul Function (see Equation 2.1) and a base temperature of 0°F. The details of the maturity calculation are included in Section 4.3.2.1.

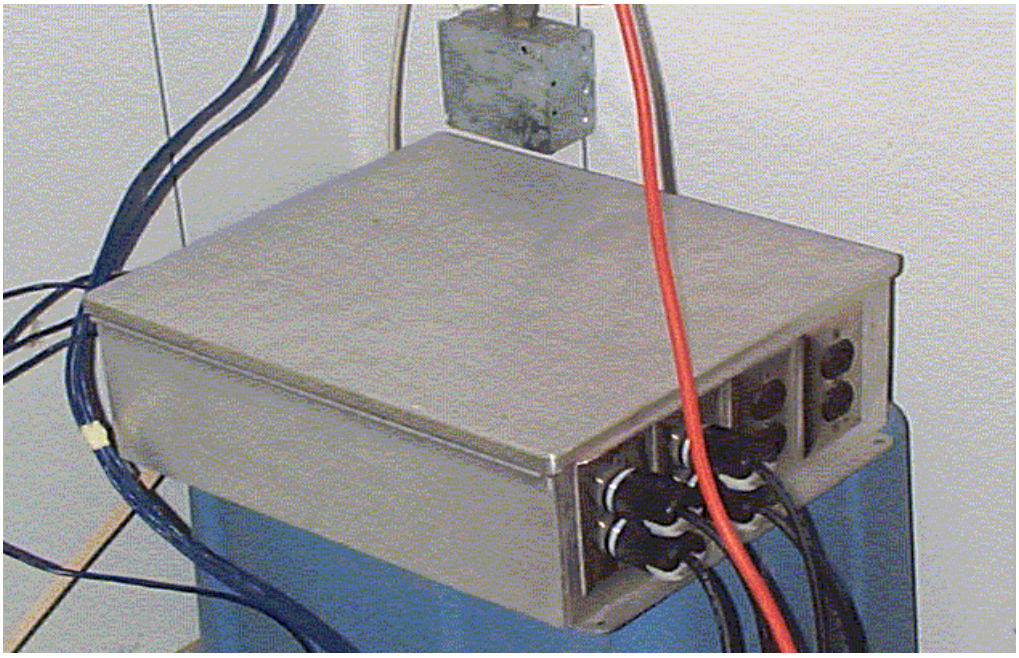


Figure 3.6 Sure Cure I/O Cabinet

The cylinder moulds used by the TMCA (Sure Cure) system (see Figure 3.7) were designed to be reusable. The moulds were constructed from steel and were heavily insulated. A heating element that applies heat to the specimen was placed inside each mould. Each mould was constructed with two receptacles. One receptacle was used to plug in thermocouples connected to the I/O cabinet for temperature monitoring of the concrete. The other receptacle was used to connect the mould to the I/O cabinet for temperature control of the concrete.

Figure 3.7 Sure Cure Cylinder Mould

3.4.1.2 Programming of the Sure Cure System for Match Curing and Temperature Recording

The Sure Cure system was programmed using the PC. The system was programmed to perform two independent functions. First, the system was programmed to follow a user designated time-temperature curve consisting of 20 data points. Also, the system was programmed to serve as a datalogger to record temperature data from thermocouples.

For the evaluation of curing conditions in the field study, the recording of concrete temperatures was necessary. The Sure Cure system was used as a datalogger in the field study to record temperature data in field trial T1. A series of three beams and three cylinders were made for each of three curing conditions (lime bath, sandpit, air). The system was programmed to record the temperatures of one beam and one cylinder specimen for each curing condition for the first 24 hours. After this period of time, the system was used to record the temperatures of one beam and one cylinder and for the remaining curing period of 2 days (see Section 3.2.1).

This Sure Cure system was also used in the laboratory studies. For the evaluation of TMCA in laboratory study LS-2, the system was programmed to follow user input pavement temperature data obtained from field trials T1 and T2 (see Section 3.2.1). The data acquired in these field studies was recorded every 10 minutes. This frequency of sampling produced over 400 data points for field trial T1 alone. However, the Sure Cure system only accepts 20 data points to be used to program a user input temperature curve. Thus, temperature data from the original data sets were taken at regular intervals (every

twentieth data point) to provide a representative time-temperature curve. The new data sets from field trials T1 and T2 were input into the Sure Cure system. These data are presented in Appendix B in Table B3.1 and Table B3.2 for the pavement temperature data from field trials T1 and T2, respectively.

The use of the Sure Cure system in conjunction with the TMCB development and evaluation in laboratory study LS-3 is described in Section 3.4.

3.4.2 The TMCB System

This section describes the development, components, calibration, evaluation of the TMCB control unit, and evaluation of the TMCB system.

3.4.2.1 Development of TMCB System

The Sure Cure system was not designed for field use, but rather for use in a laboratory. Also, the moulds provided with the system can only accommodate cylindrical specimens while beam specimens were needed for field applications. Since temperature-matched curing is a relatively simple concept it was determined a simple match curing system that can accommodate beam specimens could be developed using off-the-shelf components.

The preliminary design of the proposed system consisted of a control unit and a curing box containing a heater. The control unit would monitor the temperatures of both thermocouples embedded in the specimens and a reference thermocouple. If the temperature of the specimens decreased below the temperature of the reference, the control unit would activate the heater in the curing box. Once the specimen reached the

same temperature as the reference, the control box would deactivate the heater in the control box. Thus, the temperature of the specimen would be at the same temperature as the reference at any time. The system described below was developed in a cooperative effort with Mr. Jon A. Jonsson, a fellow graduate student at Purdue University.

3.4.2.2 TMCB System Components

This section describes the major components of the TMCB system including a control unit, a relay box, and a curing box.

The datalogger/controller chosen for the control unit was a Campbell Scientific CR10X. The CR10X was a fully programmable device with a nonvolatile memory and a battery-backed clock. A 12 Volt DC current powered the device and had the ability to record up to 500,000 data points. Analog inputs (six differential channels), a serial I/O port, digital I/O ports, pulse inputs, excitation outputs, and switched-12-Volt outputs were the connections that were available in this unit.

The six differential channels were available for thermocouple input. A Campbell Scientific AM-416, 16 channel multiplexer was used in conjunction with two of the differential channels to expand the thermocouple capacity of the system to 32 channels. These 32 channels were connected, using Type T thermocouple wire, to a standard jack panel (SJP2-36-T) from Omega Engineering. The multiplexer was connected to the datalogger by 22 AWG Type CMR, copper wire. For temperature compensation purposes, the reference junction was connected to the multiplexer.

All components (CR10X, multiplexer, and a 12 Volt rechargeable battery) were housed in a custom-built, plastic box (control unit box) (see Figure 3.8). The box measured 510 by 410 by 150 mm. In order to protect the multiplexer from moisture, it was housed in a second custom-built plastic box. This box measured 200 by 250 by 75 mm and was sealed with a desiccant inside to prevent moisture damage. A special cutout was made in the control unit box to mount the jack panel. The battery was connected to the CR10X using 18 AWG Type CL2, copper wire. The control unit was designed to be used as either a control unit for the TMCB system or a stand-alone unit to be used as a thermocouple datalogger. Two identical control units were constructed and used in various parts of this project.

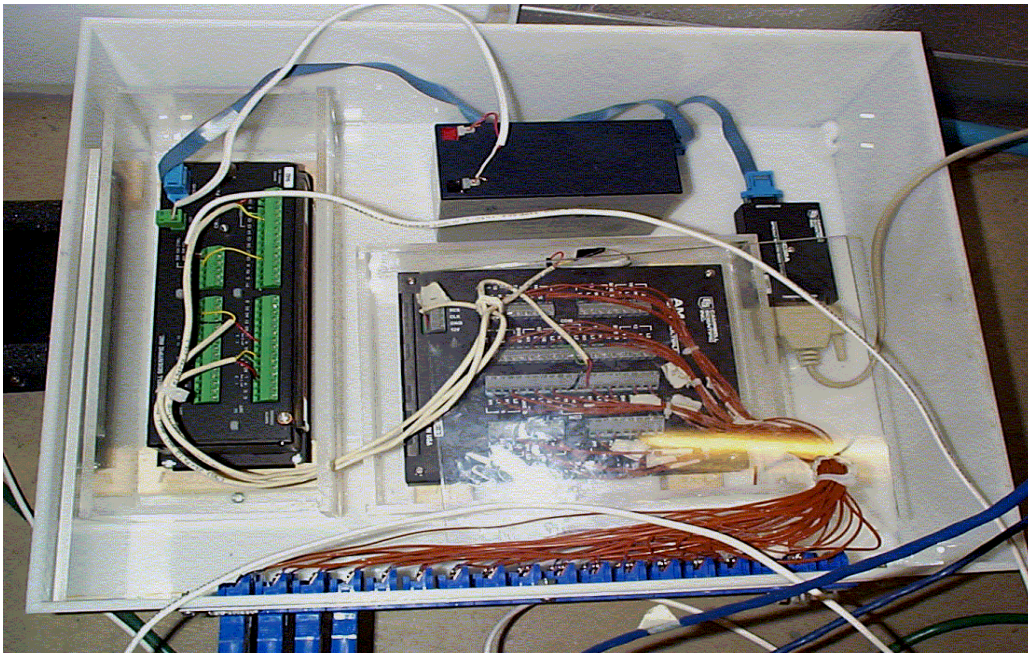


Figure 3.8 TMCB Control Unit

The main component of the relay box was an Omega Engineering solid state relay (SSR240DC25). This relay was used in conjunction with the digital I/O ports of the CR10X to control the on-off function of the heaters in the curing box. The relay took the DC signal from the CR10X and activated or deactivated the AC power to the heaters. The CR10X was connected to the relay using 18 AWG Type CL2, copper wire.

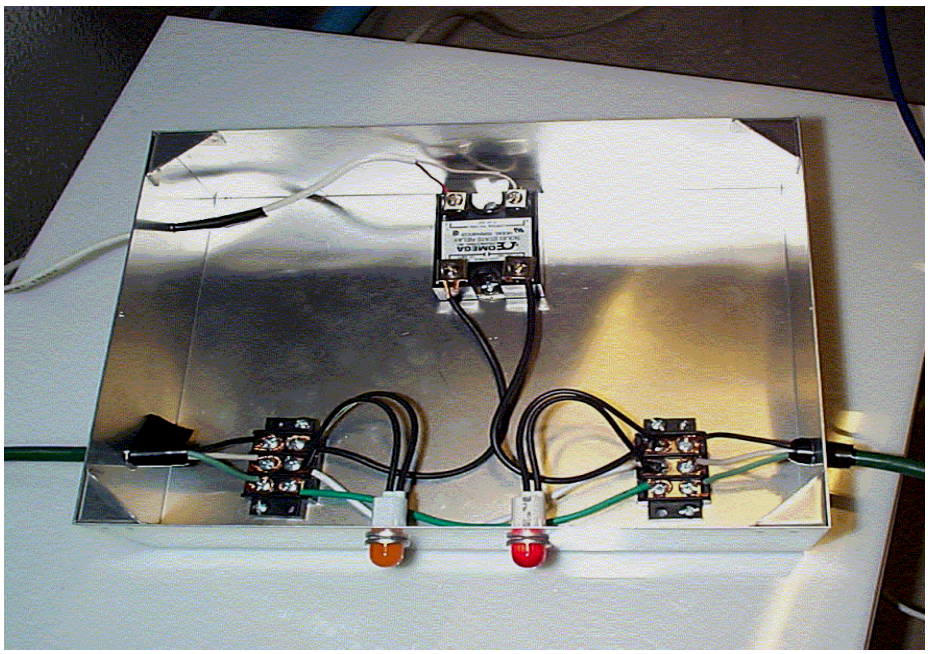


Figure 3.9 TMCB Relay Box

In order to allow the control box to be used as a stand-alone unit, the relay was housed in a separate aluminum electrical box (see Figure 3.9). The dimensions of the box were 260 by 205 by 75 mm. Cutouts in the box were made to allow passage for the wires connecting the relay to the CR10X, the AC power source, and the heaters. Two junction

terminals with a capacity to connect three conductors were mounted to the box. These terminals were used to connect the relay to the AC power. The cable used for the AC connections was suitable for outdoor use and consisted of AWG 16X3C, copper wire. The power cable had a three-prong plug and the heater cable had a three-prong receptacle. Cutouts in the box were also made to mount two indicator lights. One red light was used to indicate that the system had power. One amber light was used to indicate that the heaters were switched on.

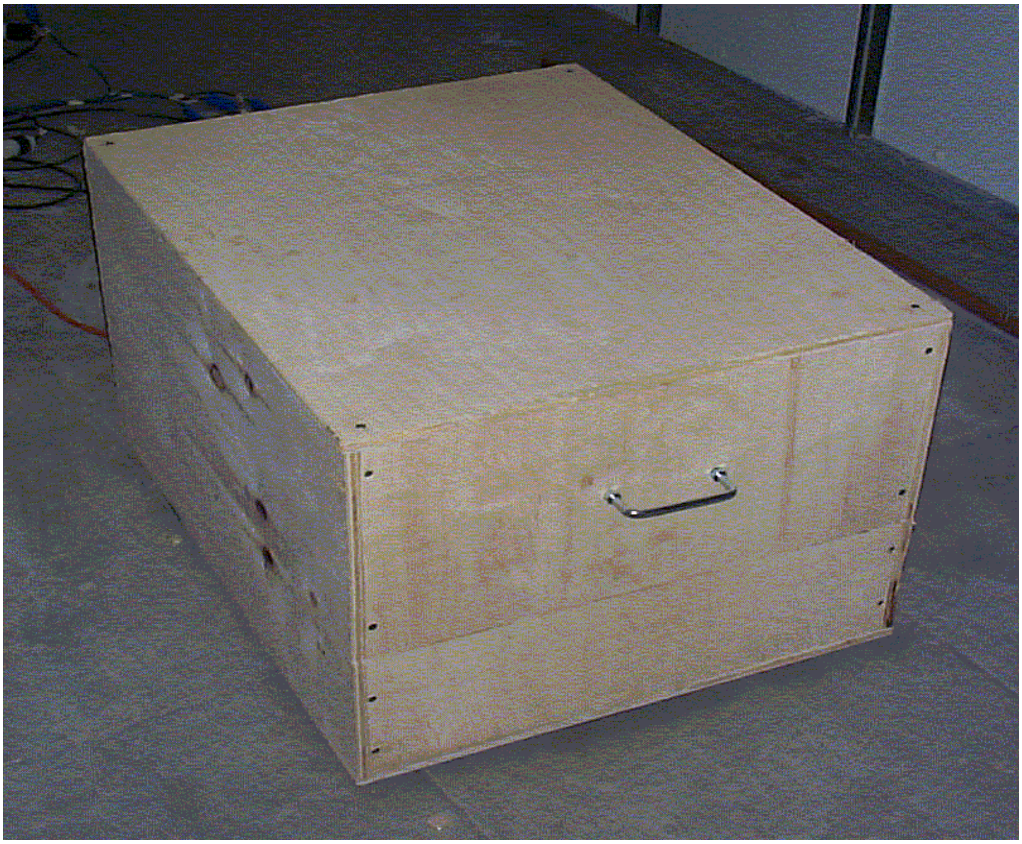


Figure 3.10 TMCB Curing Box

The curing box (see Figure 3.10) was constructed of 13 mm plywood with 25 by 50 mm standard lumber supports. The box was constructed using wood screws. It was built large enough to cure two standard beams measuring 150 by 150 by 530 mm and their forms. Two sections comprise the box. The bottom section measures 760 by 610 by 190 mm and the top section measures 760 by 610 by 290 mm. The bottom section of the box was designed with a low lifting height to allow easy placement of the concrete beams (see Figure 3.11).

Figure 3.11 Beam Specimens Placed in the Bottom Section of the TMCB Curing Box

Two 50 by 50 by 660 mm supports were positioned longitudinally in the bottom section of the curing box and affixed to the wall using wood screws. A series of six C-channel

steel supports with dimensions of 13 by 9.5 by 610 mm were placed transversely across the box on the two supports. Two strip heaters were positioned longitudinally on top of the six C-channels. A second series of six C-channel steel supports with dimensions of 13 by 4.75 mm were placed transversely on top of the two heaters, directly above the bottom six support channels (see Figure 3.12). The series of channels and heaters were positioned so that the top channel was flush with the top edge of the bottom section of the box. One wood screw was driven through each end of the six C-channel support pairs into the 50 by 50 mm support to secure their position. Additional bolt and nut pairs were used to prevent movement of the heaters between the steel supports. These pairs were placed on either side of each heater on alternating steel supports. The channels function as the support system for the beam specimens.

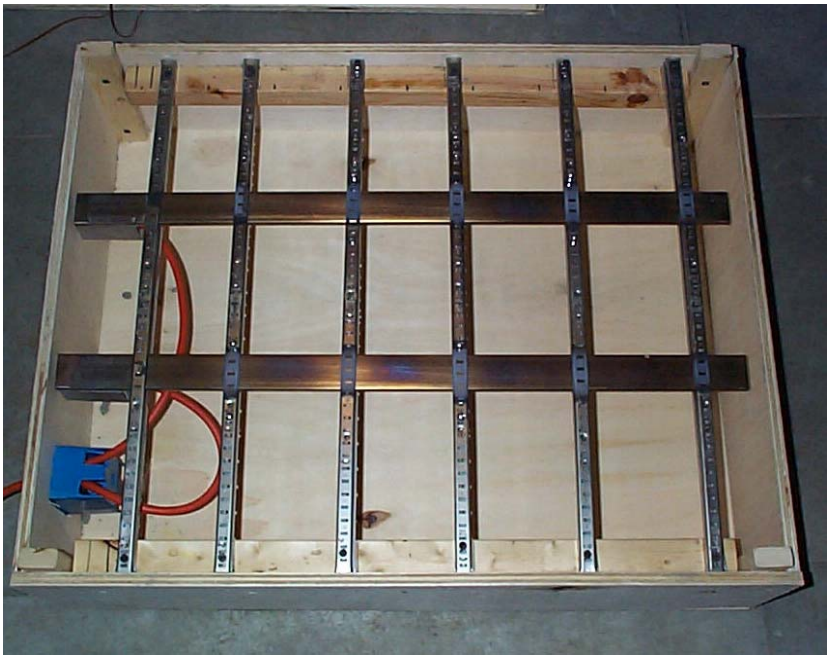


Figure 3.12 TMCB Heaters

Delta Manufacturing Co, Tulsa, Oklahoma, made the two 500 watt/120 volt channel strip heaters. Each heater measured 710 by 38 by 6.4 mm and had two connection posts. In order to provide power to the heaters, the heaters were connected to a three-pole junction terminal placed in a small box attached to the bottom section of the curing box. The heaters were wired using AWG 14 copper wire. The power cable for the heaters was also connected to the junction terminal. The power cable was suitable for outdoor use and consisted of AWG 14X3C gage, copper wire. The power cable had a three-prong plug.

In order to monitor the temperature of the curing box, one Type T thermocouple, prepared as described in Section 3.3, was installed in the center of the top section of the curing box. The thermocouple wire was connected to the control unit.

3.4.2.3 TMCB System Calibration

The main framework for the program used to run the TMCB system was developed as follows. The system read and recorded the temperatures of both a control thermocouple (Tc) and a reference thermocouple (Tr) (see Figure 3.13). These temperatures were read at a specified time interval. The system would compare the temperature of the specimen to that of the reference. The unit's ability to process logical commands based on thermocouple data was used to control the heaters in the cure box. If the temperature of the control was less than the temperature of the reference, the heaters were activated. If the temperature of the control was higher than the reference, the heaters were deactivated. The temperature from the datalogger was downloaded to a PC and inserted into a spreadsheet. Maturity values were calculated in the spreadsheet. This section describes the method used to calibrate the TMCB system to efficiently perform these processes.

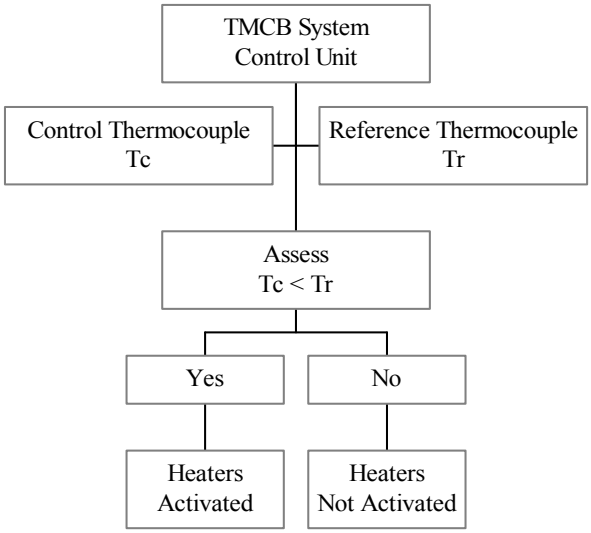


Figure 3.13 TMCB System Program Overview

Specialized software (Campbell Scientific, PC-210w) developed for use with the CR10X was obtained and installed on a personal computer to create programs for the CR10X. Programs were sent from the computer to the device via the serial I/O on the CR10X.

The following tasks were done to develop a suitable program for the TMCB system. Three preliminary tests of the TMCB system were run. Four beam specimens were prepared as described in Section 3.2.2 using mix design MD-1. Two beams were used in each test. The specimens prepared for the second test were reused in the third test to conserve materials. The thermocouples placed in the beams (placed as described in Section 3.2.2) were connected to the control unit.

As the TMCB system was designed to follow temperature–input from field concrete, it does not have the ability to follow a pre-programmed temperature curve. Thus, the Sure Cure System (see Section 3.4.1) was used to simulate the field input. A thermocouple was taped to the inside of one of the Sure Cure moulds and connected to the TMCB control unit. This thermocouple was used to provide the input for TMCB control unit. A cotton cloth was placed in the mould to slow heat loss. Concrete pavement temperature data obtained from field trial T1 of the field study were input into the Sure Cure computer as described in Section 3.4.1. The Sure Cure system controlled the temperature of the cylinder with the previously described input thermocouple to be the same temperature as that of the pavement from field trial T1. The TMCB system matched the temperature of the thermocouple that controlled the heaters (Tc) in the TMCB curing box to that of the reference thermocouple (Tr) placed in the TMCA cylinder (see Figure 3.14).

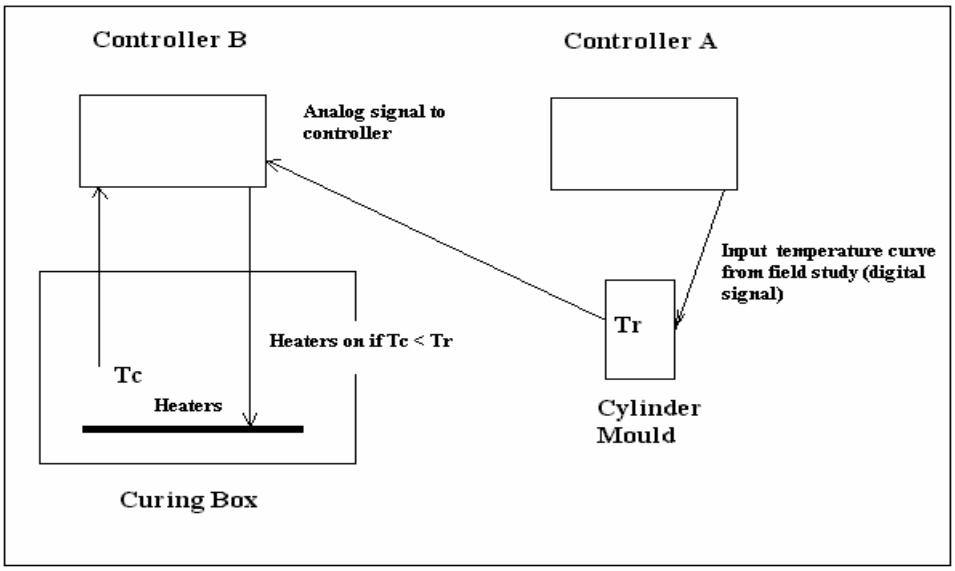


Figure 3.14 Set-Up for TMCB System Evaluation

The control program for the TMCB system was run in a loop that closed every 10 seconds. Thus, the temperature of the control thermocouple was compared to the temperature of the reference thermocouple every 10 seconds. This parameter was used to control the response time of the heaters. This short time interval was used due to a desire to quickly activate and deactivate the heaters. The system was programmed to average these temperatures and record them with the datalogger every 10 minutes.

A series of tests was run with the TMCB unit to select the best location for the control thermocouple, Tc. In the first test, Tc was located inside the 150 by 150 by 530 mm concrete beam. Two beams were placed in the TMCB curing box during this test. Although, only one beam was equipped with thermocouples as illustrated in Figure 3.1.

The results of this test indicated that it took a long time for the thermocouple located inside the beam to read the temperature of the reference thermocouple. As a result, by the time the heaters were deactivated the temperature of the box greatly exceeded the temperature of the beam. Thus, after the heaters were deactivated the temperature of the beam continued to increase. This caused the temperature of the beam to exceed the temperature of the reference thermocouple. Also, the beam took a long time to cool down. Therefore, the specimen was at a temperature greater than the reference temperature for a long period of time. The results of this test are presented in Figure 4.16.

Since the temperature of the beam was not suitable for use as the control temperature, the use of the temperature of the curing box as the control temperature was investigated in the second test of the TMCB system. The results of this test indicate that the temperature of the box responded more quickly to the heat applied by the heaters. Thus, the box temperature was better suited for use as the control temperature. However, there was a discrepancy between the temperature of the box and the temperature of the concrete specimen. The temperature of the concrete was an average of 7.5°C higher than the temperature of the box (see Figure 4.17). Thus, it was decided to try to use a different temperature as the control temperature. This temperature, termed the offset temperature, would be calculated by subtracting 7.5°C from the box temperature.

The third test of the TMCB system was run using the offset temperature as the control temperature. The results of this test indicated that the offset temperature was the most suitable temperature to use as the control temperature (see Figure 4.18). Therefore, the program used in the third test was used in further tests involving the TMCB system.

3.4.2.4 Programming of the TMCB System for Temperature Recording

In order to evaluate the working of the TMCB control unit it was initially programmed as a datalogger for all field study trials (T1-T3) and for laboratory study LS-1. The control unit was programmed to read and record the temperature of the thermocouples connected to it. The program was run at intervals of 60 seconds. Thus, the temperatures were

evaluated every 60 seconds. The control unit was programmed to average these temperatures and record them every 10 minutes.

3.4.2.5 Evaluation of the TMCB System

The TMCB system was evaluated in laboratory study LS-3. For this study, the control unit program developed during the system calibration was used with the offset as the control temperature. As previously mentioned, the TMCB system was designed for synchronous match curing in the field so it does not have the ability to follow a programmed temperature curve. Therefore, the reference temperature was again provided by the Sure Cure system as described in Section 3.4.2.3.

For the TMCB system evaluation, concrete pavement temperature data obtained from field trials T1 and T2 were input into the Sure Cure computer. The TMCB system matched the temperature of the control to that of the reference thermocouple placed in the Sure Cure cylinder. As was done in the system calibration, the program closed the control loop at 10 second intervals. The system was programmed to collect these intermediate temperature readings and record their average every 10 minutes.

3.4.3 TMCB Field Modifications

In order to accommodate the lack of AC power on a construction site, the TMCB system was modified. The strip heaters and their supports were removed from the curing box. T-shaped wooden supports made from 25 by 50 mm dimensional lumber were constructed and placed in the curing box to support the specimens. A 75 mm hole was

cut into the side wall of the bottom section of the box. This hole allowed forced air into the box. The curing box was painted to prevent water damage in the field.

A new relay box was constructed. The relay used was compatible with a DC/DC configuration. Thus, the relay took a DC signal and switched a DC current. The box used was a weather tight electrical box to which weather tight conduit was attached. The conduit was used to run the wires from the control box and the curing box. The box also housed a 12V DC battery which provided power to the fan on the heater.

The heating system used was a Zodi Hot Vent. The system uses a propane burner, heat exchangers, and a small DC powered fan to provide heat through 75 mm ventilation ducts. The ventilation ducts were connected to the curing box via the hole in the sidewall of the bottom section of the curing box. The control unit was used to switch the fan on when heat was needed in the curing box. The same system calibration and programming that is described in the following section was used with the modified TMCB system. Figure 3.13 shows the TMCB system in use during field trial T4.

Figure 3.15 TMCB System after Field Modifications

3.5 Flexural Strength Testing

The beams, prepared as described in Section 3.2 were tested to determine their flexural strengths in accordance with ASTM C 78. This test method was to determine the flexural strength of beam specimens using third-point loading of the beam specimens. The testing machine used for the flexural strength testing was a Satec Model M100 BTE-64380 with a maximum load capacity of 100,000 lbs. The beams were tested promptly after removal from their curing conditions to prevent moisture loss. A loading rate of 150 psi/min (1.04 MPa/min) was used in all experiments. (The standard specifies a loading rate between 125 and 175 psi/min (0.86 and 1.21 MPa/min)). This rate of stress was converted to load

rate for purposes of controlling the testing machine. The equivalent loading rate was 1800 lbs/min (8000 N/min) based on the equations provided in the ASTM standard.

3.6 Compressive Strength Testing

The cylinders, prepared as described in Section 3.2 were tested in accordance with ASTM C 39 in order to determine their compressive strength. The testing machine used for the compressive strength testing of the specimens prepared in the field was a Satec Model M100 BTE-64380 with a maximum load capacity of 100,000 lbs. The testing machine used for the compressive strength testing of the specimens prepared in the laboratory was a Forney Model FT-40-DR with a maximum load capacity of 250,000 lbs. The cylinders were tested promptly after removal from their curing conditions to prevent moisture loss. Neoprene pads were used to compensate for end irregularities. A loading rate of 40 psi/s (0.28 MPa/s) was used in this experiment. (The standard specifies a loading rate between 20 and 50 psi/s (0.14 and 0.34 MPa/s)). The testing required load control loading (lbs/min). To accommodate this parameter, the value of 40 psi/s (0.28 MPa/s) was converted to an equivalent loading rate of 30,000 lbs/min (133,333 N/min) based on the equations provided in the ASTM standard.

3.7 Determination of Non-Evaporable Water of Cement Paste Specimens

As previously discussed, the amount of non-evaporable water in hydrated cement is directly proportional to the degree of hydration of the cement. To establish a relationship between the maturity and degree of hydration, the amount of non-evaporable water was determined. This section describes the experimental procedure used to determine the

amount of non-evaporable water. After the paste cube specimens (see Section 3.2) were removed from their respective curing conditions, they were promptly sealed in airtight containers to prevent carbonation and moisture loss prior to testing. To obtain hardened paste samples from inside the cube, a compressive force was applied to the specimen using a Satec Model M100BTE-64380 testing machine with a maximum load capacity of 100,000 lbs. The specimens were loaded until failure. After the specimens failed, they were returned to their airtight containers to prevent carbonation and moisture loss.

The procedure used for the determination of non-evaporable water was adopted from previous work by Barneyback [1983]. Nine individually numbered porcelain crucibles were placed in an electric muffle furnace at 1050 ± 50°C for a minimum of 15 minutes to "burn-off" any excess material present on the crucible caused by handling. The crucibles were removed from the furnace and were allowed to cool in a desiccator. When the crucibles were cool, their mass was determined. Throughout this experiment, the crucibles were handled with tongs to prevent the crucibles from becoming contaminated. The contamination could cause the mass of the crucible to change.

Three paste samples were obtained from one cube taken from each of the three curing conditions. The paste samples had a mass of approximately 1g. Tongs were used to carefully remove the sample of paste from approximately the center of the previously crushed specimen. The nine samples were placed in separate crucibles and their mass was determined. The crucibles containing the specimens were placed in a laboratory oven and dried at 105 ± 5°C for 24 ± 2 hours. After this period of time, the specimens

were removed from the oven and allowed to cool in a desiccator. Next, the masses of the specimens in the crucibles were determined. The mass loss between the original sample mass, M_o, and the sample mass after the 24 hours at 105°C, M_{od}, is the mass of the evaporable water. Next, the specimens in their crucibles were transferred to an electric muffle furnace. The muffle furnace was set at 1050°C and the specimens remained in the furnace for 15 minutes. The specimens were removed from the furnace, after this period, and allowed to cool in a dessicator. After the specimens were cooled, the mass of the specimens in their crucibles was determined. The mass loss between the sample mass after 24 hours at 105°C, M_{od}, and the sample mass after 15 minutes at 1050°C, M_{mf}, is the mass of the non-evaporable water.

The percentage of non-evaporable water (%NEW) was calculated based on the original dry mass of cement in the sample, M_d. Equation 3.1 was used to calculate this percentage.

$$\%NEW = ((M_{od} - M_{mf}) / M_d) \% \qquad (3.1)$$

4 RESULTS

The results of the flexural strength tests, compressive strength tests, temperature recording, and non-evaporable water determination described in Section 3 were compiled and are presented in this section.

4.1 Flexural Strength Test Results

The results of the flexural strength tests are presented in this section. The results have been separated into two groups: field study and laboratory studies. In both cases, the flexural strengths were calculated as the modulus of rupture (MOR) as defined by ASTM C 78.

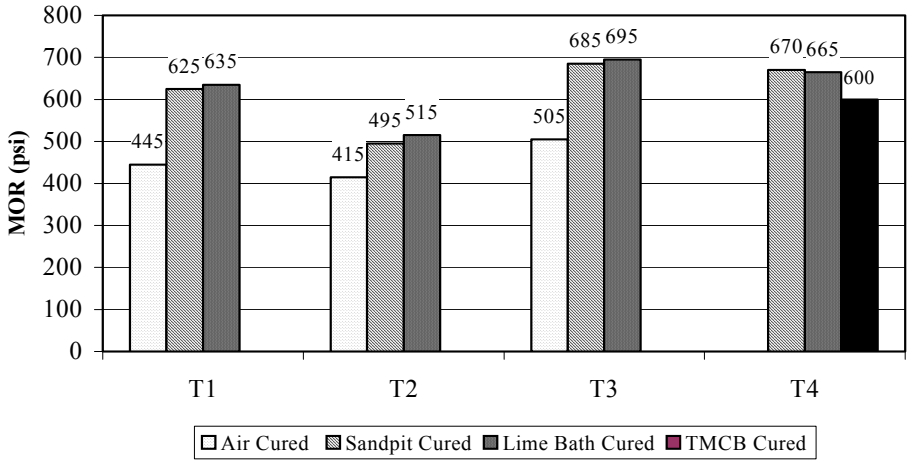
4.1.1 Field Study

Beam specimens, prepared as described in Section 3.2.1, were tested to determine their flexural strength, as described in Section 3.5.

4.1.1.1 Experimental Evaluation

To evaluate the influence of curing condition on the flexural strength properties of concrete, the flexural strengths of the beam specimens prepared in the experimental portion of the field study. For each trial of the field study, in each curing condition, the flexural strengths of the individual beam specimens (three per curing condition in field

trials T1 and T2, two per curing condition in field trials T3 and T4) were determined at 3 days. The averages of the results of these tests appear in Figure 4.1.



Note: Data for this figure are presented in Appendix C, Table C4.1.
Each bar represents the average of three specimen (T1 and T2) or two specimen (T3 and T4) strengths.
1 MPa = 145 psi

Figure 4.1 Average Flexural Strength Test Results Tested at 3 Days– Field Study

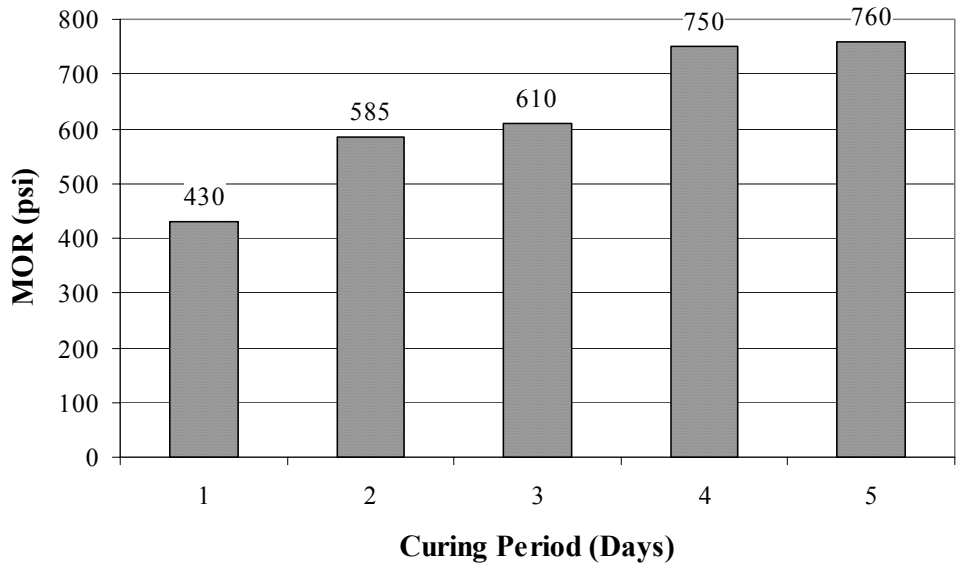
4.1.1.2 Maturity Curve Development

To develop the flexural strength-maturity relationship (maturity curve MC-1), the contractor monitored the temperature of one beam over a period of four days while testing four beams per day in flexure. For the development of maturity curve MC-2, the contractor tested three specimens per day, for four days, to determine their flexural strengths. The results of these tests appear with their respective maturity curves in Appendix D.

4.1.2 Laboratory Studies

Beam specimens, prepared as described in Section 3.2.2, were tested to determine their flexural strength, as described in Section 3.5.

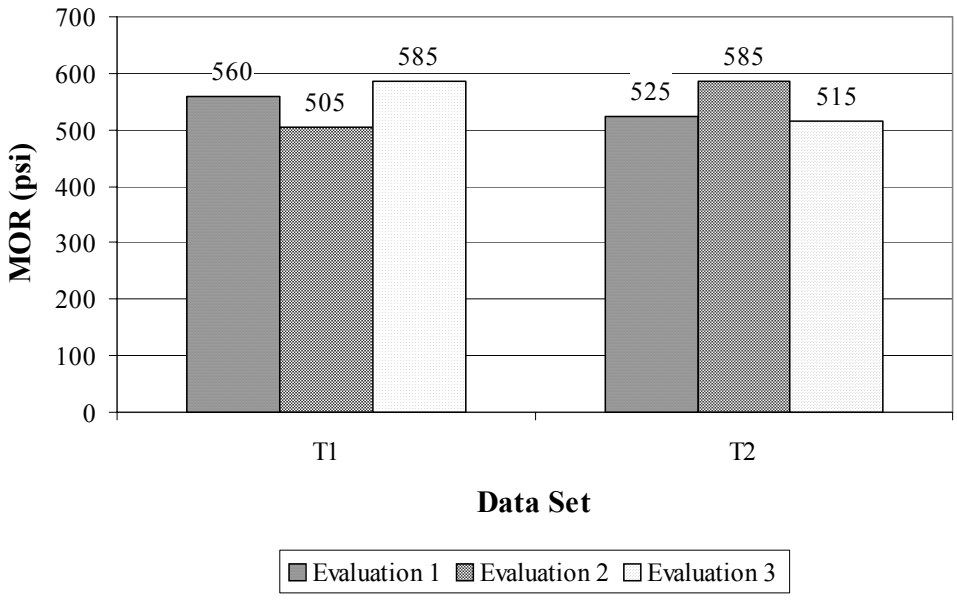
In laboratory study LS-2, the flexural strengths of the beams made for the establishment of the compressive-flexural strength relationship were determined at ages of 1, 2, 3, 4, and 5 days. Two specimens were tested at each age. The averages of the results of these tests are presented in Figure 4.2.



Note: Data for this figure are presented in Appendix C, Table C4.1.2.1.
Each bar represents the average of two specimen strengths.
1 MPa = 145 psi

Figure 4.2 Average Flexural Strength Test Results for Compressive-Flexural Strength Relationship – Laboratory Study (LS-2)

In laboratory study LS-3, the flexural strengths of the specimens were determined at the opening-to-traffic maturity to evaluate the influence of match curing (using the TMCB system) on the development of flexural strength properties. The TMCB system match-cured the specimens to two pavement temperature data sets, T1 and T2. The match curing, utilizing the individual data set, was repeated three times, each time on two beams, for a total of six beams. The average MOR values, from all six beams, for both temperature data sets, are presented in Figure 4.3.



Note: Data for this figure are presented in Appendix C, Table C4.1.2.2.
Each bar represents the average of two specimen strengths.
1 MPa = 145 psi

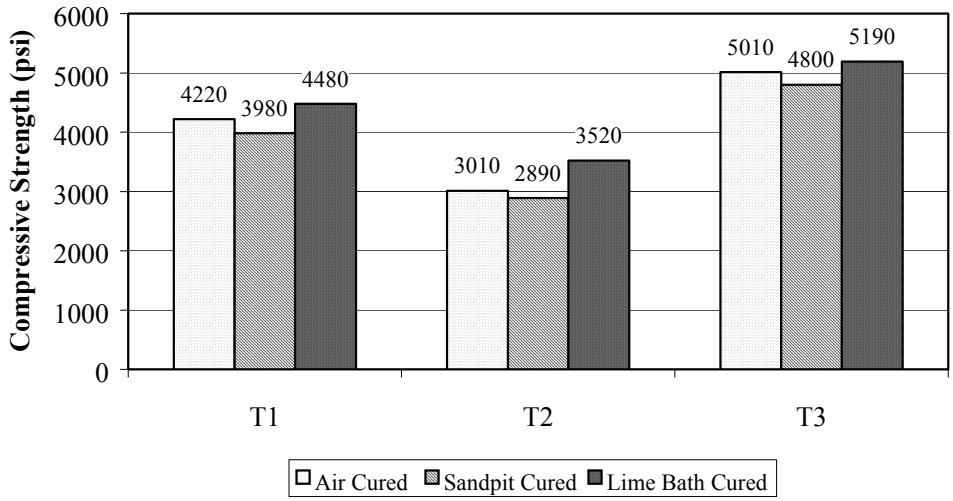
Figure 4.3 Average TMCB Flexural Strength Data – Tested at Opening-to-Traffic Maturity - Laboratory Study (LS-3)

4.2 Compressive Strength Test Results

The results of the compressive strength tests are presented in this section. The results have been separated into two groups: field study and laboratory studies.

4.2.1 Field Study

Cylinder specimens, prepared as described in Section 3.2.1, were tested at an age of three days to determine their compressive strength, as described in Section 3.6. For each trial, in each curing condition, the compressive strengths of three individual cylinder specimens were determined. The averages of the results of these tests appear in Figure 4.4.



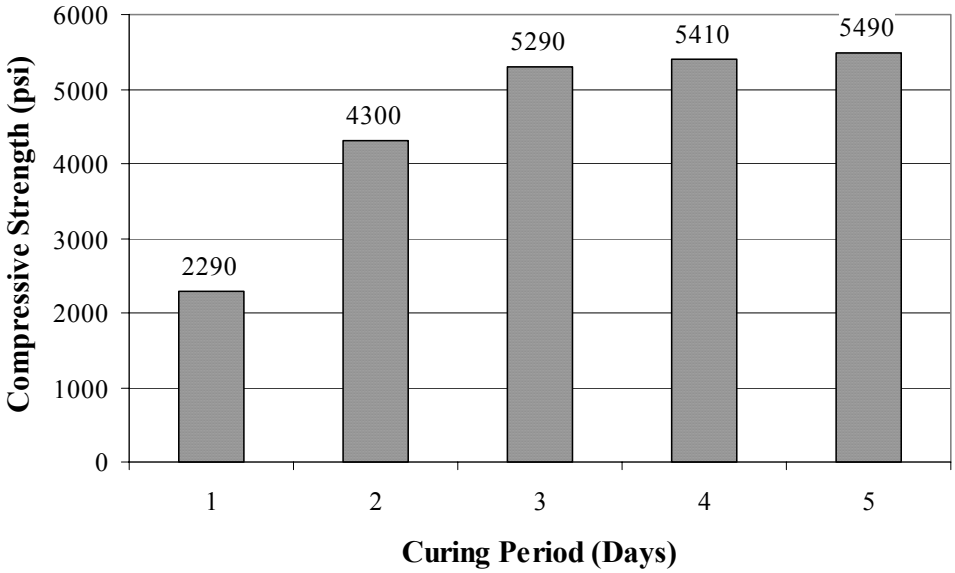
Note: Data for this figure are presented in Appendix C, Table C4.2.1.1.
Each bar represents the average of 3 specimen strengths.
1 MPa = 145 psi

Figure 4.4 Average Compressive Strength Test Results Tested at 3 Days– Field Studies

4.2.2 Laboratory Studies

Cylinder specimens, prepared as described in Section 3.2.2, were tested to determine their compressive strength, as described in Section 3.6.

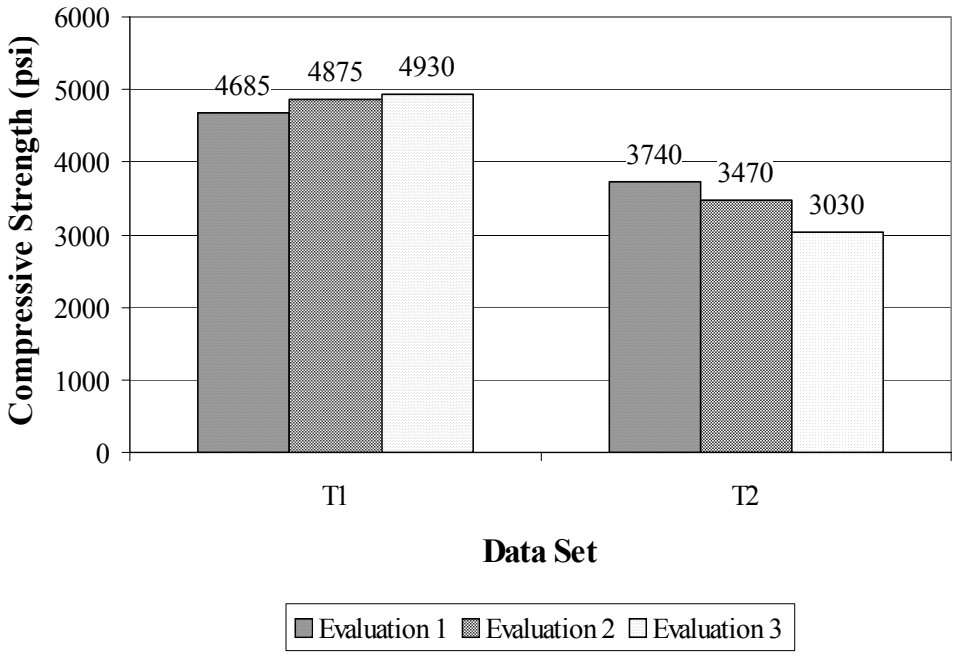
In laboratory study LS-2, the compressive strengths of the specimens made for the establishment of the compressive-flexural strength relationship were determined at ages of 1, 2, 3, 4, and 5 days. Two cylinders were tested at each age. The averages of the results of these tests are presented in Figure 4.5.



Note: Data for this figure are presented in Appendix C, Table C4.2.2.1.
Each bar represents the average of two specimen strengths.
1 MPa = 145 psi

Figure 4.5 Average Compressive Strength Test Results for Compressive-Flexural Strength Relationship - Laboratory Study (LS-2)

Also in laboratory study LS-2, the compressive strengths of the specimens were determined to evaluate the influence of match curing (using the TMCA system) on the development of compressive strength properties. The TMCA system match-cured the specimens to two pavement temperature data sets, T1 and T2. The match curing, utilizing the individual data set, was repeated three times, each time on four different cylinders, for a total of 12 cylinders. The average compressive strength, from all 12 cylinders, for both temperature data sets are presented in Figure 4.6.



Note: Data for this figure are presented in Appendix C, Table C4.2.2.2.
Each bar represents the average of four specimen strengths.
1 MPa = 145 psi

Figure 4.6 Average TMCA Compressive Strength Data – Tested at Opening-to-Traffic Maturity - Laboratory Study (LS-2)

4.3 Temperature Recording and Maturity Development

In order to evaluate the maturity development, the temperatures of the specimens and the pavement in the field study and the temperatures of the specimens in the laboratory study were continuously recorded as a function of time. This section presents the results of these measurements and describes the processing of the temperature data performed to calculate the maturity.

4.3.1 Specimen and Pavement Temperatures

The section describes the temperature data processing performed, and presents the results of the temperature data acquisition for both the field study and laboratory studies.

4.3.1.1 Temperature Data Processing

This section presents the temperature data processing necessary for the data acquired by the Sure Cure system and TMCB control unit (see Section 3.4).

In trial T1 of the field study, the Sure Cure system was used as a temperature datalogger. In order to evaluate the maturity development, time-temperature data points were needed. The Sure Cure system did not have the ability to output numerical data points. Rather, the system printed the data as a temperature-time graph. In order to obtain the desired data points, the temperatures were manually read directly from the curve in 10 minute increments and inserted into a spreadsheet. The temperatures were read from the curve with an accuracy of ±1°F (0.56°C). The Sure Cure System recorded the temperatures in Fahrenheit units. Since it was desired to use temperatures in Centigrade units, the data were converted to Centigrade in the spreadsheet.

Also in field trial T1, problems with the Sure Cure system power source occurred during the second and third day of curing (3:00 PM to 9:00 AM) resulted in the loss of temperature data from the lime-bath-cured and sandpit-cured specimens. The temperature data from the lime-bath-cured specimens was replaced with data interpolated from the remaining data points, since the temperature of the curing environment was a constant 23°C. As the temperature of the sandpit curing environment was not constant, a different method was used to replace the missing data. The temperature data for the pavement and air-cured specimens were analyzed and it was determined that the data gathered from the third day of curing resembled the data from the second day of curing. Thus, the temperature data lost from the sandpit on the second day was replaced with data from the sandpit on the third day. The last temperature before the data was lost was matched to the same temperature on the third day. Also, the first temperature from when the system came back online was matched to the same temperature on the third day. The number of data points lost was 36. The number of data points chosen to replace the lost data was 42. In order to fit the replacement data set, every sixth data point of the set was deleted.

In all trials of the field study and in laboratory studies LS-1 and LS-3, some temperature data points obtained with the TMCB control unit were lost due to system malfunctions. Since the number of points missing in any of the data sets lost was less than 6, the missing values were replaced through linear interpolation of the remaining data points.

It was desired to evaluate the maturity development of the TMCA-cured specimens from laboratory study LS-2, in relation to the maturity development of the pavement to which the specimens were match-cured. However, the system provided the maturity values in real-time and did not record the values as they developed over time. Thus, only the final maturity value was obtained. Thus, numerical temperature data points were needed to calculate the maturity values. The same technique, as previously described for trial T1 of the field study, was used to obtain the numerical temperature data points from the printed temperature-time graphs.

4.3.1.2 Field Study

The concrete temperature data from the field study were collected from beam specimens, cylinder specimens, and the pavement with the Sure Cure system and the TMCB control unit as described in Section 3.4. The data were processed as described in Section 4.3.1.1. The temperatures from the two thermocouples embedded in each of the instrumented beams were averaged before performing the analysis. To compare the thermal histories of the concrete beam specimens in each of the three curing conditions to the thermal history of the pavement, the following procedure was followed. The average beam specimen temperatures from each of the three curing conditions and the pavement temperature were plotted as a function of time. The ambient temperature was also plotted as a function of time to show its influence on the specimen and pavement temperatures. These results are presented in Figures 4.7, 4.8, 4.9, and 4.10 for field trials T1, T2, T3, and T4, respectively.

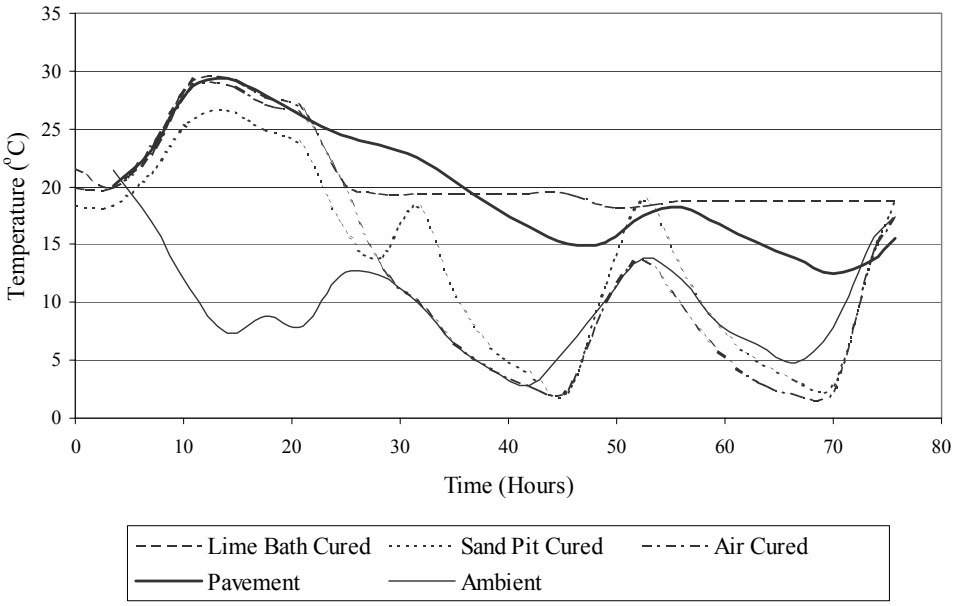


Figure 4.7 Temperature vs. Time for Beam Specimens – Field Trial T1

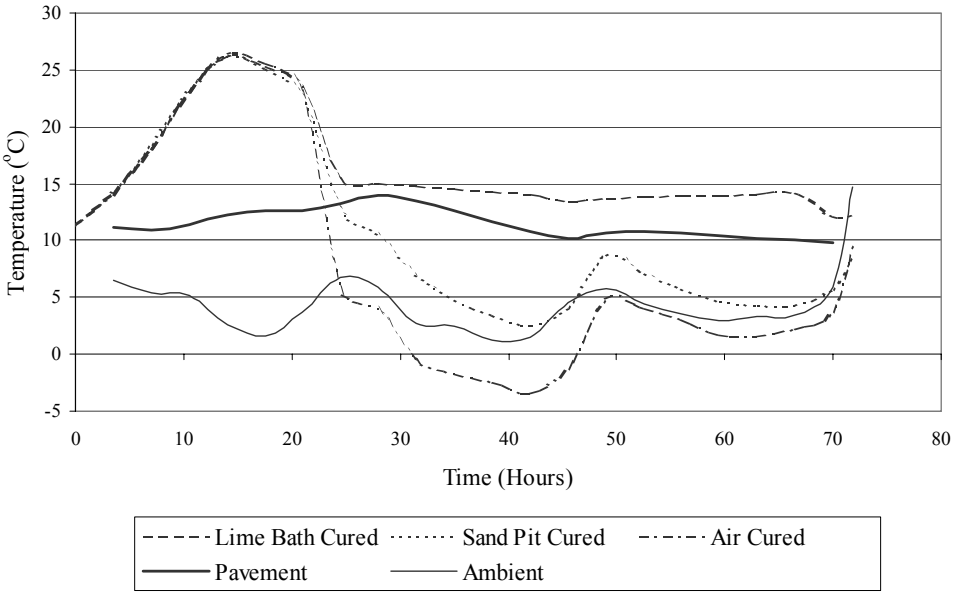


Figure 4.8 Temperature vs. Time for Beam Specimens – Field Trial T2

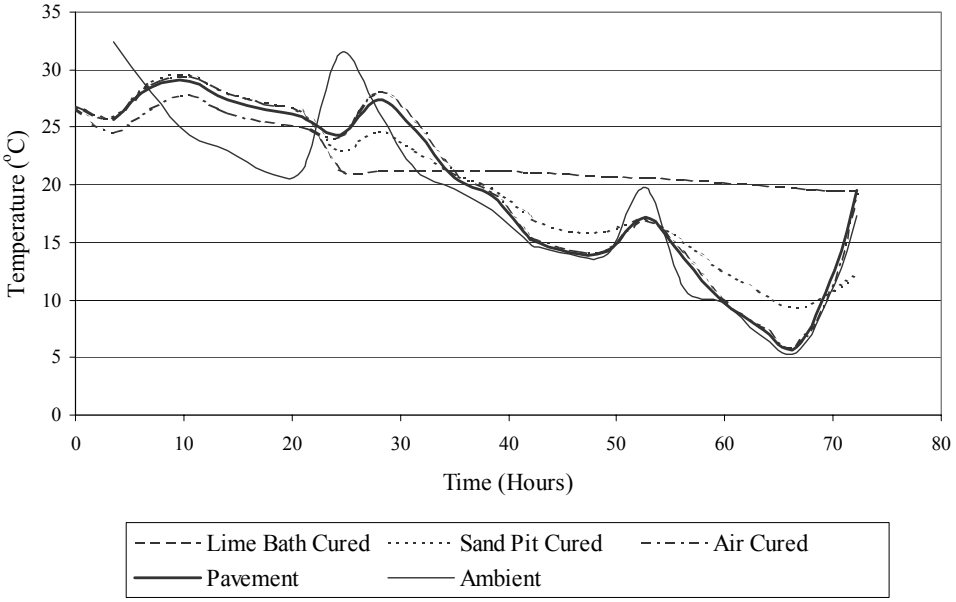


Figure 4.9 Temperature vs. Time for Beam Specimens – Field Trial T3

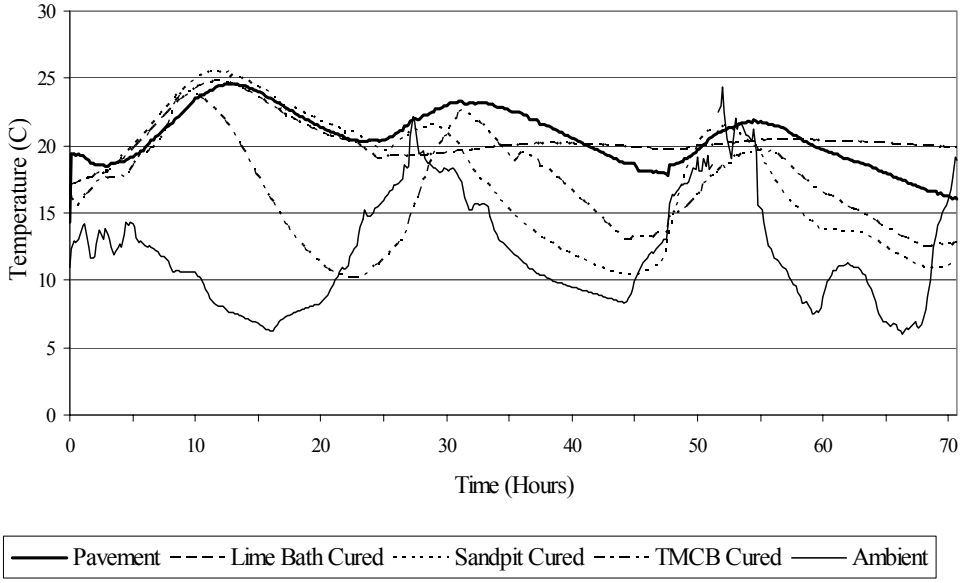


Figure 4.10 Temperature vs. Time for Beam Specimens – Field Trial T4

To compare the thermal histories of the concrete beam specimens in each of the three curing conditions to the thermal history of the cylinders in the same three curing conditions, the average beam specimen temperatures and the cylinder temperatures were plotted as a function of time. These results are presented in Figures 4.11, 4.12, and 4.13 for field trials T1, T2, and T3, respectively.

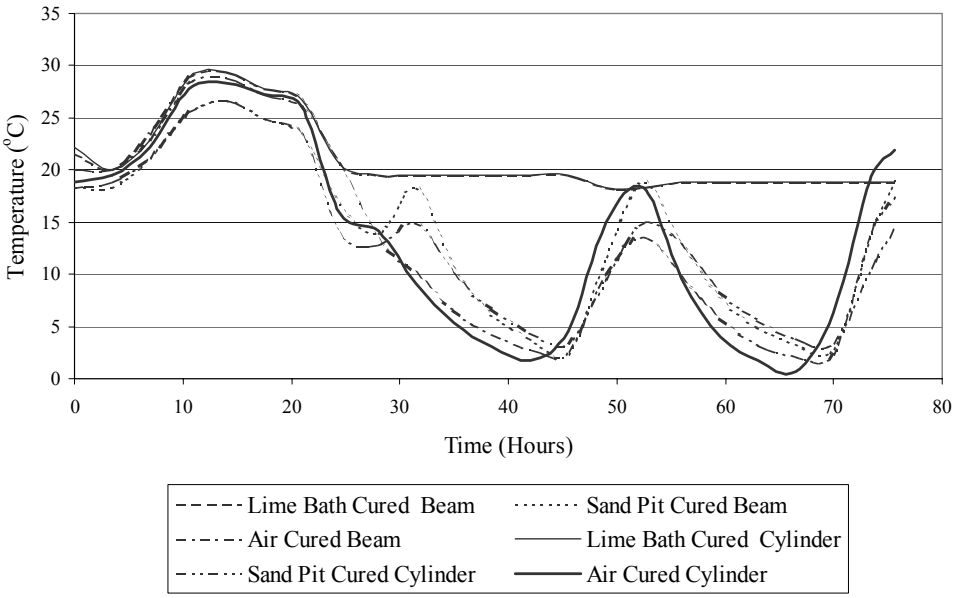


Figure 4.11 Temperature vs. Time for Beam and Cylinder Specimens – Field Trial T1

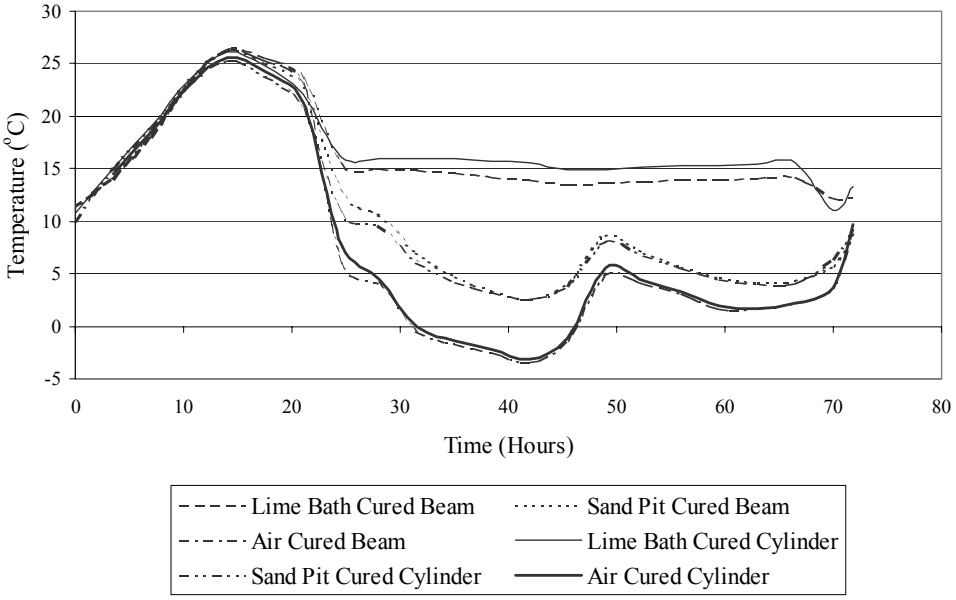


Figure 4.12 Temperature vs. Time for Beam and Cylinder Specimens – Field Trial T2

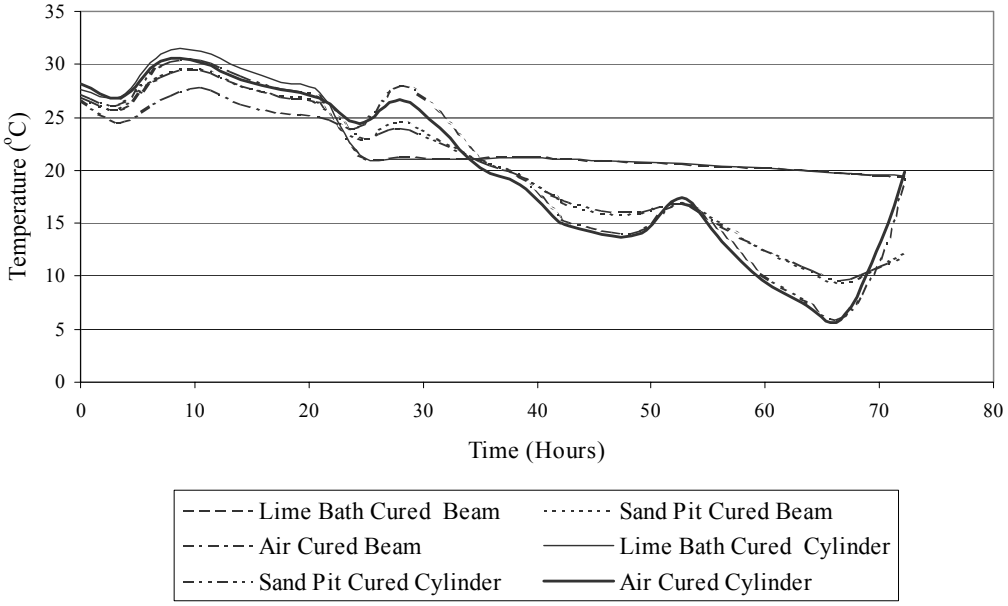


Figure 4.13 Temperature vs. Time for Beam and Cylinder Specimens – Field Trial T3

4.3.1.3 Laboratory Studies

In laboratory studies LS-1 and LS-3, temperature data were collected using the TMCB control unit as described in Section 3.4 and the data were processed as described in Section 4.3.1.1.

In laboratory study LS-1, temperature data were collected from cement paste cube specimens, and concrete cylinder specimens. To compare the thermal histories of the cement paste cube specimens in each of the three curing conditions to the thermal history of the concrete cylinder specimens, the following task was conducted. The cement paste cube specimen temperatures from each of the three curing conditions and the concrete cylinder specimen temperatures were plotted as a function of time. These data are presented in Figure 4.14.

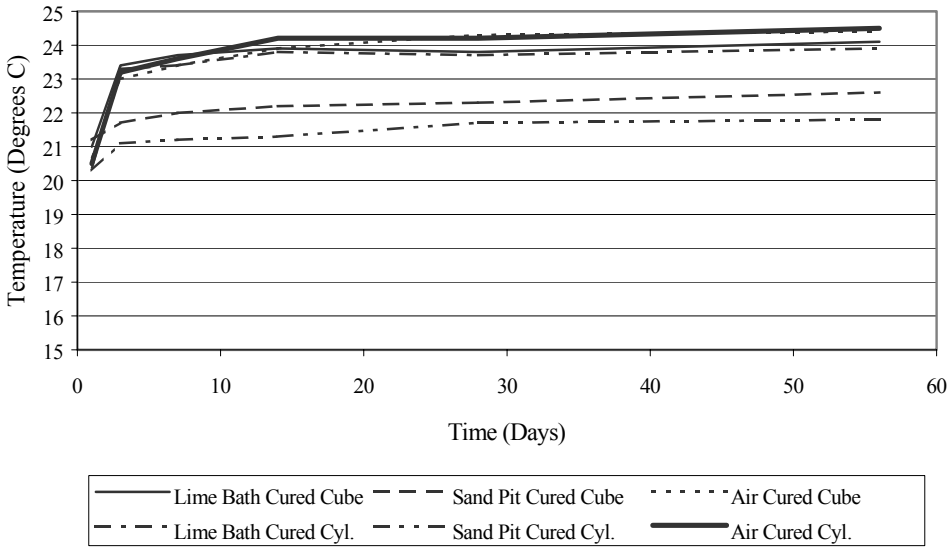


Figure 4.14 Temperature vs. Time for Cement Paste Cubes and Concrete Cylinders - Laboratory Study (LS-1)

In laboratory study LS-2, temperature data were collected for concrete cylinder specimens used to evaluate maturity development using the Sure Cure system. The system match-cured the cylinder specimens to two different pavement temperature data sets, T1 and T2. Three repetitions (each utilizing four cylinders) were run per data set. The temperatures collected were averaged for all 12 cylinders before plotting the results. These data are plotted as a function of time in Figure 4.15 and Figure 4.16 for T1 and T2 data sets, respectively. Also shown in these Figures are the reference temperatures, T1 and T2.

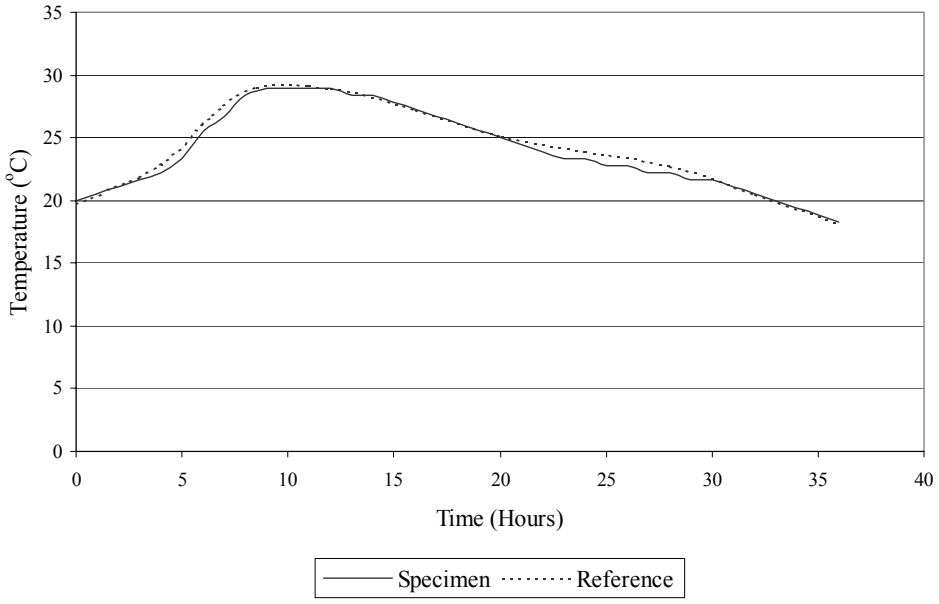


Figure 4.15 Time vs. Temperature for TMCA-Cured Specimens – T1 Data Set - Laboratory Study (LS-2)

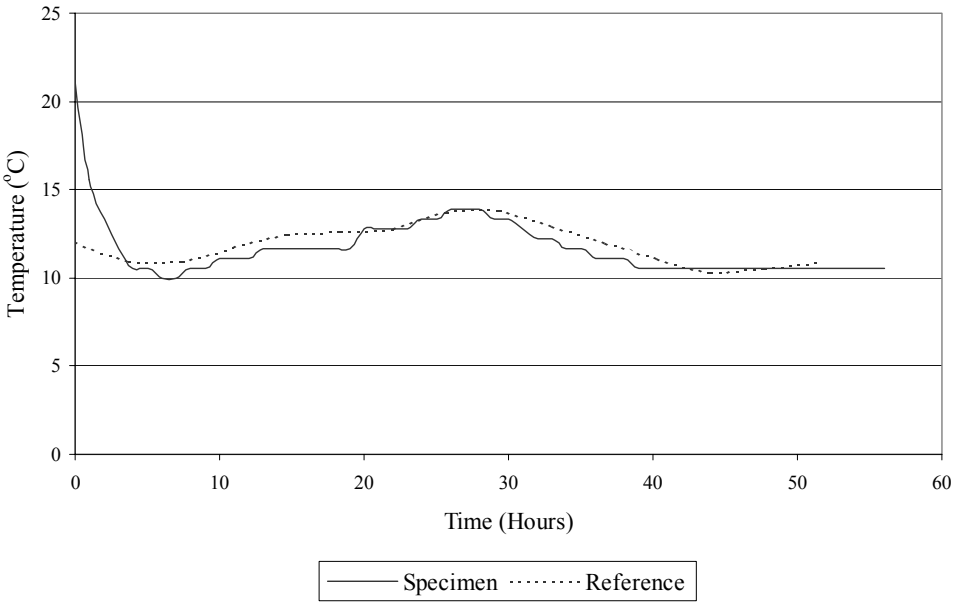


Figure 4.16 Time vs. Temperature for TMCA-Cured Specimens – T2 Data Set - Laboratory Study (LS-2)

In laboratory study LS-3, three tests were performed for purposes of TMCB system calibration were performed in which temperature data were collected from concrete beam specimens. The two thermocouples embedded in the instrumented beam were averaged before performing the analysis.

The first test of the TMCB system was run to evaluate the possibility of using the beam temperature as the control temperature. The control, reference, and curing box temperature data collected were plotted as a function of time. These results are presented in Figure 4.17. Since, as previously discussed in Section 3.4, the beam temperature could not be reliably used as a control temperature, a second calibration test was conducted.

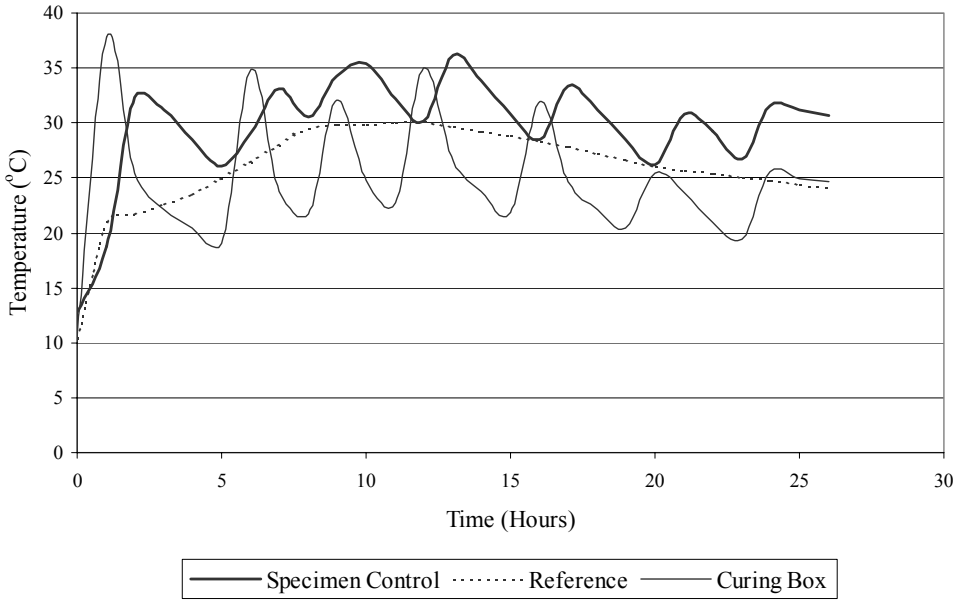


Figure 4.17 Temperature vs. Time for TMCB System Calibration – Test 1 - Laboratory Study (LS-3)

In the second test, the possibility of using the temperature of the curing box was as the control temperature was investigated. The control, reference, and beam temperature data collected were plotted as a function of time. These results are presented in Figure 4.18. These results indicated there was still a discrepancy between the temperature of the curing box and the temperature of the concrete specimen.

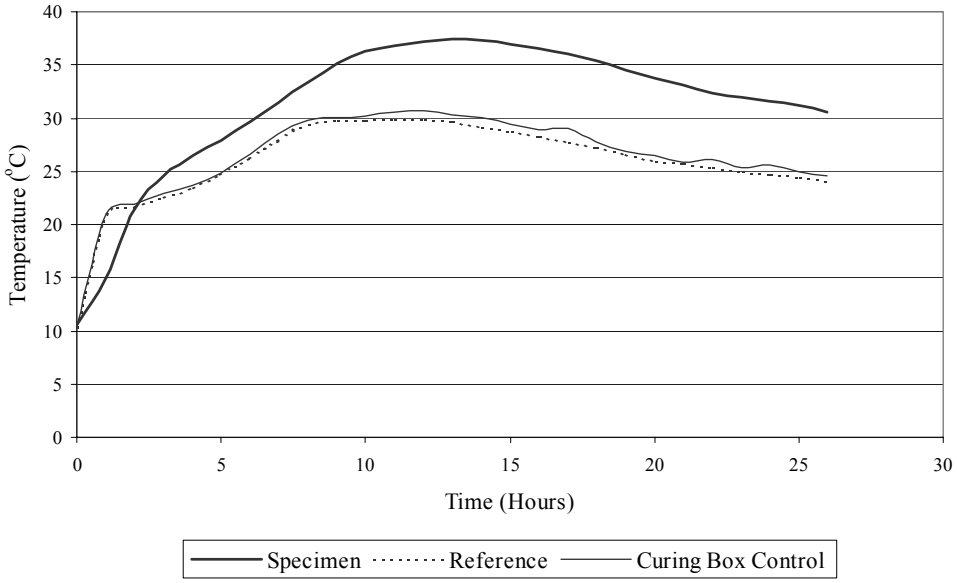


Figure 4.18 Temperature vs. Time for TMCB System Calibration – Test 2 - Laboratory Study (LS-3)

To eliminate this discrepancy, a third calibration test was conducted. The third test of the TMCB system was run using an offset temperature (curing box temperature –7.5°C) as the control temperature in order to compensate for this factor. The control, reference, offset, and beam temperature data collected were plotted as a function of time. These results are presented in Figure 4.19.

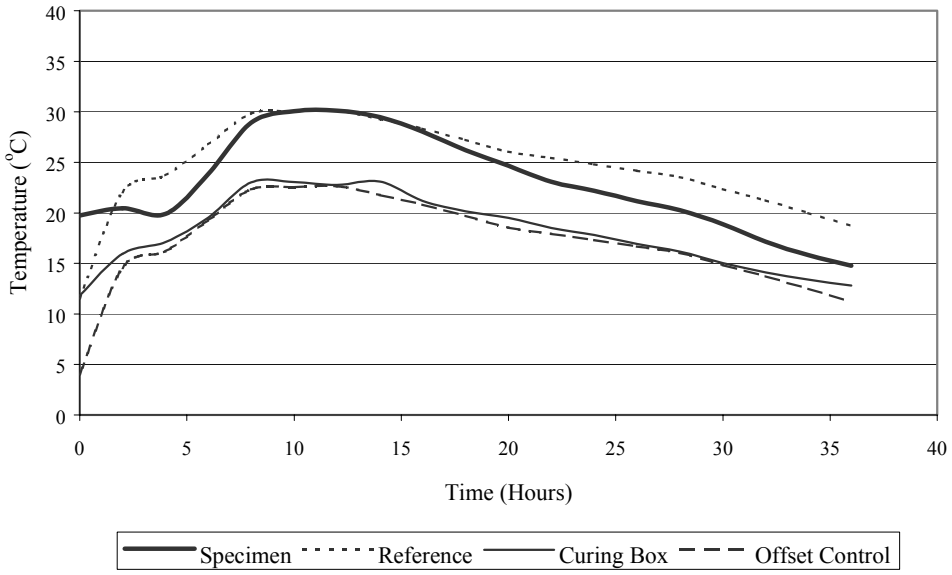


Figure 4.19 Temperature vs. Time for TMCB System Calibration – Test 3 - Laboratory Study (LS-3)

Also in laboratory study LS-3, temperature data were collected from concrete beam specimens used to evaluate maturity development when using the TMCB system (See Section 3.4). The system match-cured the beam specimens to two different pavement temperature data sets, T1 and T2. Three repetitions (each utilizing two beams) were run per data set. The temperatures collected were averaged for all six beams before plotting the results. These data are plotted as a function of time and are presented in Figure 4.20 and Figure 4.21 for data sets T1 and T2, respectively.

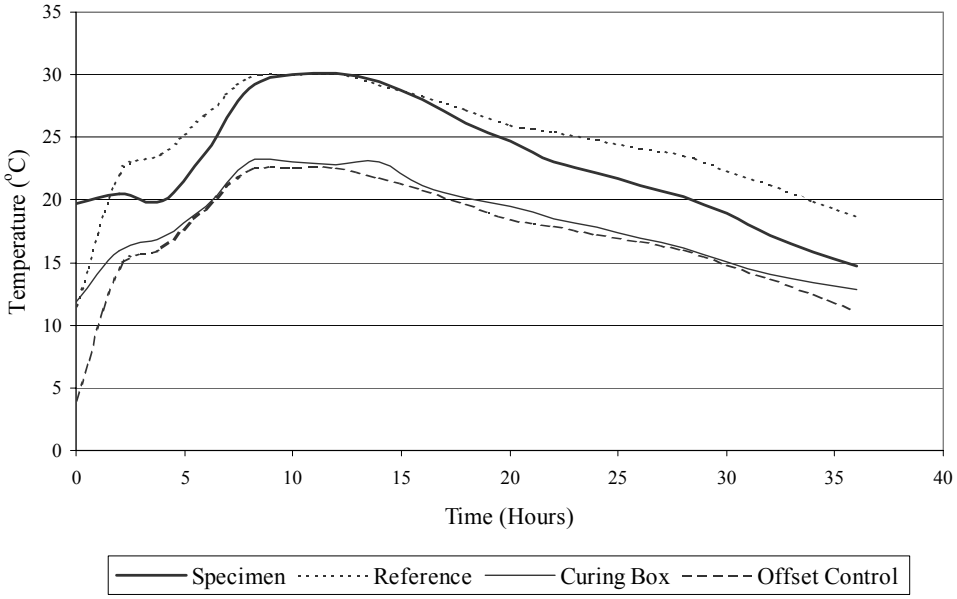


Figure 4.20 Temperature vs. Time for TMCB-Cured Beams – T1 Data Set - Laboratory Study (LS-3)

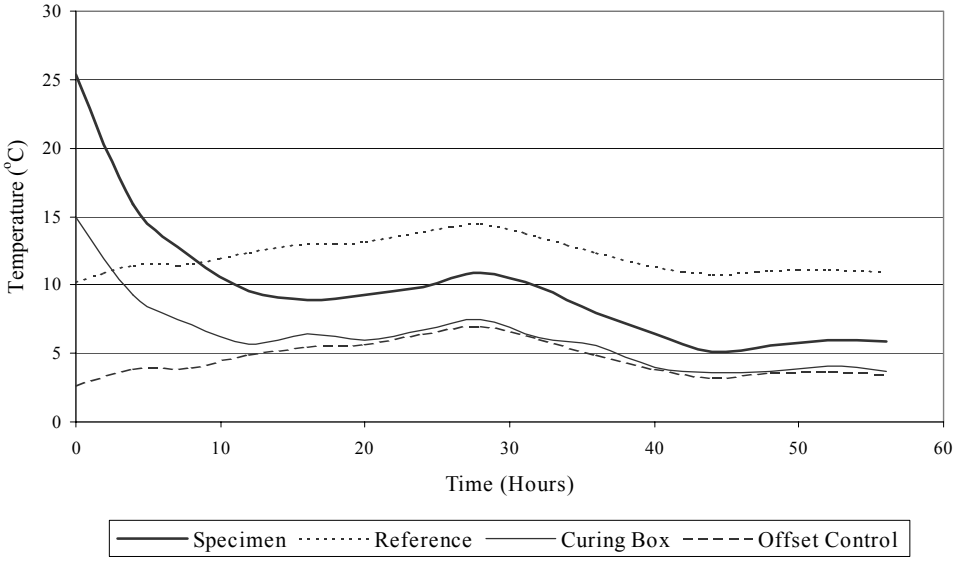


Figure 4.21 Temperature vs. Time for TMCB-Cured Beams – T2 Data Set - Laboratory Study (LS-3)

4.3.2 Specimen and Pavement Maturity Development

This section presents the calculation method used and data processing performed for the determination of the maturity of concrete test specimens, paste specimens, and pavement in all studies.

4.3.2.1 Maturity Calculation Method and Data Processing

As described in Section 4.3.1.1, the temperature data recorded during the experimental field study and all laboratory studies were inserted into a spreadsheet. For all studies, maturity values were calculated per ITM 402-99T (see Appendix A) at 10 minute increments. To account for various parameters that affected maturity data, the following processing was followed in the spreadsheet.

The commercial (Sure Cure) system used in laboratory study LS-2 recorded the maturity in units of Fahrenheit-hours. In order to be able to combine these maturity data with maturity values obtained by the contractor in the field study (which were in units of Centigrade-hours) the maturity values from the Sure Cure system were converted to Centigrade-hour units. In order to do this, the datum temperature was changed from 0°F (-18°C) to -10°C by subtracting the product of the resulting difference (8°C) by the total curing time from the Sure Cure maturity data. Thus, the final maturity values were in units of Centigrade-hours using a datum temperature of –10°C.

Due to the need to finish casting all the test specimens before temperature measurements in the pavement could commence, there was a delay between the time at which

temperature recording began in the specimens and in the pavement. In order to account for this factor, the average maturity values of all the specimens from a given trial were averaged at the time that the pavement temperature recording was initiated. This value was used as the initial pavement maturity value.

To account for specimen travel time from the jobsite to the laboratory in T1 and T2 field trials, temperature data for the air-cured cylinder and beam specimens were recorded during the trip in field trial T1. The resulting "travel" maturity was calculated and used for both T1 and T2 experiments to calculate the total maturity of the specimens that were cured in the lime bath and in the sandpit. The maturity value calculated from the beam specimen was also added to the pavement maturity value. This was not done to the maturity values calculated for field trial T3 because the travel time from the jobsite to the laboratory was only 5 minutes.

4.3.2.2 Field Study

For the development of maturity curves MC-1, MC-2, and MC-3 the contractor monitored the beam specimens for four days using a commercial maturity meter. These maturity data are presented with their respective maturity curves in Appendix D.

For all field study trials, the specimen and pavement maturity values were processed as described in the previous section. To compare the maturity development of the concrete beam specimens in each of the three curing conditions to the maturity development of the pavement the average beam specimen maturity values, from each of the three curing

conditions, and the pavement maturity values were plotted as a function of time. These results are presented in Figures 4.22, 4.23, 4.24, and 4.25 for field trials T1, T2, T3, and T4, respectively. The value of maturity required for opening the pavement to traffic is also illustrated in each of these Figures. The opening-to-traffic maturity corresponds to a flexural strength of 550 psi. These values were determined from maturity curves MC-1, MC-2, and MC-3 as presented in Appendix D.

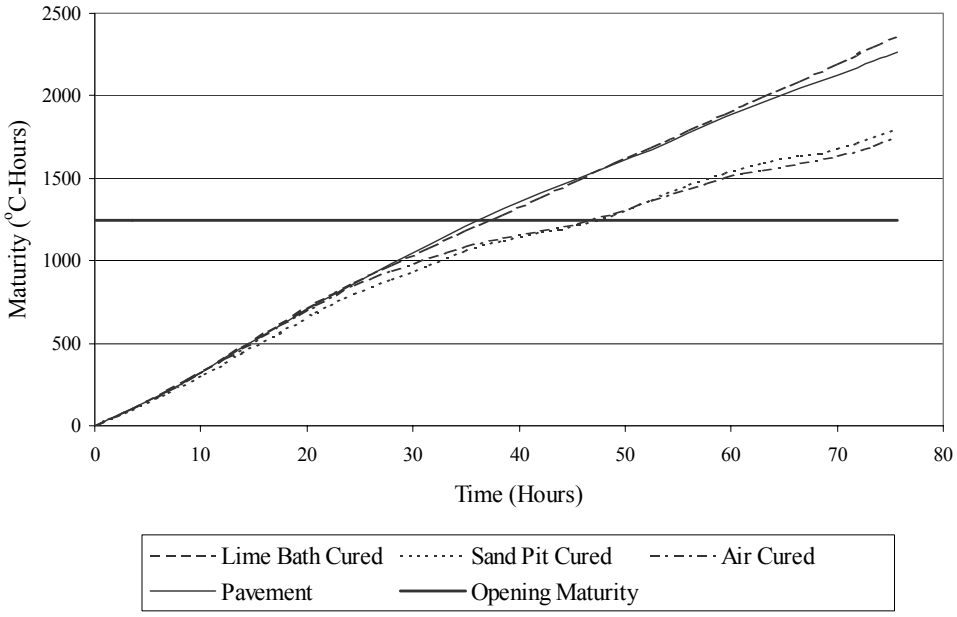


Figure 4.22 Maturity Development for Beams – Field Trial T1

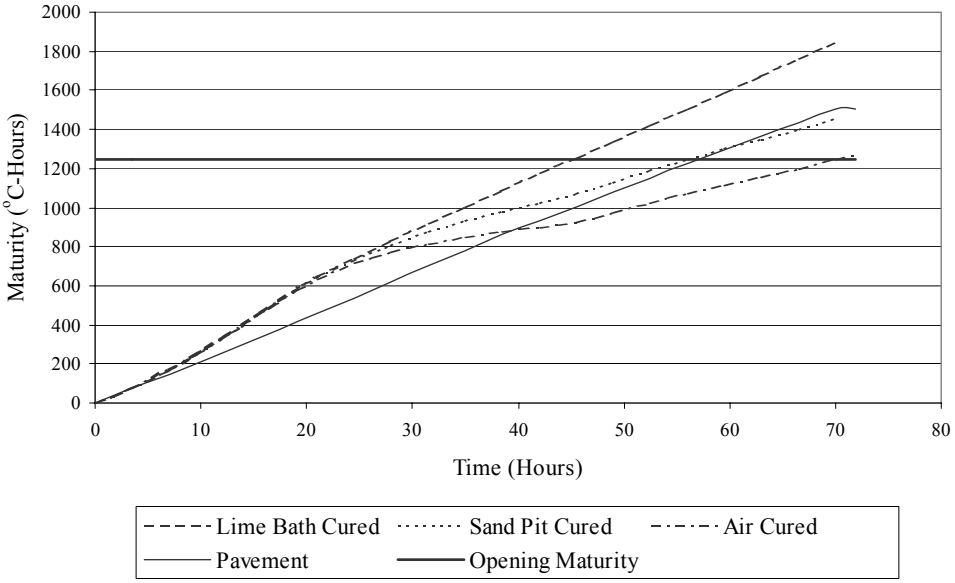


Figure 4.23 Maturity Development for Beams – Field Trial T2

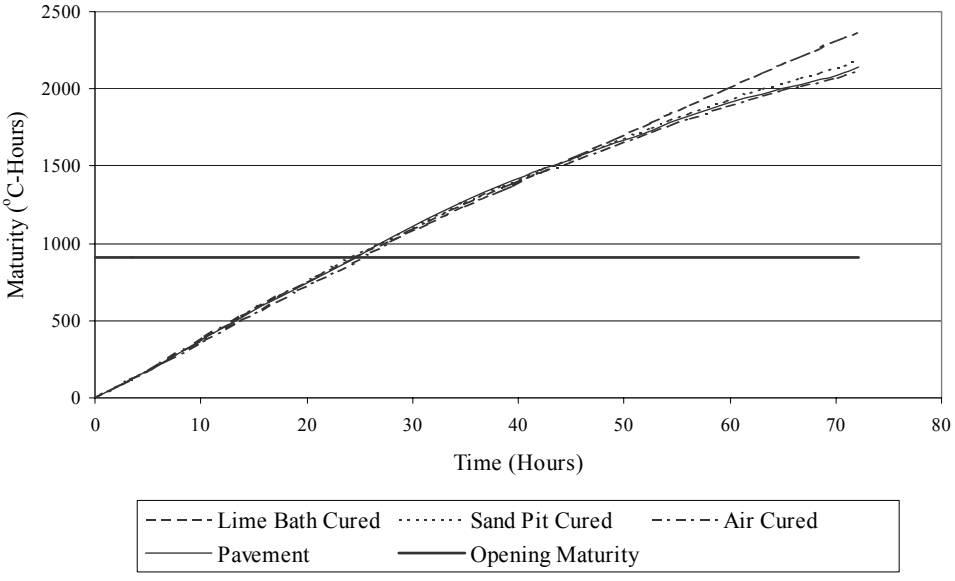


Figure 4.24 Maturity Development for Beams – Field Trial T3

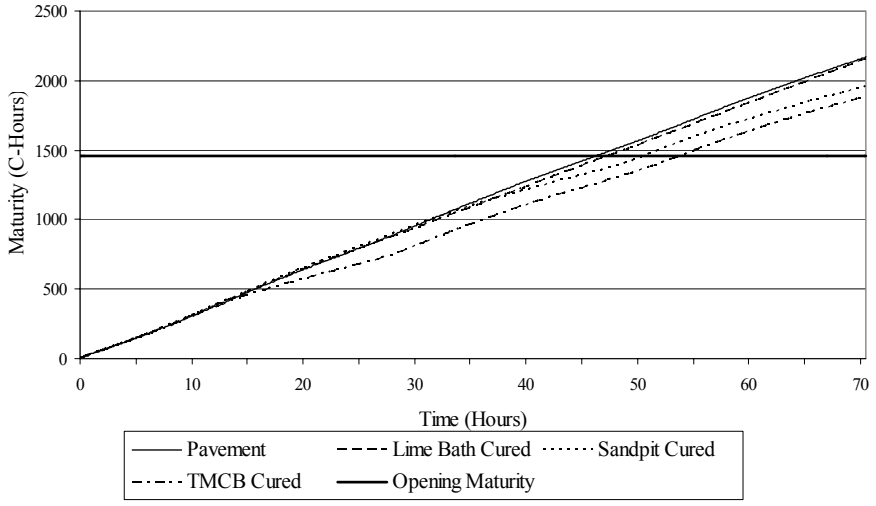


Figure 4.25 Maturity Development for Beams – Field Trial T4

To compare the maturity development of the concrete beam specimens in each of the three curing conditions to the maturity development of the cylinders in each of the three curing conditions the average beam specimen maturity and the cylinder maturity values were plotted as a function of time. These results are presented in Figures 4.26, 4.27, and 4.28 for field trials T1, T2, and T3, respectively.

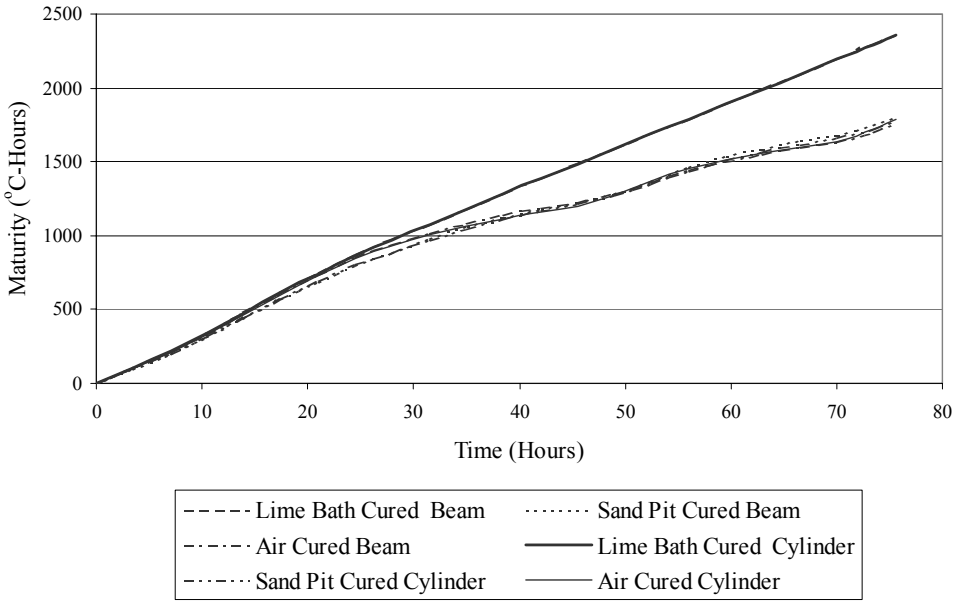


Figure 4.26 Maturity Development for Beams and Cylinders – Field Trial T1

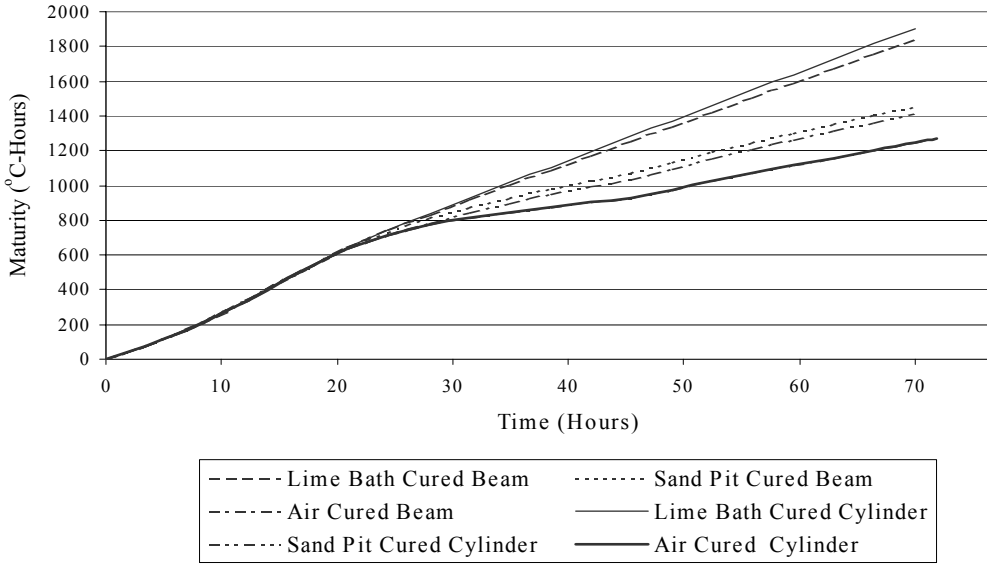


Figure 4.27 Maturity Development for Beams and Cylinders – Field Trial T2

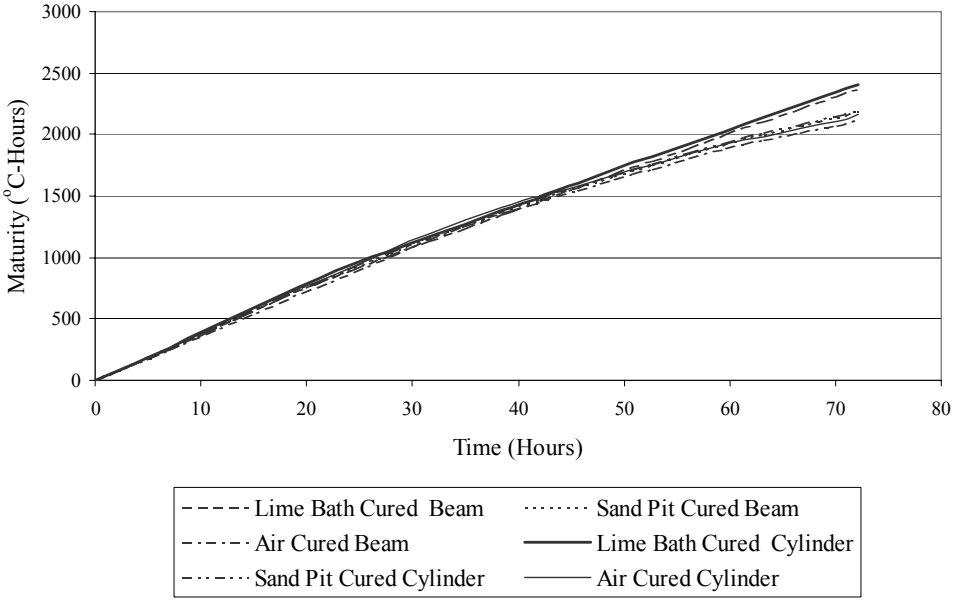


Figure 4.28 Maturity Development for Beams and Cylinders – Field Trial T3

4.3.2.3 Laboratory Studies

In all lab studies, the maturity data were calculated and processed as described in Section 4.3.2.1.

In laboratory study LS-1, the maturity values for cement paste cube specimens and concrete cylinder specimens were calculated. To compare the maturity development of the cement paste cube specimens to the maturity development of the concrete cylinder specimens, the cement paste cube specimen maturity values, from each of the three curing conditions, and the maturity values of the concrete cylinder specimens were plotted as a function of time. These data are presented in Figure 4.29.

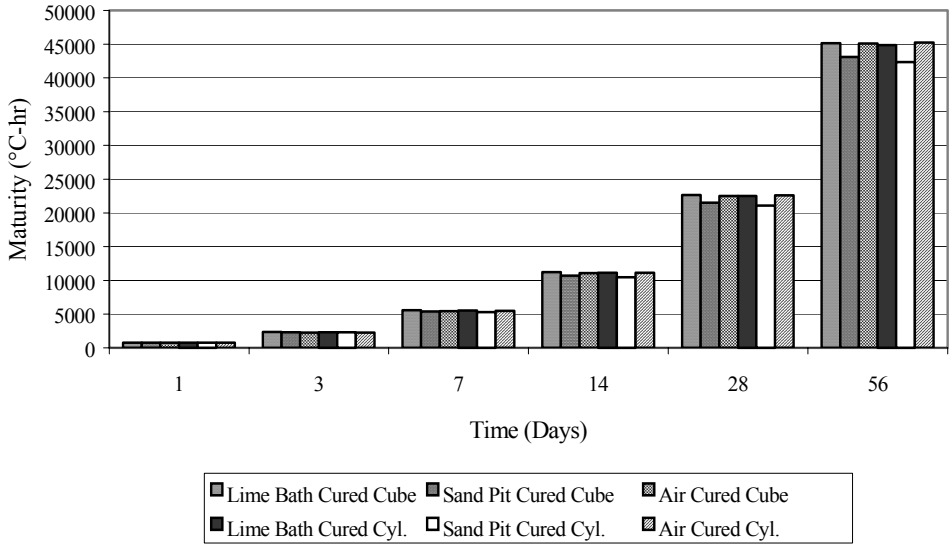


Figure 4.29 Maturity Development for Cement Paste Cubes and Concrete Cylinders - Laboratory Study (LS-1)

In laboratory study LS-2, maturity data was calculated, as described in Section 4.3.2.1, for the cylinder specimens used to evaluate the effect of TMCA on maturity development. The TMCA (Sure Cure) system match-cured the cylinder specimens using two different pavement temperature data sets, T1 and T2. Three trials were run per data set. The data for each trial were averaged per data set. Using these data, the specimen maturity values were plotted as a function of time. These data are presented in Figure 4.30 and Figure 4.31 for data sets T1 and T2, respectively.

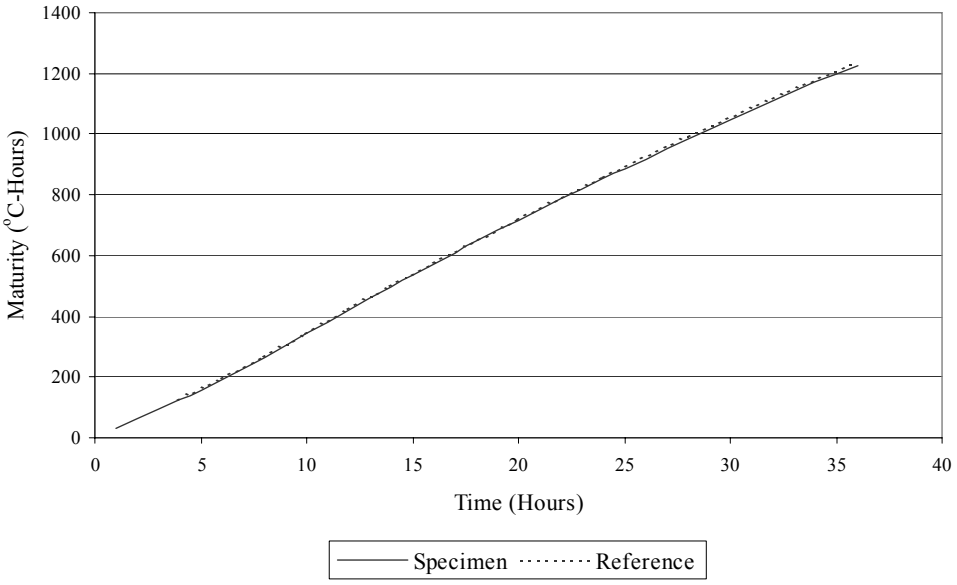


Figure 4.30 Maturity Development of TMCA-Cured Specimens – T1 Data Set - Laboratory Study (LS-2)

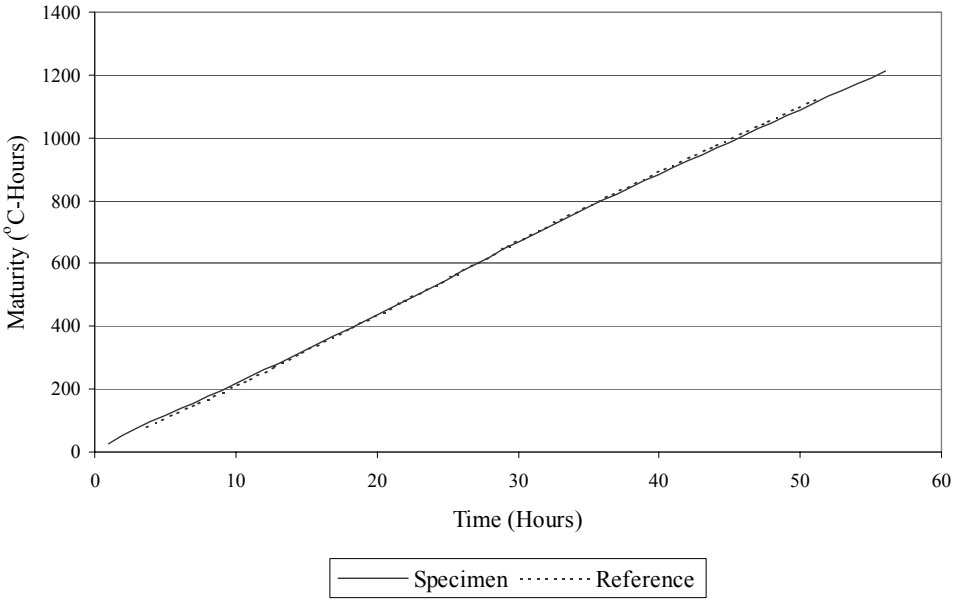


Figure 4.31 Maturity Development of TMCA-Cured Specimens – T2 Data Set - Laboratory Study (LS-2)

In laboratory study LS-3, maturity data, calculated as described in Section 4.3.2.1, were used to evaluate the TMCB system. The system match-cured the beam specimens using two different pavement temperature data sets, T1 and T2. Three trials were run per data set. The data for each trial were averaged per data set. Using these data, the specimen maturity values were plotted as a function of time. These data are presented in Figure 4.32 and Figure 4.33 for data sets T1 and T2, respectively.

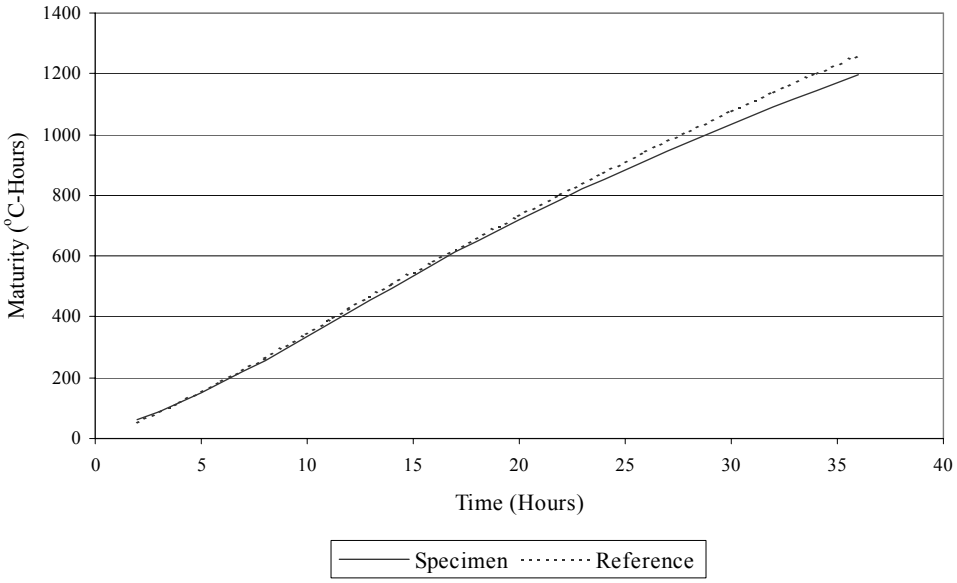


Figure 4.32 Maturity Development of TMCB-Cured Beams – T1 Data Set - Laboratory Study (LS-3)

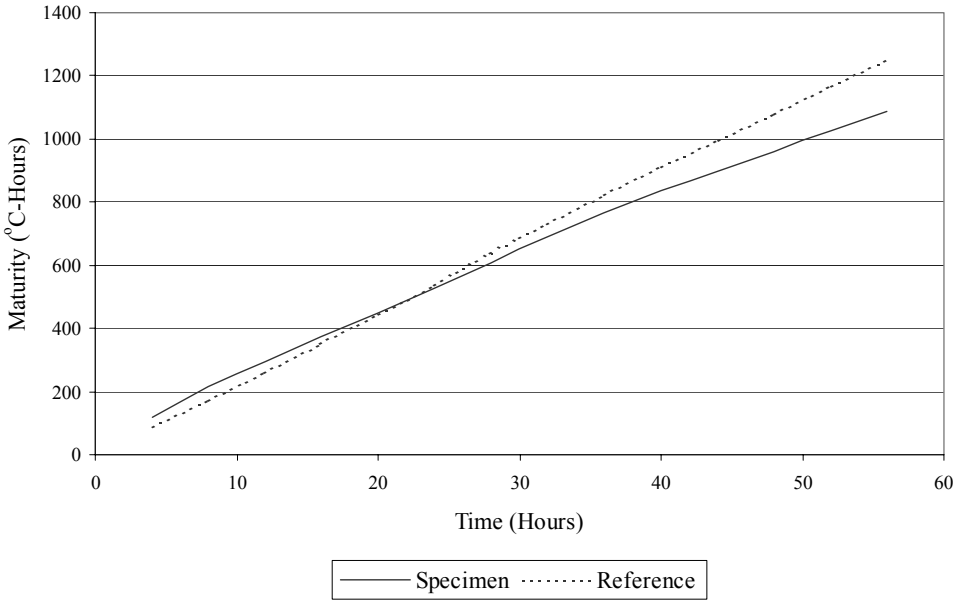


Figure 4.33 Maturity Development of TMCB-Cured Beams – T2 Data Set - Laboratory Study (LS-3)

4.4 Percent Non-Evaporable Water

In order to develop a correlation between maturity and the degree of hydration of cement, (expressed as percent non-evaporable water) the percent of non-evaporable water of cement paste cube specimens was determined as described in Section 3.7. The percent of non-evaporable water of the paste specimens was determined at 1, 3, 7, 14, 28, and 56 days. These data are presented in Figure 4.34.

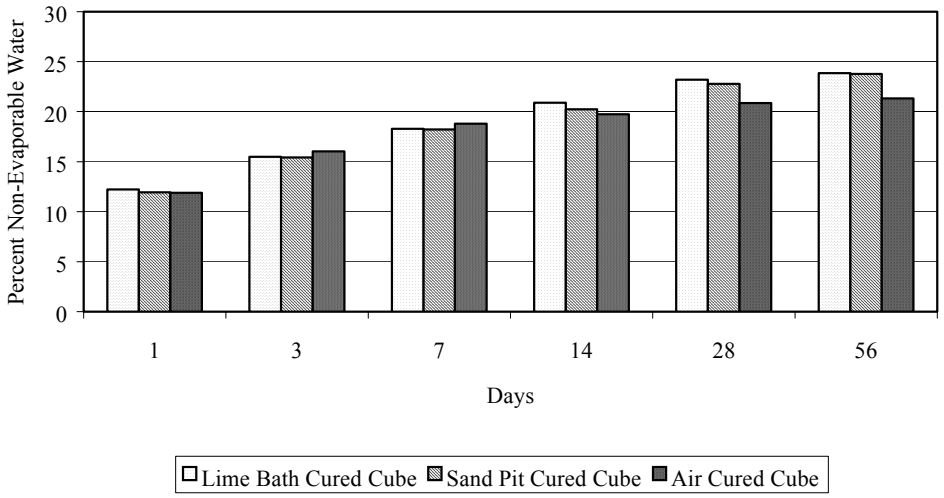


Figure 4.34 Percent Non-Evaporable Water - Laboratory Study (LS-1)

5 DISCUSSION AND DATA ANALYSIS

This section contains a discussion of the results presented in Section 4.

5.1 Relationship between Maturity and Degree of Hydration of Cement

As previously mentioned, the degree of hydration of cement in concrete is directly related to the amount of non-evaporable water contained in the hardened paste. To establish a relationship between maturity and the degree of hydration, the percents of non-evaporable water in hardened cement paste cube specimens, cured in a lime bath, a sand pit, and in air, were determined at 1, 3, 7, 14, 28, and 56 days (see Figure 4.34), as part of the LS-1 experiment. The maturity development of the cubes was also determined over this period (see Figure 4.29). These results were combined and the percent non-evaporable water was plotted as a function of the log of the maturity. A linear regression analysis was made to provide a relationship between the maturity and percent non-evaporable water. These results appear in Figure 5.1.

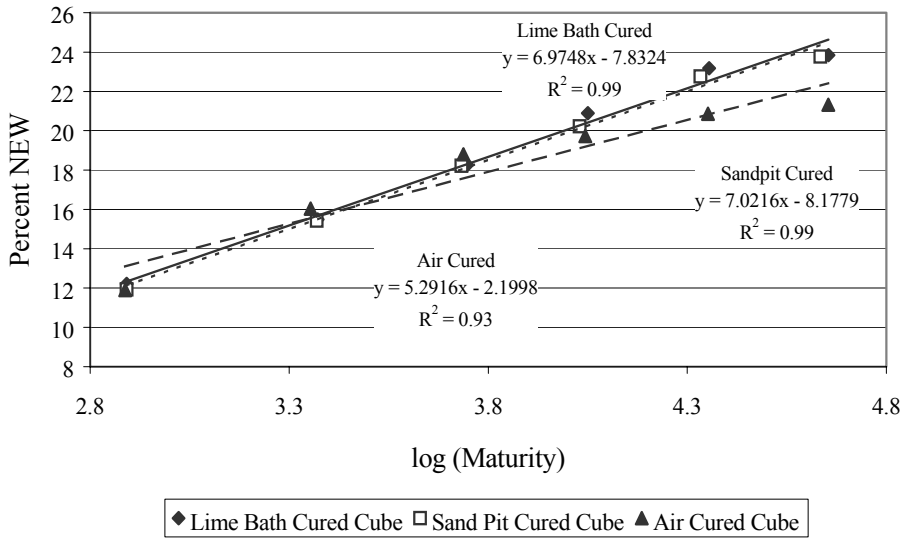


Figure 5.1 Relationship between Percent Non-Evaporable Water (NEW) and Maturity of Cement Paste

The results presented in this Figure indicate that a good that a good correlation existed between maturity and percent non-evaporable water for the paste samples cured under different curing conditions. However, the relationship between the maturity and non-evaporable water content for the air-cured specimens was different than the relationship between the maturity and non-evaporable water content for samples cured in the other two curing conditions.

As discussed in Section 2.4, cement needs moisture to continue to hydrate. The amount of moisture available to the air-cured specimens as was smaller than the amount of water available to the samples cured in the other two curing conditions. Thus, the degree of hydration of the air-cured specimens was less than the degree of hydration of the specimens in the other two curing conditions (see Figure 4.34). These results indicate

that the relationship between maturity and degree of hydration only holds true if the proper moisture is provided to the specimen while it is curing. Thus, as long as enough moisture is provided to the system, there exists a valid relationship between maturity and the degree of hydration of cement paste.

To correlate the maturity development of paste to the maturity development of concrete, companion concrete cylinder specimens were made and cured along side the paste cube specimens. The maturity development of the companion concrete specimens was shown in Figure 4.29. To determine if there was a difference between the maturity development of cement paste specimens and the maturity development of concrete specimens, the percent difference between the two specimens was determined at 1, 3, 7, 14, 28, and 56 days. These values are presented in Table 5.1.

Table 5.1 Percent Difference between Maturity of Cement Paste and Maturity of Concrete Specimens

Day	Lime-Bath-Cured	Sandpit-Cured	Air-Cured
1	3.2 %	3.8 %	0.4 %
3	0.9 %	1.7 %	-1.3 %
7	0.7 %	2.1 %	-0.6 %
14	0.7 %	2.4 %	-0.6 %
28	0.6 %	2.1 %	-0.4 %
56	0.6 %	1.8 %	-0.3 %
Average	1.1 %	2.3 %	-0.5 %

The average percent difference between the cement paste specimens and concrete specimens was 1.1, 2.3, and 0.5 percent for the lime-bath-cured, sandpit-cured, and air-cured specimens, respectively. These results indicate that the difference in maturity development between the cement paste specimens and concrete specimens was negligible. Thus, the relationship between the maturity development and degree of hydration of cement developed for paste specimens is also applicable to concrete specimens.

5.2 Relationship between Compressive Strength and Flexural Strength

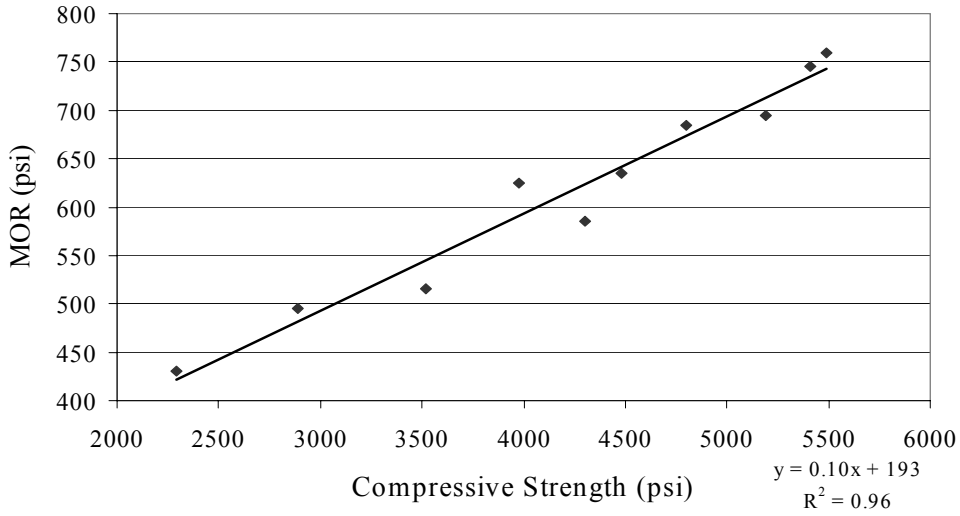
To compare the compressive strength results of TMCA specimens in laboratory study LS-2, to the flexural strengths of the specimens cured in other curing conditions a relationship between the compressive and flexural strength of the concrete was needed. The compressive and flexural strength data (see Figures 4.5 and 4.2, respectively) from

specimens prepared in trials T1 and T2 of the field study were combined with the compressive strength and flexural strength data (see Figures 4.4 and 4.1, respectively) from the specimens prepared in the laboratory and tested at 1, 2, 4, and 5 days. Flexural and compressive strength data from day 3 were eliminated because they were outliers. The beam and cylinder specimens that were air-cured in the field study were also eliminated since the air curing condition produced specimens that were different from the lime-bath-cured and sandpit-cured specimens (see section 5.3). To produce the relationship between the compressive and flexural strength of the concrete, the flexural strength data were plotted as a function of the compressive strength data and are presented in Figure 5.2. A linear regression analysis was performed to provide a relationship between the flexural and compressive strengths in the following form.

$$MOR = 0.10\ f'c + 193 \qquad (5.1)$$

MOR = modulus of rupture (psi),
f'c = compressive strength (psi).

There was a good correlation ($R^2 = 0.96$) between the compressive and flexural strengths for this concrete.



Note: 1 MPa = 145 psi

Figure 5.2 Compressive Strength – Flexural Strength Relationship

5.3 Influence of Curing Conditions on Strength Properties

The influences of the curing conditions, utilized in both field and laboratory studies, on the flexural and compressive strength of concrete are discussed in this section.

5.3.1 Flexural Strength

The influences of curing conditions, used in both field and laboratory studies, on the flexural strength of concrete are discussed in this section.

5.3.1.1 Field Study

The flexural strengths of the beam specimens were determined to evaluate the effect of lime bath, sandpit, air and TMCB curing on the flexural strength of concrete in the field

study. The flexural strength data from the beam specimens cured in the three curing conditions appear in Figure 4.1.

To determine if there was a difference in strength properties between specimens cured in the curing conditions, the averages, standard deviations, and coefficient of variations of all specimen strengths in a given trial were calculated. These results are presented in Table 5.2.

Table 5.2 Analysis of Flexural Strength Data for All Field Curing Conditions

Trial	Average MOR (psi)	Standard Deviation (psi)	Coefficient of Variance (%)
T1	576	92	15.9
T2	469	48	10.2
T3	614	101	16.4
T4	650	34	5.2

Notes: 1 MPa = 145 psi
(Trials T1 and T2: 9 specimens were tested in each trial. Trials T3 and T4: 6 specimens were tested in each trial)

According to ASTM C 78, the coefficient of variance of the test results should be less than 5.7 percent. In trials T1, T2, and T3, the coefficient of variance exceeded this value. Thus, combining the results from the three curing conditions did not yield statistically equivalent flexural strength results.

However, the coefficient of variance for trial T4 is below the ASTM value. Therefore, the results of the flexural strength tests from specimens cured in the lime bath, sandpit, and in the TMCB system could be considered equivalent.

The air-cured specimens were tested in a dry condition. Neville [1997] noted that when tested in a dry condition, specimens produce lower flexural strengths than specimens tested in a moist condition. Thus, the calculations as described above were repeated for trials T1, T2, and T3 without the air-cured specimen data to determine their effect on the coefficient of variance. The results of these calculations appear in Table 5.3.

Table 5.3 Analysis of Flexural Strength Data for Lime Bath and Sandpit Curing

Trial	Average MOR (psi)	Standard Deviation (psi)	Coefficient of Variance (%)
T1	630	25	4.0
T2	505	15	3.0
T3	685	20	2.9

Note: 1 MPa = 145 psi
(Trials T1 and T2: 6 specimens were tested in each trial. Trials T3 and T4: 4 specimens were tested in each trial)

As previously stated, the coefficient of variance of the test results should be less than 5.7 percent. In each trial, the coefficient of variance was less than this value. Thus, lime bath and sandpit curing produce specimens with equivalent flexural strengths. Air curing did

not produce specimens with flexural strengths equivalent to either of the other two curing conditions.

5.3.1.2 Laboratory Studies

The compressive strengths of the TMCA-cured specimens in laboratory study LS-2 were determined to evaluate the effect of temperature-matched curing on concrete strength properties. The average compressive strengths of the TMCA-cured specimens, for each pavement temperature data set to which they were cured, were calculated and are presented in Figure 4.5. These average values were used as an input to the compressive-flexural strength relationship developed in Section 5.2, Equation 5.1 and corresponding MOR values were determined. These results are presented in Table 5.4.

Table 5.4 MOR Values Calculated for TMCA-Cured Specimens (Compressive Strength)

Data Set / Evaluation	Average Compressive Strength (psi)	Coefficient of Variance (%)	Calculated MOR (psi)	Percent Difference from Target
T1 Evaluation 1	4685	1.71	660	20.0
T1 Evaluation 2	4875	1.23	680	23.6
T1 Evaluation 3	4930	1.22	685	24.5
T2 Evaluation 1	3740	1.87	565	2.73
T2 Evaluation 2	3470	1.45	540	-1.82
T2 Evaluation 3	3030	1.98	495	-10.0

Note: Target Flexural Strength = 550 psi
1 MPa = 145 psi

The flexural strengths of the TMCB-cured beams specimens in laboratory study LS-3 were also determined to evaluate the effect of temperature-matched curing on the flexural strength of concrete. These data are presented in Table 5.5.

Table 5.5 MOR Values for TMCB-Cured Specimens

Data Set / Evaluation	Average MOR (psi)	Coefficient of Variance (%)	Percent Difference from Target
T1 Evaluation 1	560	2.7	1.82
T1 Evaluation 2	505	4	-8.18
T1 Evaluation 3	585	5.1	6.36
T2 Evaluation 1	525	2.9	-4.55
T2 Evaluation 2	585	0.9	6.36
T2 Evaluation 3	515	4.8	-6.36

Note: Target Flexural Strength = 550 psi
1 MPa = 145 psi

Since the curing of the specimens from laboratory studies LS-1 and LS-2 continued until the opening-to-traffic maturity was reached for both data sets, their flexural strengths for each data set should have been the same. Based on the maturity curve, the target flexural strength should have been 550 psi (3792 kPa). The percent differences between the experimental flexural strengths and the target flexural strengths were calculated for each evaluation using Equation 5.2. The values are presented for laboratory studies LS-2 and LS-3 in Table 5.4 and Table 5.5, respectively.

$$\text{Percent Difference} = ((MOR_e - MOR_t) / MOR_t)\ \% \qquad (5.2)$$

MOR_e = experimental MOR (psi),
MOR_t = target MOR (550 psi).

The flexural strength results from the TMCA evaluations using the T1 data set had a large percent difference from the target value. These results were most likely due to operator induced variability. One operator tested all the specimens for the TMCA evaluations using the T2 data set and for all the TMCB evaluations. A different operator tested the specimens from the TMCA evaluation using the T1 data. Thus, these data were not included in the following conclusions.

When the MOR values calculated using the T1 data set were eliminated from the analysis, the TMCA-cured specimens matched the target flexural strength to within 10 percent. Also, the TMCB-cured specimens matched the target flexural strength values to within 8 percent.

5.3.2 Compressive Strength – Field Study

The compressive strengths of the beam specimens were determined to evaluate the effect of lime bath, sandpit, and air curing on the compressive strength of concrete in the field study. The compressive strength data from the beam specimens cured in the three curing conditions appear in Figure 4.4.

To determine if there was a difference in strength properties between specimens cured in the three curing conditions, the averages, standard deviations, and coefficient of variations of all specimen strengths per trial were calculated. These results are presented in Table 5.6.

Table 5.6 Analysis of Compressive Strength Data for All Field Curing Conditions

Trial	Average Compressive Strength (psi)	Standard Deviation (psi)	Coefficient of Variance (%)
T1	4190	230	5.49
T2	3220	290	9.01
T3	4980	190	3.82

Note: 1 MPa = 145 psi

According to ASTM C 39, the coefficient of variance of the test results should be less than 2.87 percent. In each trial, the coefficient of variance exceeded this value. Thus, combining all curing conditions did not provide equivalent compressive strength results.

As indicated in Figure 4.4, the lime-bath-cured specimens had a higher compressive strength than either the sandpit or air-cured specimens. The air-cured specimens were comparable to the sandpit-cured specimens. The air-cured specimens were tested in a dry condition. Neville [1997] noted that when tested in a dry condition, specimens produce higher compressive strengths than those tested in a moist condition. Thus, the calculations as described above were repeated excluding the lime-bath-cured specimen data to determine their effect on the coefficient of variance. The results of these calculations appear in Table 5.7.

Table 5.7 Analysis of Compressive Strength Data for Sandpit and Air Curing

Trial	Average Compressive Strength (psi)	Standard Deviation (psi)	Coefficient of Variance (%)
T1	4080	150	3.68
T2	2990	60	2.01
T3	5000	130	2.60

Note: 1 MPa = 145 psi

As previously stated, the coefficient of variance of the test results should be less than 2.87 percent. In Trials 2 and 3, the coefficient of variance was less than this value. Thus, sandpit and air curing produce specimens with equivalent compressive strengths in these trials. Lime bath curing did not produce specimens with equivalent compressive strengths to either of the other two curing conditions.

The trends observed during the compressive strength analysis were different from those observed during the flexural strength data analysis. This was due to the fact that, as previously mentioned, the testing of the air-cured specimens in a dry condition had an opposite effect on the flexural strength than on the compressive strength. Also, the ASTM specifications allow a greater coefficient of variance for the flexural strength data than allowed for the compressive strength data. Thus, the variability of the compressive

strength data caused by the different curing conditions will not necessarily be reflected in the same way in the flexural strength data.

5.4 Influence of Curing Conditions on Maturity Development

This section discusses the influences of curing conditions, including ambient temperatures, utilized in both the field study and laboratory studies on the maturity development of concrete. Also, the influence of temperature-matched curing, performed in the laboratory studies, on maturity development of concrete is discussed.

5.4.1 Field Study

This section discusses the influence of the ambient temperature on maturity development of concrete tested in all three field trials and compares the maturity of specimens cured under different conditions to the maturity of the pavement.

5.4.1.1 Influence of Ambient Temperature

The ambient temperatures near the pavement, temperatures of concrete specimens cured in the lime bath, sandpit, air, and in the TMCB system, and pavement temperatures were recorded to evaluate their effect on maturity development of concrete in the field study.

The highest ambient temperature recorded was 20°C and the initial concrete temperature was 20°C in field trial T1 (see Figure 4.7). In this trial, the lime bath-cured specimens had maturity values most closely resembling the maturity of the pavement at the end of the specimen curing period (see Figure 4.22). The specimens cured in the sandpit underestimated the pavement maturity.

This was not the case in field trial T2, during which both specimens and pavement were initially exposed to a cooler high ambient temperature (7°C) and a cooler initial concrete temperature (12°C) (see Figure 4.8). In this trial, the specimens cured in the sandpit most closely matched the maturity of the pavement, while the lime-bath-cured specimens overestimated the pavement maturity at the end of the specimen curing period (see Figure 4.23). This result was most likely due to the influence of the temperature-controlled trailer in which the curing tanks for the lime-bath-cured specimens were kept. Since the specimens were unable to cool to the temperature of the pavement, their maturity was higher than that of the pavement.

The highest ambient temperature (32°C) and highest initial concrete temperature (30°C) for all trials were recorded in field trial T3 (see Figure 4.9). In this trial, the specimens in both the lime bath and the sandpit underestimated the maturity of the pavement at the end of the specimen curing period (see Figure 4.24). However, the maturity values of all specimens at the opening-to-traffic maturity were the same. Again, the specimens in the lime bath were in a temperature-controlled environment. This condition did not allow the specimens to reach the same temperatures as the pavement. The temperatures of the sandpit-cured specimens were able to adapt to the ambient temperatures. Thus, the degree of underestimation was lesser for the sandpit-cured specimens than for the lime-bath-cured specimens. However, the ambient temperatures later in the experiment dropped below the temperature at which the lab trailer was kept. It was at this point that the maturity of the specimens cured in the lime bath begins to overestimate the maturity

of the pavement. Therefore, the degree to which the specimens cured in the lime bath match the maturity of the pavement depended upon the ambient temperature conditions. If the temperature of the pavement was either higher than or lower than 23°C, the temperature at which the lime bath was maintained, the specimens in the lime bath either underestimated or overestimated the maturity of the pavement.

In field trial T4, the highest ambient temperature (24°C) (see Figure 4.10) and the initial concrete temperature (25°C) were recorded. In this trial, both the sandpit-cured and TMCB-cured specimens underestimated the maturity of the pavement at the end of the curing period (see Figure 4.25). The lime bath-cured specimens matched the pavement maturity the closest at the end of the curing period. The moderate temperature conditions seen in this trial were similar to those seen in trial T1. The results of trial T4 are also similar to those in trial T1 in which the sandpit-cured specimens underestimated the pavement maturity and the lime bath-cured specimens matched the pavement maturity more closely.

The specimens cured in the sandpit underestimated the maturity of the pavement in both the high (field trial T3) and moderate temperature conditions (field trials T1 and T4). All of these conditions had large temperature fluctuations, varying by 32°C, 19°C and 18°C, respectively. The temperature condition in which the specimens in the sandpit most closely matched the pavement maturity was the low temperature condition (field trial T2), which only varied 6°C.

These results indicate that the different curing conditions had an effect on the times, at which the maturity required to open the pavement to traffic (equivalent to 550 psi (3792 kPa) flexural strength), was reached. In field trial T1, the pavement reached the opening maturity value at 33 hours. The specimens cured in the lime bath reached the opening maturity at the same time thus, their maturity predicted flexural strength was 550 psi (3792 kPa). The sandpit and air-cured specimens reached the opening maturity after about 43 hours. Based on the maturity achieved by the specimens in these two conditions, the predicted flexural strength of the concrete should be 530 psi (3654 kPa) at the time the pavement reached the opening maturity value.

The pavement reached the required opening maturity at 57 hours in field trial T2. The specimens cured in the lime bath, in the sandpit, and near the pavement reached the required opening maturity at 45 hours, 56 hours, and 70 hours, respectively. Their flexural strengths, as predicted by maturity, at the time the pavement reached the opening maturity value were 580 psi (3999 kPa), 550 psi (3792 kPa), and 530 psi (3654 kPa), respectively.

The amount of time it took the pavement in T3 to reach the opening maturity was 21 hours. The specimens cured in the lime bath and sandpit took 24 hours to reach the opening maturity, while the specimens cured near the pavement took 25 hours. The maturity predicted flexural strengths for the lime-bath and sandpit-cured specimens at the time the pavement reached the required maturity were both 510 psi (3516 kPa). The air-cured specimens had a predicted strength of 500 psi (3448 kPa) at the same time.

The pavement in field trial T4 took around 47 hours to reach the opening maturity. The specimens cured in the lime bath, sandpit, and TMCB system took 48 hours, 51 hours, and 54 hours, respectively to reach the same maturity. The maturity predicted strengths at the time the pavement reached opening maturity were 545 psi (3768 kPa), 540 psi (3708 kPa), and 530 psi (3639 kPa) for lime bath-cured specimens, sandpit-cured specimens, and TMCB-cured specimens, respectively.

In trial T4, the specimens cured in the TMCB system underestimated the pavement maturity throughout the curing period. This was the result of a technical problem that occurred in the field. Initially, the system was functioning as planned however the battery that controlled the fan went dead at around 10 hours into the curing period. Thus, no heat was applied to the system until the battery was replaced at a time of 24 hours. At this point, since the system was programmed at an offset of -7.5°C it was not able to compensate for the initial lower temperature and therefore underestimated the pavement maturity. It is expected that when functioning properly, that the system will perform as it did in the laboratory (See Figures 4.32 and 4.33)

5.4.1.2 Comparison between Maturity of Specimens and Maturity of Pavement

To evaluate how the maturity of the specimens differed from the maturity of the pavement, the percent differences between the pavement maturity and specimen maturity for the different curing conditions over time were calculated using the following expression.

$$\text{Percent Difference} = ((M_s - M_p) / M_p)\ \% \qquad (5.3)$$

M_s = maturity of specimen,
M_p = maturity of pavement.

The results of these calculations are presented in Figures 5.3, 5.4, 5.5, and 5.6 for field trials T1, T2, T3, and T4, respectively. All specimens spent the initial 24-hours in the temperature controlled lab trailer except the TMCB-cured specimens which were initially cured in the TMCB system.

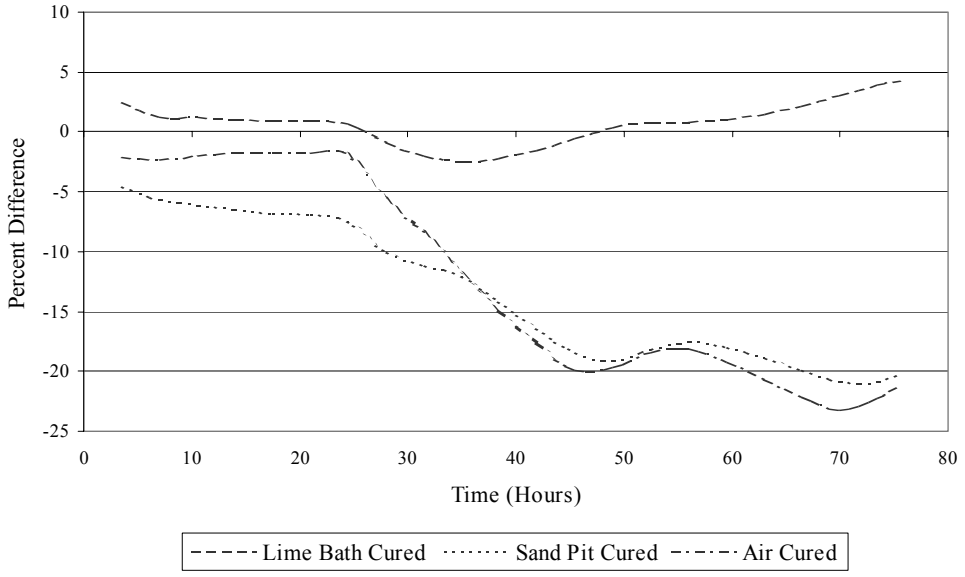


Figure 5.3 Percent Difference in Maturity over Time for Field Trial T1

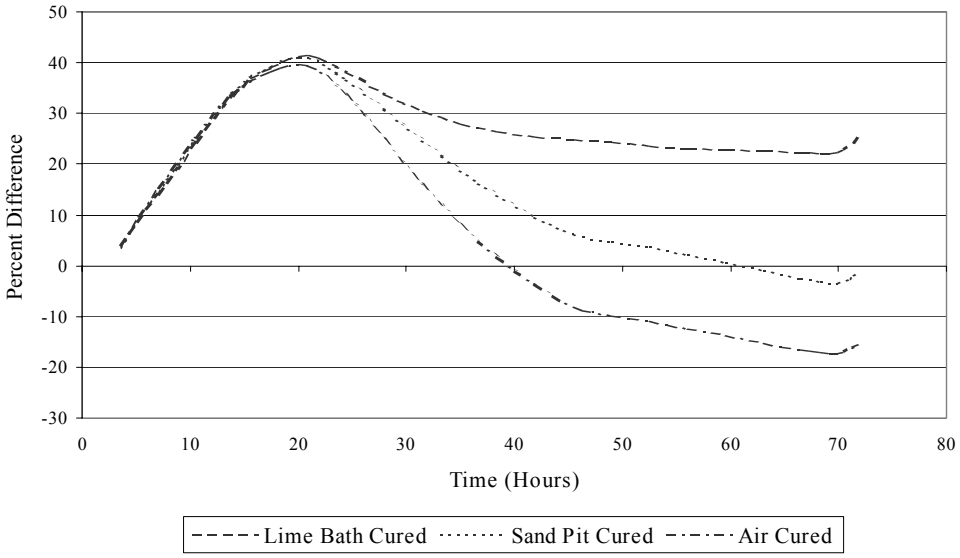


Figure 5.4 Percent Difference in Maturity over Time for Field Trial T2

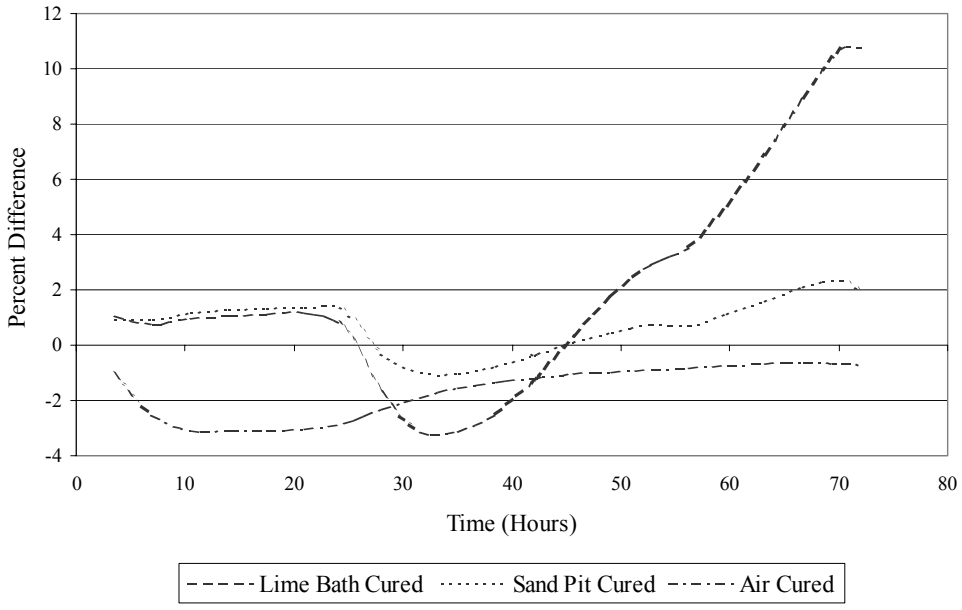


Figure 5.5 Percent Difference in Maturity over Time for Field Trial T3

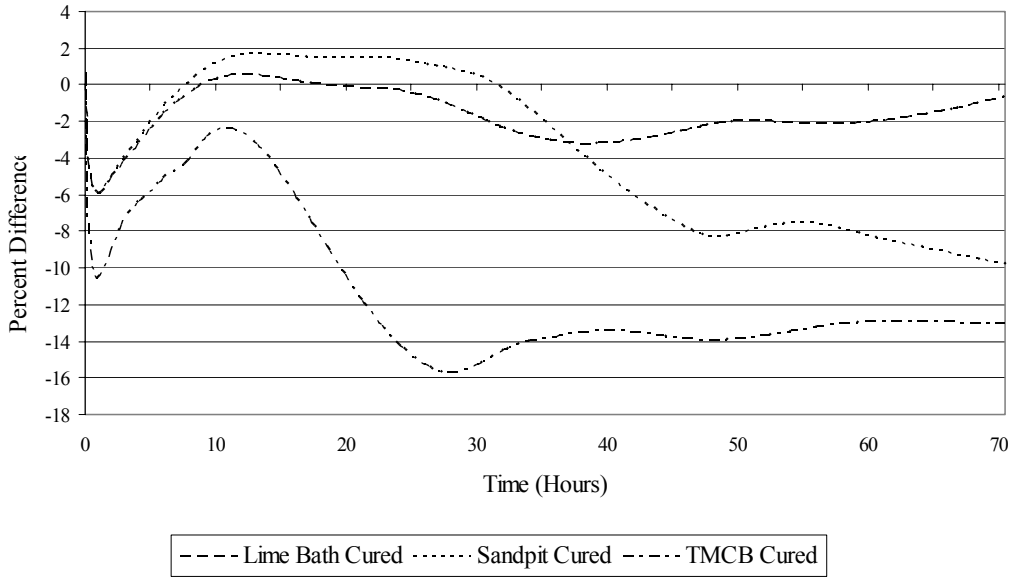


Figure 5.6 Percent Difference in Maturity over Time for Field Trial T4

For specimens from field trial T1, the maturity of the specimens cured in the lime bath showed the smallest difference from the maturity of the slab at any time, with a percent difference of less than ±5 percent over time. The other two curing conditions underestimated the maturity of the slab by approximately the same amount. The largest difference observed was about 20 percent.

After the initial cure period, the specimens cured in the sandpit most accurately represented the maturity of the slab in field trial T2. The sandpit-cured specimens underestimated the pavement maturity by only 5 percent at the end of the test period. The lime-bath-cured specimens overestimated the maturity of the slab by over 20 percent. The air-cured specimens underestimated the maturity of the slab by almost 20 percent.

In field trial T3, the specimens from all curing conditions matched the maturity of the pavement to within 4 percent up to a time of approximately 44 hours. At this point, the maturity of the lime-bath-cured specimens began to overestimate the maturity of the pavement. At the end of the curing period, the maturity from both the sandpit and air-cured specimens matched the maturity of the pavement to within 3 percent. However, the maturity of the lime-bath-cured specimens overestimated the pavement maturity by almost 11 percent.

In field trial T4, all specimens initially underestimated the maturity of the pavement. After approximately 10 hours all specimens were within +/-3 percent of the pavement maturity. The specimens cured in the lime bath stayed within this range until the end of the curing period. The specimens cured in the sand pit began to underestimate the pavement maturity after approximately 32 hours. The sandpit-cured specimens underestimated the pavement maturity by 10 percent at the end of the curing period. The TMCB-cured specimens underestimated the maturity of the pavement throughout the curing period. As previously mentioned in Section 5.4.1.1, this was the result of a technical problem.

The maturity of the air-cured specimens underestimated the maturity of the pavement in trials T1, T2, and T3. This result was most likely due to the specimen not being insulated and being allowed to dry. The lack of insulation did not allow the specimen to maintain temperature. Thus, based on maturity, air-cured specimens are not representative of the pavement concrete.

5.4.2 Laboratory Studies

In order to evaluate the effect of temperature-matched curing on maturity development, the maturity values of the TMCA and TMCB-cured specimens were determined in laboratory studies LS-2 and LS-3, respectively. The average maturity values of the TMCA-cured specimens, for each pavement temperature data set to which they were cured, were calculated at the opening-to-traffic maturity (maturity corresponding to an MOR of 550 psi). These average values were input into the maturity curve relationship (see Appendix D) and corresponding MOR values were determined. These results are presented in Tables 5.8 and 5.9 for TMCA and TMCB-cured specimens, respectively.

Table 5.8 MOR Values Calculated for TMCA-Cured Specimens (Based on Maturity)

Data Set	Average Maturity (°C-Hr)	Calculated MOR (psi)
T1	1238	549
T2	1234	548
Average	1236	549

Note: 1 MPa = 145 psi

Table 5.9 MOR Values Calculated for TMCB-Cured Specimens (Based on Maturity)

Data Set	Maturity (°C-Hr)	Calculated MOR (psi)
T1	1201	544
T2	1095	529
Average	1148	537

Note: 1 MPa = 145 psi

Since the curing of the specimens from laboratory studies LS-1 and LS-2 continued until the opening-to-traffic maturity was reached for both data sets the flexural strengths calculated for each data set should have been the same and should read the target value of 550 psi (3792 kPa). The average calculated MOR of the TMCA-cured specimens was 549 psi (3785 kPa). The average calculated flexural strength of the TMCA-cured specimens was less than 1 percent less than the target value. The average calculated flexural strength of the TMCB-cured specimens was 537 psi (3703 kPa). The average calculated flexural strength of the TMCB-cured specimens was 2 percent less than the target value. Based on maturity calculated flexural strength, the TMCA system more closely matched the target flexural strength value than the TMCB system matched the target flexural strength value. Overall, these results indicated that, on average, temperature-matched curing can estimate the target flexural strength, based on maturity, to within 1 percent.

5.5 Influence of Specimen Type on Maturity Development

To determine the effect of specimen type on maturity development, the thermal histories of both beam and cylinder specimens were determined in the field study. The temperatures of the beam and cylinder specimens were plotted as a function of time. These results appear in Figures 4.11, 4.12, and 4.13 for trials T1, T2, and T3 of the field study, respectively. As these figures indicate, the temperatures of the beams and cylinder specimens closely matched each other for a given curing condition. Based on these results, the maturity development of the specimens was also expected to be similar for both beam and cylinder specimens within a curing condition.

The maturity values of the beam and cylinder specimens were calculated and plotted as a function of time for each trial of the field study. These results are presented in Figures 4.26, 4.27, and 4.28 for field trials T1, T2, and T3, respectively. As was expected, the maturity development in the beams and in the cylinders was similar.

The percent difference between the beam specimen maturity and the cylinder specimen maturity in each curing condition was calculated (see Equation 5.4) at two specific times: the opening-to-traffic time and the end of the curing period (time at which the specimens were tested to determine strength properties). Table 5.10 contains these results.

$$\text{Percent Difference} = ((M_b - M_c) / M_b)\ \% \qquad (5.4)$$

M_b = maturity of beam specimen
M_c = maturity of cylinder specimen.

Table 5.10 Percent Difference between Beam and Cylinder Specimen Maturity

Field Study	Time (Hours)	Lime-Bath-Cured	Sandpit-Cured	Air-Cured
T1	36.3	-0.3 %	-1.3 %	-1.8 %
	70.0	-0.1 %	-1.1 %	-0.1 %
T2	57.2	2.8 %	-2.9 %	0.7 %
	70.0	3.2 %	-2.7 %	0.7 %
T3	24.7	4.0 %	1.7 %	6.2 %
	70.0	1.4 %	0.6 %	1.5 %

The average percent difference between the beam and cylinder specimens in the lime bath, regardless of time, was 1.8 percent. For the specimens cured in the sandpit and in air, these same values were 1.0 percent and 1.3 percent, respectively. Because the differences are small, the curing condition does not influence the maturity development relationship between beams or cylinders. The average percent difference for all curing conditions was 1 percent at the opening-to-traffic time and 0.4 percent at the time at which the strength properties of the specimens were determined. Since these values also

are small, the insignificant difference between maturity of the beam and cylinder specimens holds true over time.

5.6 Influence of Curing Conditions on Maturity and Strength Properties

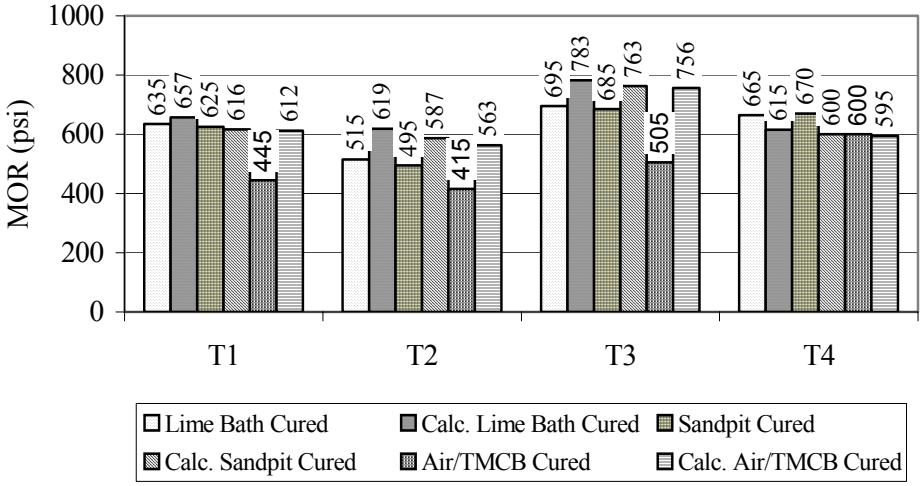
The influence of curing conditions on the strength properties of concrete was discussed in Section 5.3. The influence of curing condition on the maturity development of concrete was discussed in Section 5.4. The results discussed in these sections were combined and are discussed in this section.

5.6.1 Field Study

To evaluate the relationship between maturity and flexural strength of specimens cured in different curing conditions, the flexural strengths of the beam specimens and the maturity values of the specimens were determined for each of the four curing conditions used in the field study. The maturity predicted flexural strength was calculated for each curing condition, in each trial of the field study. These data were compiled and are presented in Figure 5.7.

In field trial T1, the average flexural strength of the lime-bath-cured specimens was the highest at 635 psi (4379 kPa). The next highest average flexural strength was the strength of the specimens cured in the sandpit at 625 psi (4310 kPa). Finally, the specimens cured in air had the lowest average flexural strength at 445 psi (3069 kPa). The maturity predicted strengths followed the same pattern. The maturity predicted strengths were 657 psi (4530 kPa), 616 psi (4247 kPa), and 612 psi (4220 kPa) for the lime-bath-cured, sandpit-cured, and air-cured specimens, respectively. The percent

difference between experimental and predicted strength was –1.2 percent and –1.3 percent for the lime-bath and sandpit-cured specimens, respectively. However, the strengths of the air-cured specimens were overestimated by the maturity method by 37 percent.



Note: 1 MPa = 145 psi

Figure 5.7 Comparison of Actual and Maturity Calculated Flexural Strengths

In the second field study trial (T2) the specimens cured in the lime bath, in the sandpit, and in air had strengths of 515 psi (3552 kPa), 495 psi (3414 kPa), and 415 psi (2862 kPa), respectively. The maturity predicted strengths were 619 psi (4268 kPa), 587 psi (4047 kPa), and 563 psi (3882 kPa) for the lime-bath-cured, sandpit-cured, and air-cured specimens, respectively. When compared to field trial T1, the data in field trial T2 exhibits a greater difference between the experimental and predicted strengths. The

maturity values overestimated the strengths by 20 percent, 19 percent and 36 percent for the lime-bath, sandpit, and air-cured specimens, respectively.

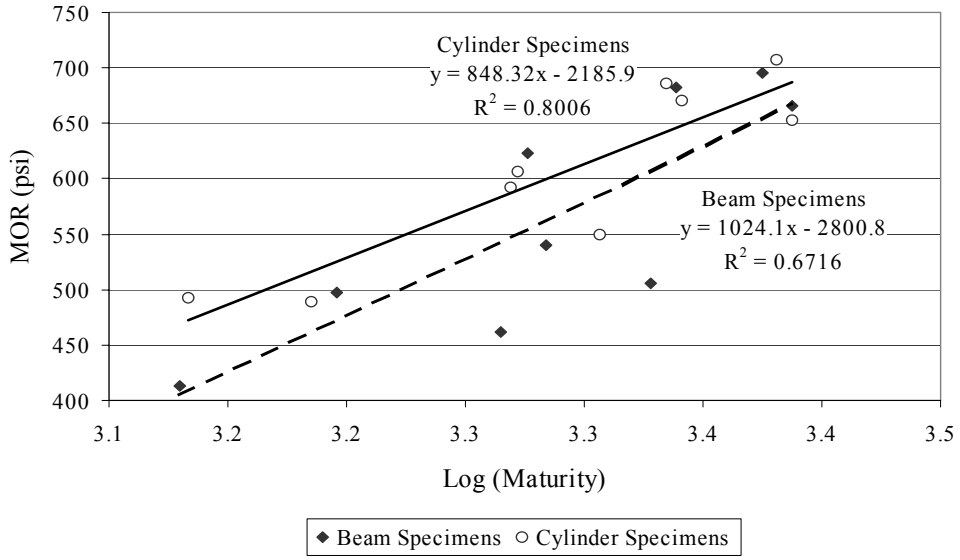
In field trial T3, the flexural strengths of the specimens are 695 psi (4799 kPa) for the lime-bath-cured specimens, 685 psi (4709 kPa) for the sandpit-cured specimens, and 505 psi (3489 kPa) for the air-cured specimens. The maturity predicted flexural strength values were 783 psi (5399 kPa), 764 psi (5268 kPa), and 756 psi (5213 kPa) for the lime-bath-cured, sandpit-cured, and air-cured specimens, respectively. The maturity values overestimated the experimental strengths by 12 percent for both the lime-bath and sandpit-cured specimens. The experimental flexural strength of the air-cured specimens was overestimated by the maturity predicted flexural strength by 50 percent.

The flexural strengths of the specimens tested in field trial T4 were 665 psi (4586 kPa), 670 psi (4621 kPa), and 600 psi (4138 kPa) for the lime-bath-cured, sandpit-cured, and the TMCB-cured specimens, respectively. The maturity predicted flexural strengths were 615 psi (4241 kPa), 600 psi (4138 kPa), and 595 psi (4103 kPa) for the lime-bath-cured , sandpit-cured , and the TMCB-cured specimens, respectively. The percent differences between the experimental flexural strength and the maturity predicted flexural strength were 8 percent, 10 percent, and 1 percent underestimations for the three curing conditions, respectively.

According to ITM 402-99T, to validate the maturity curve, the flexural strength of the specimens should not vary by more than 50 psi (345 kPa) of the maturity predicted

flexural strength. For the lime-bath-cured specimens the average difference for all trials was 66 psi (358 kPa). For the sandpit-cured specimens the average difference was 62 psi (372 kPa). For the air-cured specimens the average difference was 189 psi (1262 kPa). Although these results indicate that the maturity curve was not valid in any of the curing conditions, for two of the curing conditions the extent beyond specifications was marginal at 16 psi and 12 psi for lime bath and sandpit curing, respectively. The air-cured specimens were far outside the specification limit and the TMCB-cured specimens (only one trial) were well within the specification.

To illustrate the influence of curing conditions on maturity, the MOR data from field trials T1, T2, and T3 were plotted as a function of the log of their maturity values (as required by ITM 402-99T). The MOR values calculated using the compressive-flexural strength relationship for the field cylinders were also included to compare the difference between the maturity strength relationships of beam and cylinder specimens. These data for all curing conditions are presented in Figure 5.8.

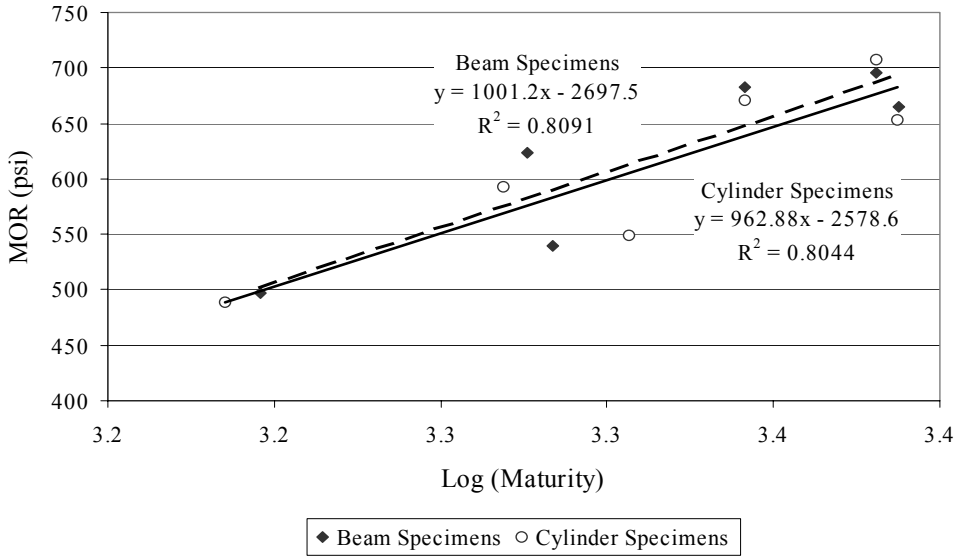


Note: 1 MPa = 145 psi

Figure 5.8 Relationship between MOR and Maturity for All Curing Conditions

The results showed that there was a fairly good correlation between MOR and maturity for the cylinder specimens cured in all conditions ($R^2 = 0.80$). When beam specimens only were used, the correlation between MOR and maturity was weak ($R^2 = 0.67$).

To improve this correlation, the air-cured specimens were removed from the data set. This was done because the air-cured specimens did not have a sufficient supply of moisture when compared to the lime-bath and sandpit-cured specimens. The remaining data was plotted again in Figure 5.9.



Note: 1 MPa = 145 psi

Figure 5.9 Relationship between MOR and Maturity for Lime-Bath and Sandpit-Cured Specimens

The result for the cylinder specimens was very similar to that obtained from the previous analysis. The results showed that there was a fairly good correlation between MOR and maturity for the cylinder specimens cured in all conditions ($R^2 = 0.80$). However, the correlation between MOR and maturity of the beam specimens improved ($R^2 = 0.81$). This indicated that the air-cured beam specimens have a greater effect on the variability of the maturity-strength relationship than the air-cured cylinders.

Also, the results of the analysis presented in Figure 5.9 indicate that, based on the maturity strength relationship, there is no significant difference between the beam and cylinder specimens.

5.6.2 Laboratory Studies

To evaluate the relationship between maturity and flexural strength of specimens cured by temperature-matched curing, the calculated flexural strengths of the cylinder specimens were determined for the TMCA-cured specimens in laboratory study LS-2. The maturity predicted flexural strength and the compressive-flexural relationship predicted flexural strength were calculated for each temperature data set to which the specimens were temperature-match cured. The flexural strengths of the cylinder specimens calculated by the compressive-flexural relationship appear in Table 5.4. The flexural strengths of the cylinder specimens calculated by maturity appear in Table 5.8. Also, the flexural strengths of the beam specimens and the maturity calculated flexural strengths were determined for the TMCB-cured specimens in laboratory study LS-3. The maturity predicted flexural strengths were calculated (see Table 5.9) and the experimental flexural strength values were determined (see Figure 4.1) for each temperature data set to which the specimens were temperature-match cured.

If the maturity curve was valid for the TMCA-cured specimens, the flexural strength calculated from the compressive-flexural strength relationship should be equal to the flexural strength calculated from the maturity curve. Similarly, if the maturity curve was to be valid for the TMCB-cured specimens, the experimental flexural strength should be equal to the flexural strength calculated from the maturity curve.

For the TMCA-cured specimens, the average flexural strength calculated from the compressive-flexural strength relationship was 608 psi (4192 kPa). The average flexural

strength calculated from maturity was 549 psi (3785 kPa). According to ITM 402-99T, to validate the maturity curve, the flexural strength of the specimens should not vary by more than 50 psi (345 kPa) from the maturity predicted flexural strength. For the TMCA-cured specimens the difference was 59 psi (407 kPa). Since the tested flexural strength was calculated with the compressive-flexural strength relationship that had a certain degree of variability associated with it ($R^2 = 0.95$), the difference between the experimental and maturity predicted flexural strengths do not necessarily negate the validity of the maturity curve for the TMCA-cured specimens.

For the TMCB-cured specimens, the average flexural strength for both data sets was 546 psi (3764 kPa). The average flexural strength calculated from maturity was 537 psi (3703 kPa). The difference between the experimental and maturity calculated values was 9 psi (62 kPa). According to the ITM 402-99T criterion, the TMCB-cured specimens validate the maturity curve.

5.7 Statistical Analysis

To confirm the results of the analyses performed in the previous sections, an analysis of variances (ANOVA) of the data was performed as described by Montgomery [1997]. The model used to analyze the data tested the null hypothesis, H_0, to determine if it should be accepted or rejected. Acceptance of the null hypothesis meant that the means (μ_1, μ_2, μ_3) of the tested data sets were not different. The null hypothesis, used in both tests was expressed as follows: H_0: $\mu_1 = \mu_2 = \mu_3$. Acceptance of the null hypothesis,

meant that the alternative hypothesis (H_a: at least one $\mu_i \neq \mu_j$) was rejected. That is, at least one mean of one of the data sets was not equal to the mean of another data set.

To determine the degree to which the means were different, the p-value (probability) was used. This value is the smallest value of α, the probability of rejecting the null hypothesis when it is actually true, for which the results are statistically significant. The analyses were run at a customary level of $\alpha = 0.05$.

To decide whether or not to reject the null hypothesis the F-test was used. The p-value was compared to the result of the F-test. For p values greater than 0.05, the null hypothesis was accepted and the means of the data sets were considered not to be different.

The statistical analyses were done using a commercial statistical analysis program. Two different statistical models were used. The first model was a two-factor factorial design with blocking. This type of model was used to determine the significance of the factors included in the analysis. The second was a randomized complete block design (RCBD). This type of analysis was done to determine which means were different.

5.7.1 Analysis of the Effect of Curing Condition on Degree of Hydration of Cement

To evaluate the effect of curing condition on percent of non-evaporable water in cement paste a RCBD analysis was done with the non-evaporable water data obtained in laboratory study LS-1. The percent non-evaporable water data for each 1g sample

obtained from the cement paste cube specimens cured in the lime bath, sandpit, and air were used. The analysis was run for the data obtained at 1, 3, 7, 14, 28, and 56 days. The results of the analysis were as follows.

The results of the analysis of the non-evaporable data obtained at 1 day indicated that there was no significant statistical difference in the amount of non-evaporable water in the specimens cured in any of the curing conditions. This result was as expected since the specimens were all cured in their moulds for the first day.

The results of the analysis of the non-evaporable data obtained at 3 days indicated that there was no significant statistical difference between the amount of non-evaporable water in the lime-bath-cured specimens and the amount of non-evaporable water in the sandpit-cured specimens. Also, there was no significant statistical difference between the amount of non-evaporable water in the specimens cured in the sandpit and the amount of non-evaporable water in the specimens cured in air. However, there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the lime bath and the amount of non-evaporable water in the air-cured specimens.

The trend observed in the data obtained at 3 days did not continue for the data obtained at 7 days. There was no significant statistical difference between the amount of non-evaporable water in the specimens cured in any of the three curing conditions. However, the correlation ($R^2 = 0.57$) among the data was weak.

The trend observed in the data obtained at 3 days was observed again for the data obtained at 14 days. There was no significant statistical difference between the amount of non-evaporable water in the lime-bath-cured specimens and the amount of non-evaporable water in the sandpit-cured specimens. Also, there was no significant statistical difference between the amount of non-evaporable water in the specimens cured in the sandpit and the amount of non-evaporable water in the specimens cured in air. However, there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the lime bath and the amount of non-evaporable water in the air-cured specimens.

A new trend was observed in the data obtained at 28 days. There was no significant statistical difference between the amount of non-evaporable water in the lime-bath-cured specimens and the amount of non-evaporable water in the sandpit-cured specimens. However, there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the lime bath and the amount of non-evaporable water in the air-cured specimens. Also, there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the sandpit and the amount of non-evaporable water in the air-cured specimens.

The trend observed in the data obtained at 28 days was observed again for the data obtained at 56 days.

In summary, there was no significant statistical difference between the amount of non-evaporable water in the lime-bath-cured specimens and the amount of non-evaporable water in the sandpit-cured specimens during the entire 56-day curing period. As was previously stated, the percent non-evaporable water is directly related to the degree of hydration of the cement. Thus, given the same ambient temperature conditions, the same degree of hydration at any time can be attained by curing in either the lime bath or the sandpit.

After 3 days, there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the lime bath and the amount of non-evaporable water in the air-cured specimens. It was not until 28 days there was a significant statistical difference between the amount of non-evaporable water in the specimens cured in the sandpit and the amount of non-evaporable water in the air-cured specimens. This result indicates that, based on degree of hydration, under no circumstance is the curing of specimens in the air the same as curing the specimens in the lime bath. The curing of specimens in air is similar to curing specimens in sand up to 28 days provided the ambient temperature conditions are equal. These results support the conclusions drawn in Section 5.1.

5.7.2 Analysis of Effect of Specimen Type and Curing Condition on Maturity Development

To evaluate the significance of the effect of curing condition and specimen type on the maturity development of concrete a two factor factorial analysis was made with the

maturity data obtained in all trials of the field study. The maturity data from the beam and cylinder specimens cured in the lime bath, sandpit, and air were used. Also, the maturity data from the pavement were used as a fourth curing condition. This analysis was run for the data obtained at the opening to traffic time in each trial. The analysis was also run at the time at which the strengths of the specimens were determined. The results of the analysis were as follows.

The results of the analysis of the maturity data from the beam and cylinder specimens in all curing conditions and the pavement, at both the opening-to-traffic time and the end of the curing period (time at which the strengths of the specimens were determined), indicated the following. The effect of the specimen type on maturity was not significant. The effect of the interaction (combined effect of the two parameters) between curing condition and specimen type on maturity was not significant. The effect of the curing condition on maturity was significant. The effect of the trial (field study trials T1-T3) was significant.

The insignificance of the specimen type was expected based on the results presented in Section 5.5. Also, the insignificance of the interaction between specimen type and curing condition was as expected based on the results presented in Section 5.6. The significance of the curing condition was as expected based on the results presented in Section 5.4.

The significance of the trial was thought to be associated with the fact that the field trial T3 maturity data was from a different concrete mix design than used in field trials T1 and

T2. This concrete mix design had a different maturity curve. Thus, the analysis of the maturity data from the beam and cylinder specimens in all curing conditions and the pavement, at the time at which the strengths of the specimens were determined, was run again without the T3 data. However, the effect of the trial was still significant. This indicated that the different mix design was not the only factor that caused the trial to be significant. Thus, it was concluded that the effect of the trial may have also been the result of the temperature effects discussed in Section 5.4.

5.7.3 Analysis of the Effect of Curing Condition on Maturity Development

To evaluate the effect of curing condition on the maturity development of concrete a RCBD analysis was made with the maturity data obtained in all trials of the field study. The maturity data from the beam specimens cured in the lime bath, sandpit, and air were used. Also, the maturity data from the pavement were used as a fourth curing condition. This analysis was run for the data obtained at the opening-to-traffic time in each trial. The analysis was also run at the time at which the flexural strengths of the beam specimens were determined.

The results of the analysis of the maturity data at the opening-to-traffic time indicated that there was no significant statistical difference between the maturity values of the specimens cured in any of the curing conditions analyzed.

The results of the analysis of the maturity data at the time the specimens were tested to determine their strengths indicated that there was no significant statistical difference

between the maturity values of the lime-bath-cured specimens and the maturity values of the pavement. There was no significant statistical difference between the maturity values of the sandpit-cured specimens and the maturity of the pavement or the maturity values of the air-cured specimens. However, there was a significant statistical difference between the maturity values of the specimens cured in the lime bath and the maturity values of the air-cured specimens. Also, there was a significant statistical difference between the maturity values of the specimens cured in the sandpit and the maturity values of the lime-bath-cured specimens.

In summary, curing specimens in all curing conditions will produce specimens with maturity values that are not statistically different from each other at the opening-to-traffic time. Also, curing specimens in all curing conditions will produce specimens with maturity values that are not statistically different from the pavement maturity. These results support the previous conclusions drawn in Section 5.4.1.2.

Based on the time at which the specimens were tested to determine their flexural strength, curing specimens in all curing conditions will produce specimens with maturity values that are not statistically different from the pavement at the opening-to-traffic time. These results also support the previous conclusions drawn in Section 5.4.1.2.

The analysis of the maturity data that was run at the opening-to-traffic time was run again with the same maturity data (from the lime-bath, sandpit, and air-cured specimens and the pavement) and with maturity data from the TMCB-cured specimens. These data

represented a fifth curing condition. The results of the analysis indicated there was no significant statistical difference between the maturity values of any of the curing conditions analyzed.

6 CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this project were to establish a correlation between maturity development and degree of hydration of cement and to establish equivalent curing methods for concrete specimens that can accurately represent the curing conditions of concrete in pavement. To achieve these objectives, the following tasks were performed.

1. The maturity development of cement in relation to cement hydration was evaluated.
2. The influences of different specimen curing conditions and specimen types on the flexural strength, compressive strength, and maturity development of pavement concrete were evaluated.

6.1 Conclusions

Based on the research results presented in this document, the following conclusions were drawn from the study.

1. There existed a good correlation between maturity development of cement paste and the degree of hydration of cement. This correlation was valid only if sufficient moisture was available for continuous hydration of the specimens. The maturity-

degree of hydration correlation could also be extended to concrete since the maturity development in cement paste and concrete was found to be similar.

2. With respect to flexural strength of the specimens, curing specimens in the lime bath or in the sandpit produced specimens with equivalent flexural strengths. Air curing of specimens did not produce specimens with a strength equivalent to the strength of specimens cured in either the lime bath or sandpit.
3. The temperature-matched curing technique was able to produce specimens with strengths within 10 percent of the flexural strength required for opening the pavement to traffic. This result was repeated in the field based on maturity values.
4. With respect to compressive strength, the specimens cured in the sandpit and the specimens cured in air were the most similar. The strengths of the specimens cured in the lime bath were different than the strengths of the specimens cured in the other two curing conditions.
5. The ambient temperature in which the concrete was cured had a significant influence on the maturity development of the concrete. The sandpit-cured specimens most accurately matched the maturity development of the pavement in the field study (within 6 percent). The lime-bath, sandpit and air-cured specimens all matched the maturity of the pavement to within 14 percent. The temperature-match cured specimens matched the maturity development in the pavement to within 1 percent in laboratory studies.
6. It appears that there was no difference between the maturity development in beam specimens and cylinder specimens.

7. Air curing of specimens has a greater effect on the maturity-strength relationship of beam specimens than on cylinder specimens. Also, the TMCB-cured specimens validated the maturity curve for the concrete.

6.2 Recommendations and Implementation

6.2.1 Curing Methods

Currently INDOT specifies two different types of field curing: lime bath and sandpit curing. Lime bath curing is used for QC/QA pavement construction for specimens made to determine the 7 day flexural strength of the concrete. Sandpit curing is used for estimating opening-to-traffic strengths of the pavement concrete. The constant temperature of the lime bath provides a uniform curing environment that should provide repeatable results (based on maturity) from batch to batch. However, due to the inability of the lime-bath-cured specimens to adjust to environmental conditions these specimens may not always provide an accurate representation of the strength of the pavement concrete. Thus, it is not recommended that the lime-bath-cured specimens be used for opening-to-traffic purposes. Specimens cured in the sandpit have the ability to adjust to the temperature of the environment, as does the concrete in the pavement. Therefore, these specimens are more appropriate for opening-to-traffic purposes. Thus, current INDOT specifications are appropriate.

Temperature match curing has the ability to provide specimens with an accurate representation of the maturity of the pavement. However, most commercial systems are

costly. Less expensive in-house systems can be developed that would provide satisfactory results, however, the TMCB system developed in this study needs more development before it could be implemented. Further, sandpit curing provides results that are statistically equivalent to the maturity of the pavement. Thus, INDOT needs to determine if the extra expense of TMC systems is worth the increase in accuracy when current methods provide satisfactory results.

6.2.2 Further Research

A method for converting between the strength of specimens cured in a given curing condition to the strength of the pavement is needed. An attempt was made to perform a regression analysis of the maturity data obtained in this study to develop such a relationship. However, the ANOVA results indicated that the trial (field trials T1-T3) was a significant factor (see Section 5.7.2). Since it was significant, the trial would have to have been included in the regression equation. Thus the use of the equation would have been limited to these three field studies.

To develop an equation with a broader range of uses, a greater number of trials need to be conducted. This experimental setup would remove the effect of the trial on the maturity development. Thus, the equation developed would be based only on the different curing conditions. Also, to base this equation on the strength of the pavement, cores of the pavement concrete should be taken and evaluated. The proposed form of the equation is shown in Equation 6.1.

$$\ln(MOR) = a_0 + a_1C1 + a_2C2 + a_3C3 \quad (6.1)$$

MOR = Modulus of Rupture
C1 = Curing Condition 1 Indicator Variable
C2 = Curing Condition 2 Indicator Variable
C3 = Curing Condition 3 Indicator Variable
a_n = Constant

BIBLIOGRAPHY

ASTM [1995] "Standard Practice for Estimating Concrete Strength by the Maturity Method," ASTM C 1074-93, *Annual Book of Standards, Vol. 04.02 Concrete and Aggregates*, pp. 537-543.

Barneyback, Jr., R. S. [1983] "Alkali-Silica Reaction in Portland Cement Concrete," PhD. Thesis, Purdue University, May 1983.

Bickley, J. A. [1975], "Practical Application of the Maturity Concept to Determine In Situ Strength of Concrete," Transportation Research Record, n. 558, pp. 45-49.

Byfors, J. [1980], "Plain Concrete at Early Ages," Swedish Cement and Concrete Research Institute, Rep. 3:80.

Carino, N. J. [1991] "The Maturity Method," Chapter 5 in *Handbook on Nondestructive Testing of Concrete*, Malhotra, V. M. and Carino, N. J., Eds., CRC Press Inc., Boca Raton, FL, pp. 101-146.

Copeland, L. E., and Kantro, D. L., Verbeck, G. [1962], "Chemistry of Hydration of Portland Cement, Part III-Energetics of the Hydration of Portland Cement," *Proceedings of the 4th International Symposium on Chemistry of Cement*, NBS Monograph 43, Washington, 453.

Freiesleben Hansen, P., and Pedersen, E. J. [1977], "Maturity Computer for Controlled Curing and Hardening of Concrete," *Nordisk Betong*, 1, 19.

Grove, J. D. and Cable, J. K. [1997] "Early Opening of Portland Cement Pavement Using Maturity," Unpublished review.

Hossain, M. and Wojakowski, J. [1995], "Construction and Performance of a Fast-track Concrete Pavement in Kansas," *Transportation Research Record*, n. 1465, July 1995, pp. 1-8.

Iowa Department of Transportation [1997-1], "Strength of PCC by Maturity Method Review Team," Unpublished review.

Iowa Department of Transportation [1997-2], "Method of Testing the Strength of Portland Cement Concrete Using the Maturity Method," Materials I. M. 383, May 2, 1997.

Kosmatka, S. H. and Panarese, W. C. [1988], *Design and Control of Concrete Mixtures*, Thirteenth Edition, Portland Cement Association (PCA), Skokie, IL, pp. 137-150.

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

Montgomery, D. C. [1997], *Design and Analysis of Experiments*, Fourth Edition, John Wiley and Sons, Inc., New York, NY, pp. 171, 243.

Mukherjee, P. K. [1975], "Practical Application of Maturity Concept to Determine In Situ Strength of Concrete," Transportation Research Record, n. 558, pp. 87-92.

Naik, T. R. [1985], "Maturity Functions Concrete Cured during Winter Conditions," *Temperature Effects on Concrete*, Naik, T. R. Ed., ASTM STP 858, 107.

Nantung, T. E. [1997] "Maturity Method," Unpublished review, Indiana Department of Transportation.

Neville, A. M. [1997], *Properties of Concrete*, Fourth Edition, John Wiley and Sons, Inc., New York, NY, pp. 319-360, 600.

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

Powers, T. C. and Brownyard, T. L. [1948], "Studies of the Physical Properties of Hardened Portland Cement Paste," Bulletin 22, Reprinted from *Journal of the American Concrete Institute* (October 1946-April 1947), *Proceedings*, Vol. 43, 1947.

Rastrup, E. [1954], "Heat of Hydration in Concrete," *Magazine of Concrete Research*, 1(2), 79.

Saul, A. G. A. [1951], "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure," *Magazine of Concrete Research*, 2(6), 127.

Wastlund, G. [1956], "Hardening of Concrete as Influenced by Temperature," General Report of Session BII, *Proceedings*, RILEM Symposium Winter Concreting (Copenhagen 1956), Danish Institute for Building Research Copenhagen.

Whiting, D., Nagi, M., and Okamoto, P. A. [1994], "Early Strength Gain of Rapid Highway Repair Concrete," *Concrete International: Design and Construction*, v. 16, n. 8, August 1994, pp. 28-35.

APPENDIX A – ITM 402-99T

Appendix A – ITM 402-99T

Revised 08/16/99

INDIANA DEPARTMENT OF TRANSPORTATION

MATERIALS & TESTS DIVISION

STRENGTH OF PORTLAND CEMENT CONCRETE PAVEMENT (PCCP) USING THE MATURITY METHOD

ITM 402-99T

1.0 SCOPE

1.1 This test method covers the maturity concept as a non-destructive method to determine in-place concrete flexural strength in the field for opening of PCCP to traffic.

1.2 The values stated in either SI metric or acceptable English units are to be regarded separately as standard, as appropriate for a specification with which this ITM is used. Within the text, English units are shown in parenthesis. The values stated in each system may not be exact equivalents; therefore each system shall be used independently of the other, without combining values in any way.

1.3 This ITM may involve hazardous materials, operations, and equipment. This ITM does not purport to address all of the safety problems associated with the ITMs use. The ITM user’s responsibility is to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2.0 REFERENCES

2.1 AASHTO STANDARDS

T 23, Making and Curing Concrete Test Specimens in the Field

T 97, Flexural Strength of Concrete

T 119, Slump of Hydraulic Cement Concrete

T 126, Making and Curing Concrete Test Specimens in the Laboratory

T 152, Air Content of Freshly Mixed Concrete by the Pressure Method

T 196, Air Content of Freshly Mixed Concrete by the Volumetric Method

M 241, Concrete Made by Volumetric Batching and Continuous Mixing

2.2 ASTM STANDARDS

E-574 Standard Specifications for Duplex Base Metal Thermocouple Wire with Glass Fiber or Silica Fiber Insulation

2.3 ITM STANDARDS

403, Water-Cementitious Ratio

802, Random Sampling

909, Verifying Thermometers

3.0 TERMINOLOGY

3.1 Terms and Abbreviations. Definitions for terms and abbreviations will be in accordance with 101, except as follows.

3.1.1 Equivalent Age. The time in days or hours at a specified temperature required to produce a flexural strength equal to the flexural strength achieved by a curing period at temperatures different from the specified temperature.

3.1.2 Maturity Function. A mathematical expression that uses the measured temperature history of a cementitious mixture during the curing period to calculate a maturity index that is indicative of the flexural strength at the end of that period.

3.1.3 Maturity Index. An indicator of flexural strength that is calculated from the temperature history of the cementitious mixture by using a maturity function.

3.1.4 Maturity Method. A technique for estimating concrete flexural strength that is based on the assumption that samples of a given concrete mixture attain equal flexural strengths if they attain equal maturity index values.

3.1.5 Maturity Curve. A curve established by plotting the flexural strength values vs time-temperature factor values.

3.1.6 Maturity-Strength Relationship. A relationship between the beam flexural strength and maturity index that is obtained by testing beam specimens whose temperature history up to the time of test has been recorded.

3.1.7 Time-Temperature Factor (TTF). TTF is a calculated value determined from time and temperature readings used to indicate the flexural strength of the concrete.

4.0 SIGNIFICANCE AND USE

4.1 This ITM shall be used to determine in-place flexural strength of concrete for opening of PCCP to traffic.

4.2 The hydration of cement and gain in strength of the concrete are dependent on both curing time and temperature. Thus, the strength of the concrete may be expressed as a function of time and temperature. This information may then be used to determine the strength of concrete without conducting destructive tests.

5.0 APPARATUS

5.1 Beam molds: Beam molds shall have the nominal dimensions of 150 mm x 150 mm x 500 mm (6 in. x 6 in. x 20 in.) in accordance with AASHTO T 23 and T 126.

5.2 Flexural Strength Testing Machine: A testing machine in accordance with AASHTO T 97 used to determine the flexural strength of concrete by breaking simply supported beams loaded at third points.

5.3 Maturity Meter: A device that automatically measures, computes and displays a time-temperature factor.

5.4 Hand-held Digital Thermometer: A verified thermometer having a thermocouple input connector and a power source. The minimum temperature measuring range shall be 0 °C to 66 °C (32 °F to 150 °F).

5.5 Type T Thermocouple Assembly: A Type T thermocouple assembly shall be two thermocouple elements having connection head and protecting tube in accordance with ASTM E 574. The coating from one end of the two thermocouple elements shall be stripped 13 mm (0.5 in.) and the ends twisted together to form a thermocouple assembly.

5.6 Concrete Mixing Equipment- The mixers shall be equipped with a metal plate or plates on which are plainly marked the gross volume of the unit in terms of mixed concrete, discharge speed, and the weight-calibrated constant of the machine in terms of a revolution counter or other output indicator in accordance with AASHTO M 241. The capacity of the concrete mixer shall be large enough to place twelve beams at one time and to conduct all other tests.

6.0 GENERAL

6.1 This is a three step process.

6.1.1 Laboratory procedure in accordance with 7.0.

6.1.2 Field procedure in accordance with 8.0.

6.1.3 Validation procedure in accordance with 9.0.

6.2 The concrete shall be in accordance with 501.

6.3 An excel based spread sheet computer program furnished by the Department shall be used to calculate TTF and is based on the following equation.

$$\sum TTF = \sum [(((T2 + T3)/2) + 10) (A1- A2)]$$

Where:

TTF, Time-Temperature Factor in ℃ x Hours

A1 - Age in hours

A2 - Previous age in hours

T2 - Concrete temperature in ℃ at measuring age

T3 - Previous temperature of concrete in ℃

7.0 LABORATORY PROCEDURE

7.1 Prior to construction a relationship between the TTF and the concrete flexural strength as measured by destructive methods through testing of beams shall be developed in the laboratory using project materials and the project concrete mix design.

7.2 Prepare concrete mixture and cast a minimum of twelve beams in accordance with AASHTO T 126. Tests for air content, slump and water-cementitious ratio shall be performed for each batch and recorded in accordance with AASHTO T 152, AASHTO T 119 and ITM 403 respectively.

7.3 A thermocouple assembly shall be inserted near each end of a test beam used to monitor temperature to the approximate mid-depth and such that they are approximately 75 mm (3 in.) from each side. This beam shall be designated temperature control beam. Secure the loose end of the assembly to the beam box to prevent being inadvertently pulled out of the beam during first 24 h of curing. This beam shall be the last beam to be tested for flexural strength.

7.4 The beams shall be covered with wet burlap and polyethylene sheeting upon initial set. The forms, wet burlap and polyethylene sheeting shall be removed after 24 h following casting. All beams shall be stored in a testing facility in accordance with 507.09, until each has been tested.

7.5 The TTF and flexural strength at four different ages shall be determined. Three specimens cast shall be tested for flexural strength in accordance with AASHTO T 97. The TTF shall be recorded directly by using maturity meter or calculated from a temperature reading by hand-held thermometer and at the same time the three specimens tested for flexural strength. The two readings for TTF shall be used in the

development of the maturity curve. The first three beams shall be tested for flexural strength at 24 h after the casting. The remaining tests shall be spaced at 12 h intervals and span a range in flexural strength that includes the desired flexural strength.

7.5.1 When a maturity meter is used, the TTF values are computed by the meter and it shall remain connected to the temperature control beam until the test is completed.

7.5.2 When a hand-held thermometer is used, the measured temperature shall be recorded and entered in the spread sheet program to obtain values of TTF. An initial temperature of the first three beams shall be recorded at the time of casting. See ATTACHMENT I for a sample sheet.

7.6 The spread sheet program shall be used to determine maturity-strength relationship and maturity curve. The TTF number corresponding to the desired flexural strength shall be used to determine when the PCCP has reached opening flexural strength. An example computer print out for Maturity-Strength Development is provided by ATTACHMENT II.

7.7 The influence of maturity on flexural strength of concrete is mix specific; therefore, a maturity-strength relationship and maturity curve established for one mix shall not be used for another mix.

7.8 The computed R^2 value obtained from regression analysis of the maturity-strength relationship shall be 0.95 or higher. The R^2 value can be found on the maturity curve chart. When R^2 value is below 0.95, the

TTF value will not be generated. Therefore the trial batch is unacceptable, and a new trial batch will be required.

8.0 FIELD PROCEDURE

8.1 The tined concrete prior to curing shall be instrumented by inserting thermocouple assembly in to the plastic concrete.

8.2 A minimum of two thermocouple assemblies shall be placed within 30 m (100 ft.) of the end of each production day. Thermocouple assemblies shall be placed at random points determined in accordance with ITM 802 longitudinally along the PCCP. Thermocouple assembly shall not be placed within 1.5 m (5 ft) of transverse joint. The twisted end of thermocouple assembly shall be placed into the concrete until the end is at approximately the pavement mid-depth and 0.5 m (1.6 ft) from the edge of the plastic PCCP. Insertion may be accomplished by attaching the twisted end to a 6 mm (0.25 in.) diameter wooden dowel. The concrete shall be consolidated around the dowel. The portion of the dowel that protrudes above the PCCP shall be cut or broken off after the concrete is hardened.

8.3 The data may be collected by a maturity meter or a hand-held thermometer. When a maturity meter is used, the thermocouple assembly connector end shall be connected to a maturity meter in accordance with the manufacturer’s instructions. When a hand-held thermometer is used, the thermocouple assembly connector end is connected to the thermometer when a temperature is taken. An initial temperature of the concrete shall be taken immediately after the thermocouple assembly is inserted.

An example for maturity data recording sheet is provided by ATTACHMENT I.

8.4 The PCCP may be opened to traffic when the calculated TTF reaches the required TTF corresponding to the desired flexural strength as determined in accordance with 7.0.

9.0 VALIDATION PROCEDURE

9.1 Field Validation tests shall be conducted on the third sublot of every fourth lot to determine if the concrete being produced is represented by the maturity curve.

9.1.1 A minimum of three additional beams shall be cast in accordance with AASHTO T 23 at the time of the QC air content test for sublot.

9.1.2 A thermocouple assembly shall be inserted near each end of a test beam used to monitor temperature to the approximate mid-depth and
such that they are approximately 75 mm (3 in.) from each side. Insertion may be accomplished by attaching the twisted end to a 6 mm (0.25 in.) diameter wooden dowel. The concrete shall be consolidated around the dowel. This beam shall be designated temperature control beam. Secure the loose end of the assembly to the beam box to prevent being inadvertently pulled out of the beam during first 24-h of curing. This beam shall be the last beam to be tested for flexural strength.

9.1.3 The beams shall be covered with wet burlap and polyethylene sheeting upon initial set. The forms, wet burlap and polyethylene sheeting shall be removed after 24 h following casting. All beams shall be cured in a testing facility in accordance with 507.09, until each has been tested.

9.1.4 The TTF values of the three beams shall be monitored with a maturity meter in accordance with 7.5.1 or by temperature reading by hand-held thermometer in accordance with 7.5.2 until the TTF value reaches the required TTF value corresponding to the desired flexural strength. At the same time these three beams shall be tested for flexural strength in accordance with AASHTO T 97.

9.1.5 The average flexural strength of these three beams shall be compared against the desired flexural strength of PCCP. If the average of these tests is within 350 kPa (50 psi) of the original curve for the concrete mixture, the maturity curve is considered validated. If the average value is not within these limits, the maturity process is not valid. A computer printout example for validation of maturity curve is provided by ATTACHMENT III.

10.0 REPORT

10.1 Copies of all computer printouts, diskettes and field data shall be submitted to the Engineer upon completion of the work. All the wooden dowels and thermocouple assemblies shall be cutoff flush with the surface of the PCCP upon completion of the work.

ATTACHMENTS for ITM 402-99T

ITM 402-99T

Attachment I

Indiana Department of Transportation

Maturity TestingTime Temperature Factor (TTF) Worksheet

Contractor: ABC CONSTRUCTION CO.

Project No.: R-99999

Curve No.: 3

Description: I-999 RECONSTRUCTION

Date: 10/22/98

Time: 3:00 PM

Datum Temp: - 10 ° C

Reading					
Number	Date / Time	Temperature	Age	TTF (C°-hrs)	Sum of TTF (C°-hrs)
1	5/5/98 8:00 A	28 ° C			
2	5/6/98 8:00 A	27 ° C	24.0 hrs.	900.0	900.0
3	5/7/98 8:00 A	26 ° C	48.0 hrs.	876.0	1,776.0
4	5/8/98 8:00 A	25 ° C	72.0 hrs.	852.0	2,628.0
5	5/9/98 2:30 P	20 ° C	102.5 hrs.	991.3	3,619.3
6	5/10/98 3:30 A	18 ° C	115.5 hrs.	377.0	3,996.3
7					
8					
9					
10					
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Signature

Contractor Representative

ITM 402-99T | Indiana Department of Transportation | Attachment II

MATURITY TESTING - CURVE DEVELOPMENT

Contractor: ABC CONSTRUCTION CO.

Curve No.: 3

Contract No.: R-99999

Date: 05/05/99

Time: 1:48 PM

Location: I-999 RECONSTRUCTION

Beam Number	Actual Load * (N)	Depth (mm)	Width (mm)	Flexural Coefficient	Flexural Strength (kPa)	Age at Break (hrs.)	Temperature-Time Factor: Channel 1 (C°-hrs)	Channel 2 (C°-hrs)	Average TTF (C°-hrs)
1	24,500	152	152	0.1301	3,188	24	784	784	784
2	24,500	152	152	0.1301	3,188	24	784	784	784
3	24,500	152	152	0.1301	3,188	24	784	784	784
4	32,000	152	152	0.1301	4,164	36	1,566	1,591	1,579
5	32,500	152	152	0.1301	4,229	36	1,566	1,591	1,579
6	32,250	152	152	0.1301	4,197	36	1,566	1,591	1,579
7	35,600	152	152	0.1301	4,633	48	2,262	2,285	2,274
8	35,000	152	152	0.1301	4,555	48	2,262	2,285	2,274
9	35,000	154	152	0.1268	4,437	48	2,262	2,285	2,274
10	40,000	152	152	0.1301	5,205	60	2,858	2,852	2,855
11	40,500	152	150	0.1319	5,341	60	2,858	2,852	2,855
12	40,000	152	152	0.1301	5,205	60	2,858	2,852	2,855

Plastic Test Results

Test No:	P7
Air Content:	5.8%
Slump:	51 mm
W/C Ratio:	0.420

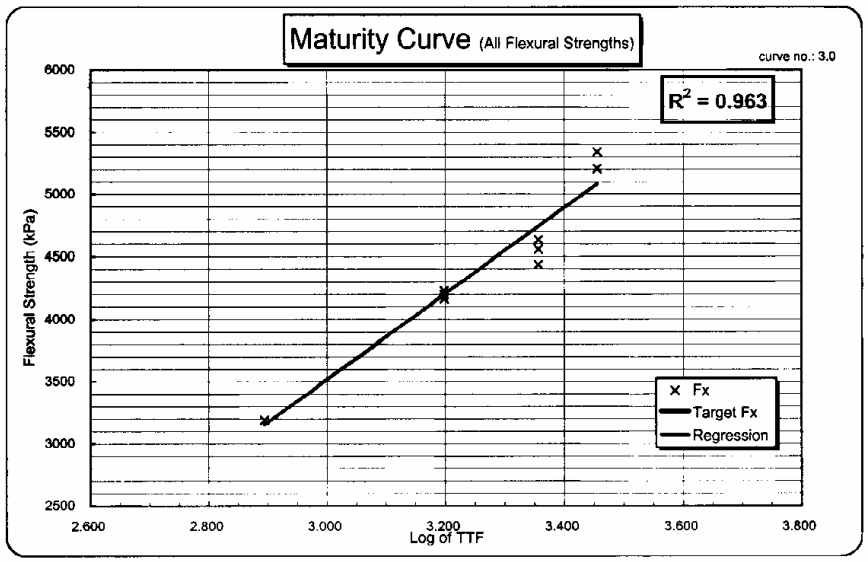
Beam Monitoring

Equipment Used:	Maturity meter
Starting Temperature:	20 ° C

Maturity Criteria for Opening Slab to Traffic

(Equivelant to 3792kPa flexural beam strength)

TTF (C°-hrs)	1,203
Log of TTF	3.080



Mix No.: 54648

Mix Ingredients

Material	Type	Manufacturer / Plant
Cement	Type 1	Gray Bros. Industries
Fly Ash	Type C	Just Ash
Coarse Agg.	#8 Stone	Stone World / (3rd St. Plant)
Fine Agg.	#23 Sand	Just In Time Sand Co. / (Red River)

Admixture	Type	Source	Dosage
Water Reducer	SLS 5500	XL Chemical	14.00 mL/m³
A. E. Agent	SOP2500	XL Chemical	14.00 mL/m³

Comments:

Signature

Contractor Representative

ITM 402-99T

Indiana Department of Transportation

Attachment III

MATURITY TESTING - CURVE VALIDATION

Contractor: ABC CONSTRUCTION CO.

Curve No.: 3

Project No.: R-99999

Date: 05/10/99

Description: I-999 RECONSTRUCTION

Time: 8:09 AM

Beam Number	Actual Load * (N)	Depth (mm)	Width (mm)	Flexural Coefficient	Flexural Strength (kPa)	Age at Break (hrs.)	Temperature-Time Factor: Channel 1 (C°-hrs)	Temperature-Time Factor: Channel 2 (C°-hrs)	Temperature-Time Factor: Average TTF (C°-hrs)
1	30,210	152	152	0.1301	3,931	36	1,275	1,275	1,275
2	30,200	152	152	0.1301	3,930	36	1,275	1,275	1,275
3	30,100	152	152	0.1301	3,917	36	1,275	1,275	1,275
				Average	3,926 kPa			Average	1275
								Log	3.106

Plastic Test Results

Test No: P71

Air Content: 6.0%

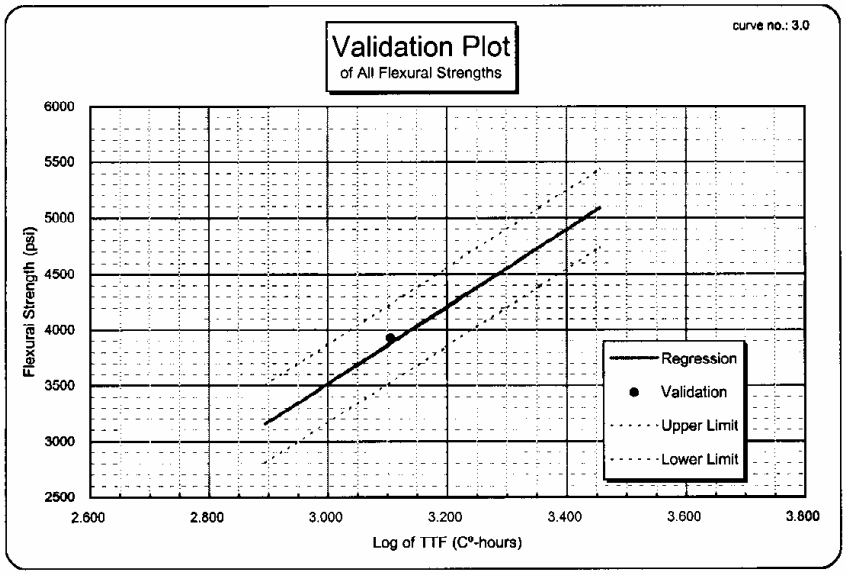
Slump: 2 in.

W/C Ratio: 0.396

Beam Monitoring

Equipment Used: Digital thermometer

Starting Temperature: 22 ° C



Summary			
Predicted Beam Break*	Actual Beam Breaks (average)	Difference from Target	Result
Lower Limit 3,529 kPa Target 3,879 kPa Upper Limit 4,229 kPa	3,926 kPa	47 kPa above	Within Acceptable Range

* Predicted beam break results were obtained by plotting the validation TTF on the mix maturity curve (above). Upper and lower limits are as specified for the test method.

Comments:

Signature

Contractor Representative

APPENDIX B – TMCA / TMCB TEMPERATURE DATA SETS

Appendix B – TMCA / TMCB Temperature Data Sets

Table B3.1 Temperature Match Cure Data from Field Study Trial T1

Time (Hours)	Temperature (°C)
0.00	19.75
4.00	22.50
8.00	25.47
12.00	25.24
16.00	24.05
20.00	21.97
24.00	21.32
28.00	20.51
32.00	16.98
36.00	14.41
40.00	12.33
44.00	11.64
48.00	16.67
52.00	18.17
56.00	14.81
60.00	12.37
64.00	10.63
68.00	9.88
72.00	16.12
76.00	20.90

Table B3.2 Temperature Match Cure Data from Field Study Trial T2

Time (Hours)	Temperature (°C)
0.00	12.07
3.67	10.98
7.33	10.93
11.00	11.71
14.67	12.46
18.33	12.63
22.00	12.76
25.67	13.78
29.33	13.82
32.00	12.98
35.67	11.97
39.33	11.07
43.00	10.29
46.67	10.54
50.33	10.82
54.00	10.65
57.67	10.43
61.33	10.15
65.00	10.02

APPENDIX C – DATA FOR FIGURES

Appendix C – Data for Figures

Table C4.1 Data for Figure 4.1

	MOR1	MOR2	MOR3	Average MOR	SD	CV
T1	(psi)	(psi)	(psi)	(psi)	(psi)	(%)
Air Cured	455	495	435	445	15	3.4
Sandpit Cured	590	640	640	625	30	4.8
Lime Bath Cured	650	620	730	635	20	3.1
T2						
Air Cured	420	400	420	415	10	2.4
Sandpit Cured	500	505	485	495	10	2.1
Lime Bath Cured	520	590	505	515	10	1.9
T3						
Air Cured	495	515	n/a	505	15	3.0
Sandpit Cured	665	700	n/a	685	25	3.6
Lime Bath Cured	485	695	n/a	695	n/a	n/a
T4						
TMCB Cured	600	680	n/a	600	n/a	n/a
Sandpit Cured	660	675	n/a	670	10	1.5
Lime Bath Cured	665	520	n/a	665	n/a	n/a

Outliers not included in calculations

Table C4.2 Data for Figure 4.2

Day	MOR1	MOR2	Average MOR	SD	CV
	(psi)	(psi)	(psi)	(psi)	
1	420	440	430	15	3.5
2	575	590	585	10	1.7
3	610	555	610	n/a	n/a
4	750	745	750	5	0.7
5	785	730	760	40	5.3

Outliers not included in calculations

Table C4.3 Data for Figure 4.3

T1 Data	MOR1	MOR2	Average MOR	SD	CV
	(psi)	(psi)	(psi)	(psi)	
Evaluation 1	570	550	560	15	2.7
Evaluation 2	490	520	505	20	4.0
Evaluation 3	605	560	585	30	5.1
All T1 Evaluations			550	40	7.3
T2 Data					
Evaluation 1	535	515	525	15	2.9
Evaluation 2	580	585	585	5	0.9
Evaluation 3	495	530	515	25	4.8
All T2 Evaluations			540	35	6.5
All Evaluations			545	35	6.4

Table C4.4 Data for Figure 4.4

	f'c1	f'c2	f'c3	Average f'c	SD	CV
T1	(psi)	(psi)	(psi)	(psi)	(psi)	(%)
Air Cured	3940	4180	4260	4220	60	1.42
Sandpit Cured	4060	3980	3900	3980	80	2.01
Lime Bath Cured	4460	4500	4890	4480	30	0.67
T2						
Air Cured	2770	3060	2960	3010	70	2.33
Sandpit Cured	2920	3020	2720	2890	70	2.42
Lime Bath Cured	3440	3500	3620	3520	90	2.56
T3						
Air Cured	4890	5120	4870	5010	160	3.19
Sandpit Cured	4750	4810	4850	4800	40	0.83
Lime Bath Cured	5110	5320	5140	5190	110	2.12

Outliers not included in calculations

Table C4.5 Data for Figure 4.5

Day	f'c1	f'c2	Average f'c	SD	CV
	(psi)	(psi)	(psi)	(psi)	
1	2270	2310	2290	30	1.31
2	4620	4300	4300	n/a	n/a
3	5810	5290	5290	n/a	n/a
4	5410	5970	5410	n/a	n/a
5	5450	5530	5490	55	1.00

Outliers not included in calculations

Table C4.6 Data for Figure 4.6

T1 Data	f'c1	f'c2	f'c3	f'c4	Average f'c	SD	CV
	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	
Evaluation 1	5090	4660	4620	4770	4685	80	1.71
Evaluation 2	4930	4810	4890	4620	4875	60	1.23
Evaluation 3	4890	5010	4890	4930	4930	60	1.22
All T1 Evaluations					4840	120	2.48
T2 Data							
Evaluation 1	3660	3780	3980	3780	3740	70	1.87
Evaluation 2	3460	3420	3540	3460	3470	50	1.45
Evaluation 3	3100	2980	2980	3060	3030	60	1.98
All T2 Evaluations					3380	310	9.17
All Evaluations					4080	780	19.12

Outliers not included in calculations

APPENDIX D – MATURITY CURVES

Appendix D – Maturity Curves

Maturity Curve MC-1

MATURITY TESTING - CURVE DEVELOPMENT

Contractor: Berns Construction Co.

Curve No.: 3
Date: 10/13/98
Time: 9:00 a

Project No.: 9801
Description: R-23197
I-70 Rest Park Hancock County.

Beam Number	Actual Load * (lbs.)	Depth (in.)	Width (in.)	Flexural Coefficient	Flexural Strength (psi)	Age at Break (hrs.)	Temperature-Time Factor: Channel 1 (C°-hrs)	Temperature-Time Factor: Channel 2 (C°-hrs)	Temperature-Time Factor: Average TTF (C°-hrs)
1	5,700	6	6	0.0833	475	24	733	751	742
2	5,600	6	6	0.0833	467	24	733	751	742
3	5,400	6	5 15/16	0.0842	455	24	733	751	742
4	5,600	6	6	0.0833	467	24	733	751	742
5	6,700	6	6	0.0833	558	48	1,270	1,289	1,280
6	7,200	6	6	0.0833	600	48	1,270	1,289	1,280
7	6,800	6	6	0.0833	567	48	1,270	1,289	1,280
8	6,100	5 7/8	5 15/16	0.0878	536	48	1,270	1,289	1,280
9	7,000	6	6	0.0833	583	72	1,827	1,848	1,838
10	7,300	6	5 15/16	0.0842	615	72	1,827	1,848	1,838
11	7,100	6	6	0.0833	592	72	1,827	1,848	1,838
12	7,000	6	6	0.0833	583	72	1,827	1,848	1,838
13	7,500	6	6	0.0833	625	96	2,476	2,501	2,489
14	7,900	6	6	0.0833	658	96	2,476	2,501	2,489
15	8,600	6 1/16	6	0.0816	718	96	2,476	2,501	2,489
16	8,100	6	6	0.0833	675	96	2,476	2,501	2,489

Plastic Test Results

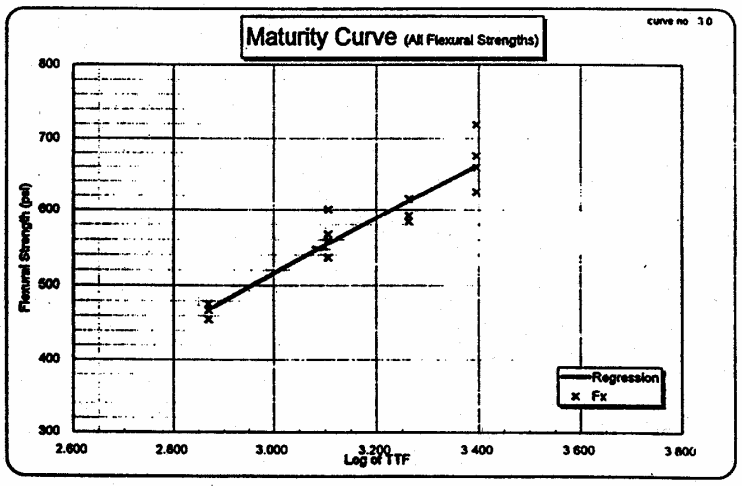
Test No: P68
Air Content: 6.9%
Slump: 2 in.
W/C Ratio:

Beam Monitoring

Equipment Used: Maturity meter
Starting Temperature: 18 ° C

Maturity Criteria for Opening Slab to Traffic
(Equivalent to 550psi flexural beam strength)

TTF (C°-hrs) 1,247
Log of TTF 3.096



Mix No.: 512

Mix Ingredients

Material	Type	Manufacturer / Plant
Cement	Type 1	Lonestar
Fly Ash	-	-
Coarse Agg.	#6 Stone	Stony Creek
Fine Agg.	#23 Sand	Connersville

Admixture	Type	Source	Dosage
Water Reducer	WRDA 82	W.R. Grace	15 00 oz/cy
A. E. Agent	Daravair 1400	W.R. Grace	2.10 2.86 oz/cy

Comments:

Signature

Contractor Representative

Maturity Curve MC-2

ITM 402-98T

Indiana Department of Transportation

MATURITY TESTING - CURVE DEVELOPMENT

Contractor: E & B Paving, Inc.

Contract No.: R-23892

Curve No.: 1

Date: 08/25/99

Time: 11:00 AM

Location: SR 231, Lafayette (40990081)

Beam Number	Actual Load * (N)	Depth (mm)	Width (mm)	Flexural Coefficient	Flexural Strength (kPa)	Age at Break (hrs.)	Temperature-Time Factor		
							Channel 1 (C°-hrs)	Channel 2 (C°-hrs)	Average TTF (C°-hrs)
1	27,590	152	152	0.1301	3,590	24	862	845	854
2	29,370	152	152	0.1301	3,822	24	862	845	854
3	28,925	152	152	0.1301	3,764	24	862	845	854
4	32,930	152	152	0.1301	4,285	36	1,235	1,210	1,223
5	32,930	152	152	0.1301	4,285	36	1,235	1,210	1,223
6	31,150	152	152	0.1301	4,054	36	1,235	1,210	1,223
7	36,045	152	152	0.1301	4,691	48	1,622	1,597	1,610
8	36,490	152	152	0.1301	4,749	48	1,622	1,597	1,610
9	38,270	152	152	0.1301	4,980	48	1,622	1,597	1,610
10	40,050	152	152	0.1301	5,212	60	2,025	1,994	2,010
11	38,715	152	152	0.1301	5,038	60	2,025	1,994	2,010
12	39,160	152	152	0.1301	5,096	60	2,025	1,994	2,010

Plastic Test Results

Test No:	1.0
Air Content:	5.6%
Slump:	50 mm
W/C Ratio:	0.410

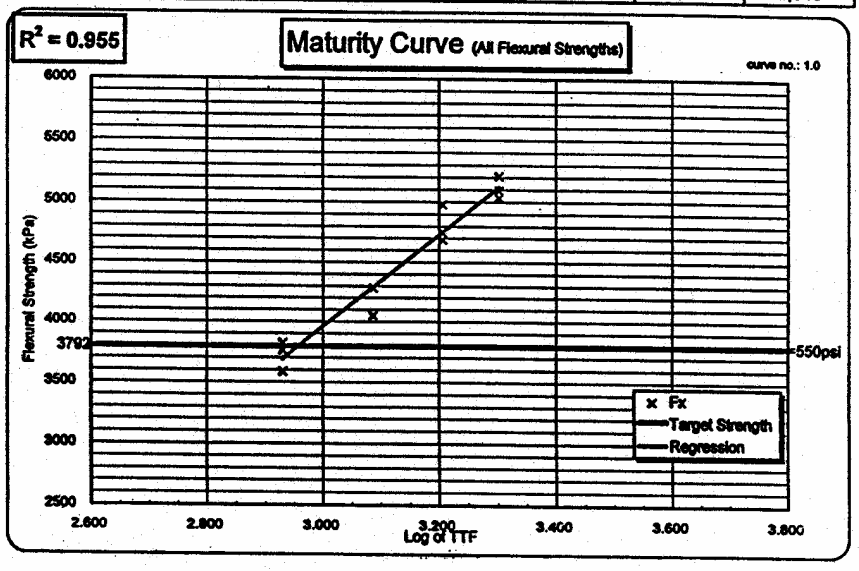
Beam Monitoring

Equipment Used:	Maturity meter
Starting Temperature:	22 ° C

Maturity Criteria for Opening Slab to Traffic

(Equivalent to 3792kPa flexural beam strength)

TTF (C°-hrs)	906
Log of TTF	2.957



Mix No.: Class A - Fly

Mix Ingredients

Material	Type	Manufacturer / Plant
Cement	Type 1	Lonestar, Greencastle, IN
Fly Ash	Class C	Mineral Solutions, Will County
Coarse Agg.	AP 8	Vulcan Materials, Monon, IN
Fine Agg.	#23 Natural	Vulcan Materials, West Lafayette

Admixture	Type	Source	Dosage
Water Reducer	WRDA 82	W. R. Grace	4 oz
A. E. Agent	Daravair 1400	W. R. Grace	3 oz

Comments:

Signature

Contractor Representative

Maturity Curve MC-3

ITM 402-98T

Indiana Department of Transportation

MATURITY TESTING - CURVE DEVELOPMENT

Contractor: Berns Construction Co.

Curve No.: 1

Contract No.: R-25152

Date: 04/25/01

Location: I465 & I74

Time: 9:00 AM

Beam Number	Actual Load * (N)	Depth (mm)	Width (mm)	Flexural Coefficient	Flexural Strength (kPa)	Age at Break (hrs.)	Temperature-Time Factor		
							Channel 1 (C°-hrs)	Channel 2 (C°-hrs)	Average TTF (C°-hrs)
1	24,000	152	152	0.1301	3,123	24	839	816	828
2	24,910	152	152	0.1301	3,242	24	839	816	828
3	25,350	152	153	0.1293	3,277	24	839	816	828
4	26,700	150	152	0.1336	3,568	36	1,207	1,178	1,193
5	26,250	150	150	0.1354	3,554	36	1,207	1,178	1,193
6	26,700	150	150	0.1354	3,615	36	1,207	1,178	1,193
7	28,900	150	150	0.1354	3,913	48	1,567	1,538	1,553
8	29,400	152	152	0.1301	3,826	48	1,567	1,538	1,553
9	28,500	150	152	0.1336	3,808	48	1,567	1,538	1,553
10	30,700	150	152	0.1336	4,102	60	1,938	1,911	1,925
11	32,000	152	152	0.1301	4,164	60	1,938	1,911	1,925
12	29,400	150	150	0.1354	3,981	60	1,938	1,911	1,925

Plastic Test Results

Test No:	148.0
Air Content:	7.0%
Slump:	51 mm
W/C Ratio:	0.425

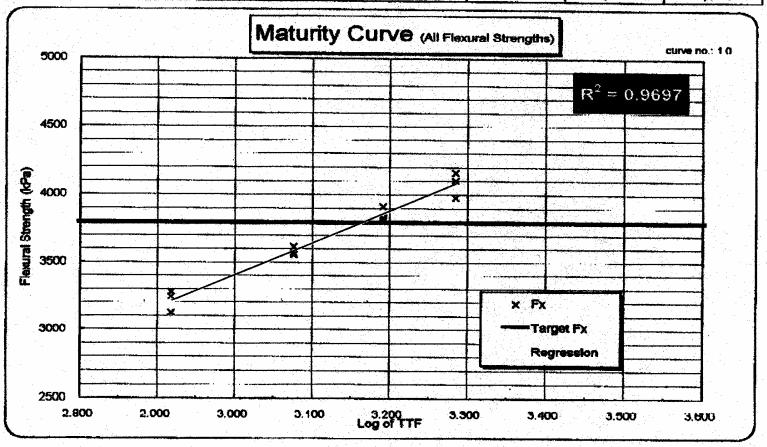
Beam Monitoring

Equipment Used:	Digital thermometer
Starting Temperature:	18 ° C

Maturity Criteria for Opening Slab to Traffic

(Equivelant to 3792kPa flexural beam strength)

TTF (C°-hrs)	1,460
Log of TTF	3.164



Mix No.: 001

Mix Ingredients

Material	Type	Manufacturer / Plant
Cement	Type 1	LoneStar, (Greencastle, IN)
Fly Ash	Type C	Mineral Solutions (Rockport, IN)
Coarse Agg.	#8Stone	Marting Marietta (Indy, Kentuck Ave.)
Fine Agg.	#23 Sand	Martin Marietta (Belmont Plant)

Admixture	Type	Source	Dosage
Water Reducer	WRDA 82	WR Grace	188.00 mL/m³
A. E. Agent	Darvair 1400	WR Grace	35.00 mL/m³

Comments: Cement 264.022/Flyash41.529

Signature

Contractor Representative

Page 1 of 1