Utilization of Maturity Meters for Concrete Quality Assurance

Final Report

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METRIC CONVERSION TABLE

Symbol	When you know	Multiply by	To find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
Volume				
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
Temperature (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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16. Abstract

The maturity method is a non-destructive technique used to estimate in-place strength of concrete. The technique is relatively new and no good knowledgebase is available in most organizations about its field implementation. Florida Department of Transportation (FDOT) is currently considering to incorporate suitable specifications for using the maturity method as a quality assurance (QA) tool. The intent is to minimize complete dependence on conventional cylinder-testing procedure. The objective of this research was to investigate the effects on *concrete maturity index* and *strength* due to *type* and *location* of maturity sensors, and on developing specific guidelines for QA. The experimental data were collected from an under-construction bridge on I-95 in West Palm Beach, Florida. Two types of maturity sensors, *sacrificial* (in which data logger and sensor are encapsulated) and *non-sacrificial* (sensor and data logger are separate) were investigated. The maturity sensors were placed near the top, middle and bottom portions of drilled shafts and columns. The maturity method was found to be a reliable strength measuring technique. Results indicated that both sensor types were comparable in accuracy and the selection should depend on their cost and field conditions. Bottom sensors in drilled shafts and top sensors in columns gave lower (or conservative) values of in-place strength than the sensors at other locations. A set of concrete QA guidelines is proposed in the report for possible implementation by the FDOT.

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EXECUTIVE SUMMARY

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The objective of this research was to investigate the effects on *concrete maturity index* and *strength* due to *type* and *location* of maturity sensors, and on developing specific guidelines for QA. The experimental data were collected from an under-construction bridge on I-95 in West Palm Beach, Florida (I-95 mobility project). Two types of maturity sensors, *sacrificial* (in which data logger and sensor are encapsulated) and *non-sacrificial* (sensor and data logger are separate) were investigated. The maturity sensors were placed near the top, middle and bottom portions of drilled shafts and columns.

The maturity method was found to be a reliable strength measuring technique. Results indicated that both sensor types were comparable in accuracy and the selection should depend on their cost and field conditions. Bottom sensors in drilled shafts and top sensors in columns gave lower (or conservative) values of in-place strength than the sensors at other locations. A set of concrete QA guidelines is proposed in the report for possible implementation by the FDOT.

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Chapter 1

INTRODUCTION

1.1 Background

Determination of in-place strength of concrete is an important measure for the quality assurance of concrete structures. This information is often used to determine the schedule for subsequent construction activities, opening of structure for traffic or occupancy, and evaluation of contractual specifications and construction claims. Typically, cylinder and occasionally beam specimens cast from the same batch of concrete as that used in the construction project, and cured under standard conditions are tested for in-situ strength (Goodrum et al., 2004).

Concrete strength development is controlled by the degree of hydration which in turn depends on time and temperature of hydration. As a result, the strength development in a structure is not uniform due to differences in internal thermal gradients. Because of the differences in placement conditions and the thermal history of test specimens and actual structure, results derived from test specimens may not accurately reflect the actual concrete strength in the structure (Tikalsky et al., 2003). In addition, there may be differences in the hygral (moisture) history between the fabricated specimens and the actual structure.

The *maturity method* is a non-destructive technique for estimating concrete strength in real-time at critical locations within the structure based on the thermal history of concrete at that location. It allows measuring in-place concrete strength and hence construction critical decisions (such as when to remove forms/shores, when to apply post-tensioning, when to expose concrete pavement to live loads, or when to terminate cold-weather protection, etc.) can be made based on the actual strength of the structure. This accurate and quick estimation of strength results in accelerated construction and considerable cost savings (Goodrum et al., 2004).

The basic premises of the maturity method are: (1) concrete derives strength from the hydration of cement; (2) the hydration of cement produces heat; and (3) if the amount of heat can be measured, then an estimation of the extent of the hydration reaction can be made, and from that, the strength of the concrete can be predicted (Luke et al., 2002). Although the maturity concept has been in existence for over fifty years, technology to implement it accurately and economically has become widely available only in the last two decades (Crawford, 2000). Both ASTM (C1074-04) and AASHTO (T325-04) have developed applicable standards for the test method (ASTM C1074, 2004; AASHTO T325, 2004).

By testing concrete with the maturity method, the numbers of required quality control specimens can be drastically reduced. Quality control is also improved because the strength estimates are based on data from the structure instead of laboratory-cured specimens. In addition, data could be obtained continuously from the time concrete is poured to approximately 90 days; hence the strength development in pozzolanic concretes (in which the hydration reaction continues for a longer duration than the normal non-blended concrete) can be studied more accurately (Crawford, 2000). The method is extremely beneficial for fast track projects where small windows for quality control are available. Testing errors associated with improper specimen handling are also reduced (Myers, 2004).

The research presented in this report was conducted to develop a protocol for incorporating the maturity method in concrete quality assurance (QA) program of Florida Department of Transportation (FDOT). The rationale is to replace part of conventional cylinders testing procedure with maturity technique to expedite construction and achieve cost savings.

1.2 Problem Statement and Research Significance

The current FDOT specification 346-9 requires contractors to prepare three “Quality Control (QC) cylinders” for each concrete LOT (50 yd^3, or one day production, whichever is less). In addition, FDOT prepares three “Verification cylinders” and two “Hold cylinders” (to be used if the strength difference between QC and Verification cylinders is more than 750 psi) from one of every four consecutive LOTS of each mix design. This current QA practice results in a large number of cylinders to be cast, cured and tested. There is a need to develop suitable specifications to minimize the number of cylinders by replacing a part of cylinders testing with maturity method.

Moreover, FDOT specification 353-10.1 requires that the concrete pavement slabs should be kept closed to the traffic until the compressive strength of 2200 psi is reached. The strength should be verified either by cylinder test results as specified in 353-5 or by the maturity method as described in 353-10.2. The specification 353-10.2 requires contractors to develop standard strength-maturity relationship charts for the project-specific concrete mixtures according to ASTM C1074 standard practice. The charts are to be verified by the Engineer on the first day of production of concrete or on subsequent days as desired by the Engineer. These strength-maturity relationships charts are valid for those particular concrete mix designs only. Besides, the procedure described in ASTM C1074 standard is quite general and selection of certain parameters (such as the proper maturity index function, datum temperature, and supplemental strength prediction method) depends on the local specifications, test conditions and discretion of the Engineer. Therefore, the FDOT sponsored this study to develop specific procedure in order to supplement the existing ASTM C1074 standard.

If the option of using the maturity method is left to the contractors they will most likely not use it as is evident from the Florida experience. This research study is an attempt to develop a standard protocol for the incorporation of the maturity method for concrete QA/QC which is easier to follow by the contractors and the FDOT personnel.

1.3 Scope and Objectives

This research project has four main objectives:

1. Comparison of different types of maturity equipment, in particular maturity sensors, and development of clear guidelines regarding their selection criteria.
2. Development of standard strength-maturity relationship charts for selected concrete mixtures commonly used by the FDOT.
3. Investigation of suitable location(s) for installation of maturity sensors in different types of structural elements (i.e. drilled shafts, columns and bridge decks/slabs).
4. Development of a Quality Assurance (QA) protocol for implementing the maturity method in the existing FDOT specifications.

Two broad types of maturity sensors were considered in this investigation that can be termed as *Sacrificial* and *Non-sacrificial* (abbreviated as S-type and NS-type respectively for the purpose of this report). The S-type sensors encapsulate a thermistor, and a data logger in a closed canister. The data is recorded on a memory chip which operates with an internal battery. These sensors cannot be removed from the structure after the placement of concrete and hence called sacrificial sensors. The NS-type sensors consist of a thermocouple wire which is placed inside the structure at a specific location and connected with the maturity meter which stays outside the structure. The maturity meter serves as a data logger as well as a reader. In this research, the *IntelliRock*™ system is selected to study S-type sensors while *Humboldt*™ system is used to investigate NS-type sensors.

The experimental data were collected from a 6-lane highway concrete bridge which is currently under construction on I-95 near the Lake Worth exit, in West Palm Beach, Florida. This project is also called as "I-95 Mobility Project". To achieve objectives 1, 2 and 4, it was required to test one type of structural element (drilled shaft, or column, or bridge deck) to verify the strength-maturity calibration curves in the field. To fulfill the objective 3, the scope of experimental investigation in the field need to be extended. It was decided to test three drilled shafts, three columns, and three bridge decks to find the suitable location of maturity sensors in these elements. Due to a number of hurricanes in 2004 and 2005, the project is substantially delayed which restricted the experimental investigations to drilled shafts and columns only (The deck construction at the project site is expected to start in December 2005. Due to the limited time available, it is not possible to include the results of bridge decks in this report). A number of DOTs and other organizations have already established guidelines for the placement of maturity sensors in the bridge decks (Myers, 2000; Luke et al., 2002; Goodrum et al., 2004). It is suggested to consider these guidelines to determine the suitable location of maturity sensors in bridge decks or slabs.

Initially, data were collected from three drilled shafts and three columns. However, it was found that the data from one column are inconsistent either due to the displacement of maturity sensors during concrete placement or short circuiting of wires connecting maturity sensors with the maturity meters. The data collected from the other two columns were very consistent hence it was decided to discard the faulty data of one column. The findings shown in this report are now based on the data collected from three drilled shafts and two columns. These data are very consistent and can be used with full confidence to drive any conclusions.

1.4 Organization of the Report

This report is organized as follows: it begins with an introduction of the maturity method, a statement of the research problem, objectives, scope, and significance of the research (Chapter 1). In Chapter 2, a brief literature review on the maturity method concept, its advantages and limitations, and its extent of use in other state DOTs is presented. Next, in Chapter 3, the methodology and protocol used to carry out the investigations are described. Results and analysis of findings are discussed in Chapter 4. Further discussions, conclusions and recommendations made on the basis of the experimental findings are included in the last chapter (Chapter 5). The detailed experimental data is available in the appendixes.

Chapter 2

LITERATURE REVIEW

2.1 The Maturity Concept

The concept of maturity was evolved in 1950's when several researchers from England conducted studies about accelerated curing of concrete (Carino and Lew, 2001). There was a need for a procedure to account for the combined effects of time and temperature on strength development for different elevated temperature curing methods. These ideas led to the famous *Nurse-Saul maturity function* shown below (Nurse, 1949):

$$M = \sum_{0}^{t} (T - T_o)\Delta t \qquad (2.1)$$

Where:

M = Maturity index, (°C-hours) commonly known as *Temperature-Time Factor (TTF)*

T = Average concrete temperature, °C during the time interval Δt

T_o = Datum temperature

t = Elapsed time (hours or days)

Δt = Time interval (hours or days)

A key variable in equation 2.1 is the datum temperature (T_o). Approximate values for the datum temperature are provided in ASTM C1074. However, the datum temperature is affected by parameters such as cement fineness, particle size distribution, water-to-cement ratio, cement composition, admixtures, and initial temperature. Consequently, the accuracy of the strength estimation can be improved by measuring the exact datum temperature for the concrete mixture (Goodrum et al., 2004). ASTM C1074 specifies the procedure for measuring the datum temperature. The issue of datum temperature is elaborated in section 2.4 of this chapter.

The Nurse-Saul function is based on the assumption that the initial rate of strength gain is a linear function of temperature. Later, it was realized that this linear approximation might not be valid when curing temperatures vary over a wide range (Carino and Lew, 2001). In 1977, Freiesleben and Pedersen introduced an *Equivalent Age maturity function,* which assumes that the rate of strength development increases exponentially with time (Freiesleben and Pedersen, 1977). Their proposed equation for calculating the equivalent age is shown below:

$$t_e = \sum \left[e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \right] \Delta t \qquad (2.2)$$

where:

t_e = Equivalent Age (EqA)at a specified temperature T_s (hours or days)

Q = Apparent activation energy constant

T_a = Average temperature of the concrete during time interval Δt

T_s = Specified temperature

Δt = Time interval in hours or days.

The ASTM C1074 recommends both maturity functions and specifies procedures for calculating the datum temperature and activation energy constant. Research has shown that the Equivalent Age function accounts for temperature more accurately over a wide temperature range than the Temperature-Time Factor (Tikalsky et al., 2003). However, the Temperature-Time Factor (TTF) is somewhat easier to understand and apply, and hence used by the majority of DOTs (Luke et al, 2002).

2.2 Limitations of the Maturity Method

The maturity method has some inherent limitations as described by ASTM C1074 and other researchers (Carino and Lew, 2001; Luke et al., 2002). First, it assumes that the concrete is maintained in a condition that permits cement hydration. If there is insufficient water, hydration will cease, and this method will produce erroneous results.

Second, the method does not take into account the effects of early-age concrete temperature on the long-term ultimate strength. It has been shown that the temperature conditions of early days have a significant effect on the ultimate concrete strength (Carino and Lew, 2001). Experiments have shown that the actual concrete strength for a cold weather placement and a hot weather placement would not be same for a given maturity index. Some researchers have proposed correction factors to account the effect of curing temperature on early age strength (Tank and Carino, 1991). These correction factors are based on parameters which can only be determined through extensive testing of concrete; hence their practical use in real-life is very limited.

Finally, the method does not actually test the strength quality, like a Schmidt Hammer test or Windsor Probe test. It needs to be supplemented by other indications of the potential strength of the concrete mixture (Luke et al., 2002).

Hence it is crucial that any practical applications of the maturity method accounts for these limitations.

2.3 The Maturity Method Procedure

The maturity method procedure consists of three fundamental steps which are: (1) Establishment of the appropriate strength-maturity relationship for the specific concrete mixture that will be used in the construction (also called strength-maturity calibration curve); (2) Verification of the strength-maturity relationship; and (3) Measurement of the in-place maturity index and estimation of the in-place strength using the strength-maturity calibration curve. These steps are schematically shown in Figure 2.1.

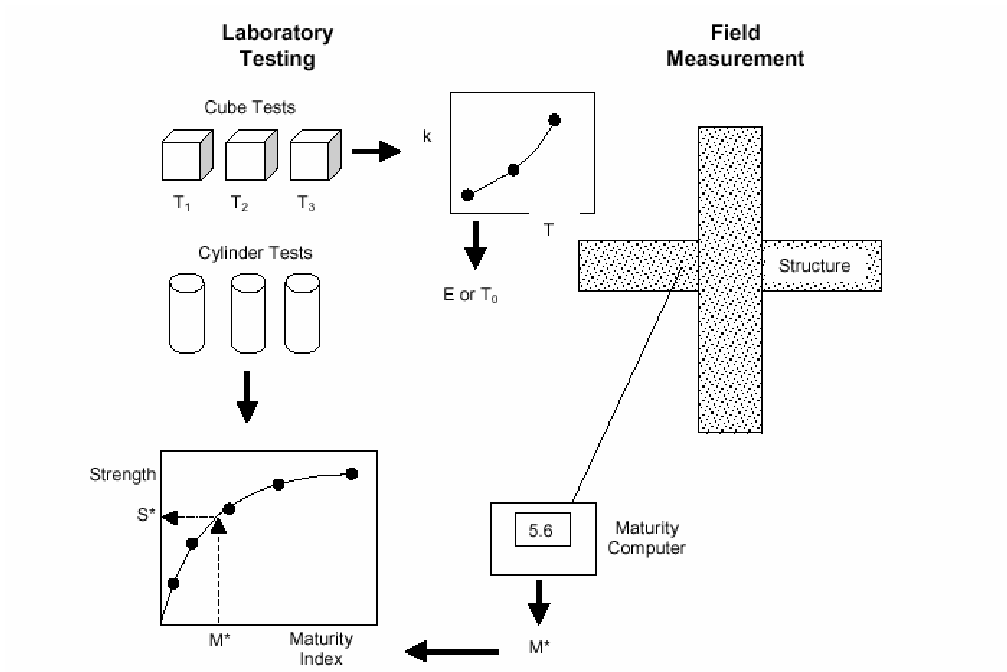


Figure 2.1: Schematic Representation of the Maturity Method (Carino and Lew, 2001)

2.3.1 Establishment of the Strength-Maturity Relationship

To develop the strength-maturity relationship, cylindrical concrete specimens are prepared using the mixture proportions and constituents of the concrete to be used in construction. These specimens are prepared according to the usual procedures for making and curing test specimens in the laboratory. After the cylinders are molded, maturity sensors are embedded at the centers of at least two cylinders. The sensors are connected to instruments that automatically compute maturity or to temperature recording devices.

The specimens are cured in a water bath or in a moist curing room. At ages of 1, 3, 7, 14 and 28 days, compression tests are performed in at least two specimens. At the time of testing, the average maturity value for the instrumented specimens is recorded. If maturity instruments are used, the average of the displayed values is recorded. If temperature recorders are used, the maturity is evaluated according to Eq (2.1) or Eq (2.2). If Eq (2.1) is used, ASTM recommends that the datum temperature be taken as 0°C if ASTM Type I cement is used without admixtures and the expected curing temperature is within 0°C and 40°. For Eq. (2.2), activation energy of 41.5 kJ/mol is recommended. For other conditions or when maximum accuracy is desired, the best value of the datum temperature or activation energy should be determined experimentally according to the procedures specified in the ASTMC1074 standard. A recording time interval of one-half hour or less should be used for the first 48 hours, and longer time intervals are permitted for the remainder of the curing period (Carino and Lew, 2001).

Next, a plot of the average maturity versus the average compressive strength of the test cylinders is prepared. A best-fit curve is then drawn through the data or regression analysis is performed to determine the strength-maturity relationship. One of the popular strength-maturity relationships is the following logarithmic equation proposed by Plowman (1956):

$$f_c = a + b\log(M) \qquad (2.3)$$

where:

a = strength for maturity index

b = slope of line

M = maturity index (°C-h or °F-h)

Equation (2.3) is popular because of its simplicity; it plots a straight line when a log scale is used for the maturity index axis, but it has limitations. It does not provide a good representation of the relationship between strength and maturity index for low or high values of the maturity index. It predicts that strength keeps on increasing with maturity index, that is, there is no limiting strength (Carino and Lew, 2001). Despite its limitations, Eq. (2.3) is used by most of the DOTs due to its simplicity and easy interpretation (Luke et al, 2002).

The ASTM standard assumes that the initial temperature of the concrete in the field is approximately the same as the laboratory temperature when the cylinders are prepared. If the actual early-age temperatures are significantly greater than the laboratory temperatures, the limiting in-place strength is reduced. Thus the in-place strength may be over-estimated by the strength-maturity relationship (Carino and Lew, 2001).

2.3.2 Verification of the Strength-Maturity Relationship

Verification of the strength-maturity relationship is very important to confirm that the predictive equation is applicable to the particular concrete mixture. For verification purposes, another set of concrete cylinders is prepared taking sample from the field concrete (e.g., from a ready-mix concrete truck) and cured under same standard conditions. The maturity sensors are installed in at least one cylinder. At least two cylinders are tested for compressive strengths at 1, 3, 7, 14 and 28 days respectively and the corresponding maturity values are recoded from the cylinder with a maturity sensor. If all the data fit within the permissible range of ±10% of the established strength-maturity curve, the corresponding curve can be used for in-place concrete strength estimation with confidence. If the data range is larger than ±10%, it is recommended to re-establish the curve and again verify it.

Some researchers recommended that the strengths and corresponding maturities from successful verifications should be added to the data set for the strength-maturity relationship to define a more accurate relationship. Refinements should continue until a comfortably significant number of tests are accumulated (Luke et al., 2002).

2.3.3 Estimation of In-place Strength of Concrete

The procedure for estimating the in-place strength requires measuring the in-place maturity. As soon as is practicable after concrete placement, maturity sensors are placed in the fresh concrete. The sensors should be installed at locations in the structure that are critical in terms of exposure conditions and structural requirements. The sensors are connected to maturity meters after concrete placement. When a strength estimate is desired, the maturity index from the maturity meter is recorded. Using the maturity index and the previously established strength-maturity relationship, in-place compressive strengths at the locations of the sensors are estimated.

2.4 Selection of Appropriate Datum Temperature

Theoretically, the datum temperature is the temperature below which hydration of cement ceases. The ASTM C1074 standard specifies "For Type I cement without admixtures and a curing temperature range from 0 to 40°C, the recommended datum temperature is 0°C. For other conditions and when maximum accuracy of strength estimation is desired, the appropriate datum temperature can be determined experimentally according to the procedures in Appendix A1".

Some types of maturity instruments that compute temperature-time factor may not employ the appropriate datum temperature, and therefore may not indicate the true value of the factor. The value of the temperature-time factor displayed by the instrument can be corrected for the datum temperature as follows:

$$M_c = M_d - (T_o - T_d)\, t \qquad (2.4)$$

where:

M_c = the corrected temperature-time factor, degree-days or degree-hours

M_d = the temperature-time factor displayed by the instrument, degree days or degree-h

T_o = the appropriate datum temperature for the concrete, °C

T_d = the datum temperature incorporated in the instrument, °C

t = the elapse time from when the instrument was turned on to when a reading was take, days or h.

The datum temperature is more properly regarded as a parameter reflecting the initial rate of strength gain rather than the temperature below which no strength is gained. Hence some researchers recommended using three different datum temperatures to reflect three general rates of initial strength gain, i.e. *slow*, *normal* and *fast*. According to Lew et al. (2002), a datum temperature of -10°C should be applied to concretes that gain strength slowly, like fly ash concrete or concrete cured under cold conditions. A datum temperature of 0°C should be applied to normal strength-gain concretes. For fast very early strength concrete, a datum temperature of 6.5°C has been shown to give very good results and should be used.

2.5 Survey Results of other DOTs using the Maturity Method

Several published surveys regarding use of the maturity method in the state DOTs are found in the literature review (Lew et al., 2002). The first was a two part survey conducted by Rens (2001) at the University of Colorado in 1998 with a follow-up survey in 2000. The initial 1998 survey, which received an 88% return, found that 57% of the responding states were already utilizing the maturity method. Of those 35% were doing so in strict accordance with ASCT C1074 standard, while 17% had modified the method to their particular uses. Interestingly, only 50% of the respondents were aware of the limitations of the maturity method as discussed in section 2.2 of this report. Continued research was favored by 69% of the respondents, and several commented that they felt the procedures for developing the strength-maturity relationships were not partical.

The follow-up survey by Rens in 2000 sought information about the difficulties and limitations of the method, changes in usage, and suggestions for further study. Forty percent respondents were found to be actively engaged in research, and the same percentage had incorporated the maturity method within the previous two years. It was also found that 77% of the respondents agree that cylinders need to be cured under field conditions for better reflection of in-place strength.

Tikalsky et al. (2001) conducted another survey regarding the use of the maturity method in the state DOTs. Thirty-one agencies took part in the survey. They found that the quality control was the intended use of the method in 8 states, 5 utilized it for structural acceptance, saw cutting was the objective in 2 states, formwork removal in 3 states, and opening of pavement to traffic in 4 states. Twenty-one states are using or researching using the method for highways, 5 for columns, 11 for bridge super structures and 7 for substructures.

Their results also indicated that 29 out of 31 DOTs surveyed are using the Temperature-Time Factor for calculating the maturity index. The reasons behind this selection are its simplicity and good strength predictions. They also found that 21 states are using the method for highways, 5 for columns, 11 for bridge superstructures and 7 for substructures. The performance of the maturity method was rated “excellent” in 5 states, “good” in 14, “fair” in 4, and “poor” in 3 while 5 states did not provide any ratings.

2.6 Summary

The literature suggests that the maturity method is a suitable non-destructive in-place strength measuring technique that can be used as a tool for quality control and quality assurance. DOT representatives throughout the United States have reported that the maturity method is being used to predict critical concrete strengths for actions such as opening the pavement to traffic, timing of joint sawing, structural acceptance, and formwork removal. Due to its simple application using readily available equipment, the use of maturity method is growing in all applications for reducing construction costs and time schedules. The Temperature-Time Factor (TTF) is adopted by most the DOTs for measuring the maturity index. A datum temperature of 0°C is recommended for calculating the TTF unless otherwise specified. The maturity method has certain limitations which should be considered while implementing this method especially in very cold or hot environments.

Chapter 3

METHODOLOGY AND EXPERIMENTAL DESIGN

3.1 Methodology

The methodology adopted in this research is depicted in Figure 3.1. All testing is carried out according to ASTM C1074-04 standard.

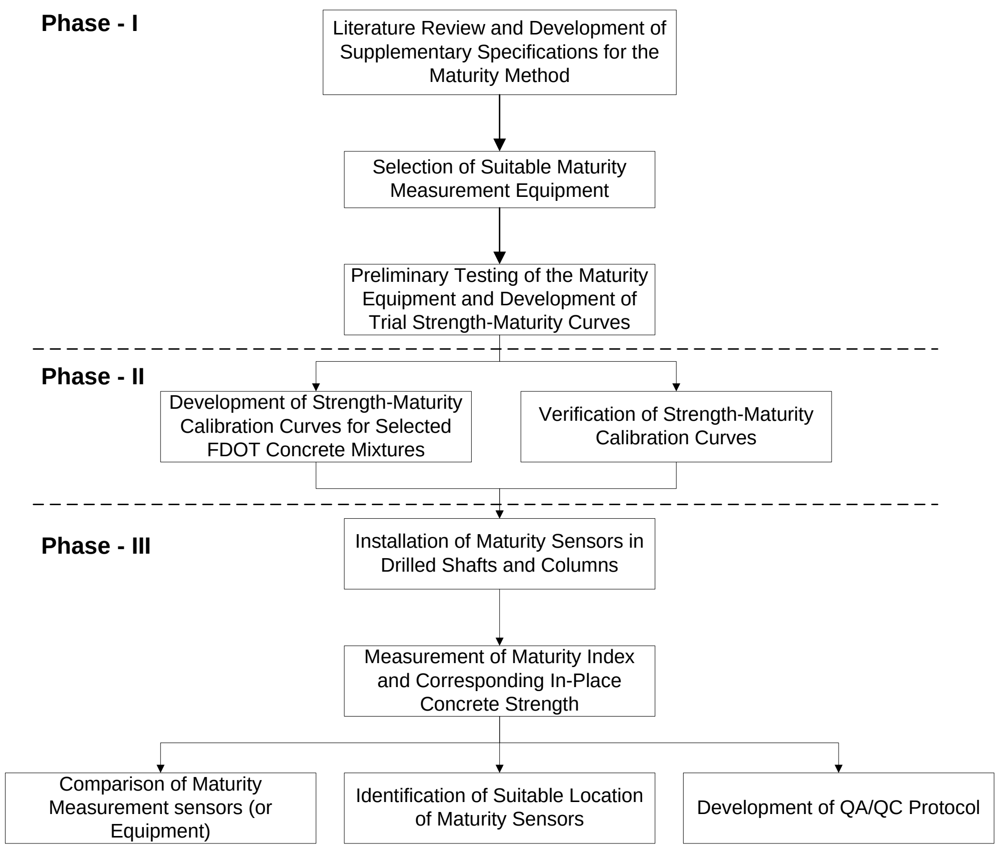


Figure 3.1: An Outline of Methodology adopted in the Research

As shown in Figure 3.1, the research was conducted in three phases. The first phase started in August 2003 and completed in August 2004. The work on the second phase began in January 2005 and finished in February 2005. The last phase was started in March 2005 and completed in October 2005. The different steps of methodology are explained in the following sections along with necessary experimental details.

3.2 Literature Review and Development of Supplementary Specifications for the Maturity Method

An extensive literature search was done to review published and unpublished research papers, reports and articles on the use and applications of the maturity method in the United States and else where. Particular emphasis was placed on the technical reports published by various DOTs. The literature helped to identify the scope and use of the maturity method in different structural applications.

In the light of the reviewed literature, supplementary specifications for the use of the maturity method in the I-95 Mobility Project were prepared. The purpose was to provide explicit details to the I-95 mobility project contractors about the implementation of the maturity method in this project. These specifications are included in Appendix F.

The sensitivity of the maturity method depends on various variables such as the concrete mix design, aggregate type and size, type and location of maturity sensors, amount of retarder in the mixture and curing conditions. Initially, it was decided to incorporate all these variables in the research design. However, after preliminary testing as described in section 3.4, it was realized that some variables are not important and their inclusion will result in extensive experimentation costs as well as time. Hence with the consultation of the research team, it was decided to further consider three variables in the final research design which were concrete mix design, type and location of maturity sensors in the structural elements.

3.3 Selection of Suitable Maturity Equipment

Two types of maturity equipment were used in this research which can be distinguished on the basis of functionality of their maturity-measuring sensors.

3.3.1 The Sacrificial Sensors

The first type of equipment uses *Sacrificial* sensors (abbreviated as S-type for the purpose of this report). The S-type sensors encapsulate a thermistor, and a data logger in a closed canister. The data is recorded on a memory chip which operates with an internal battery. These sensors cannot be removed from the structure after the placement of concrete and hence called sacrificial sensors. The *IntelliRock*™ system developed by Engius LLC was selected to study the S-type sensors and is illustrated in Figure 3.2.

Figure 3.2: The IntelliRock™ Handheld Reader and a Logger

The system consists of three components as follows:

i) A logger: A sacrificial sensor that calculates the maturity index within the structure where it is placed. The logger measures 1.5 inch by 1.5 inch diameter. The battery life of the logger is 3 months with a shelf life of 5 years.

ii) A reader: The reader is used to communicate with and download maturity and temperature data from the loggers. The reader can save up to 200 loggers data.

iii) Software: The *IntelliRock*™ software facilitates the downloading of the estimated maturity index and temperature data from the reader into a computer. The software creates data files in two formats, an Excel format file (.CVS) and a Secure format file (.SEC) as shown in Figure 3.4.

Figure 3.3: Data Transfer Process from the Reader to the Computer in the IntelliRock™ System (Goodrum et al., 2004)

3.3.2 The Non-Sacrificial Sensors

The Non-Sacrificial sensors (hereafter referred to as NS-type sensors) consist of a thermocouple wire which is placed inside the structure at a specific location and connected with the maturity meter which stays outside the structure. The maturity meter serves as a data logger as well as a reader. In this research, *Humboldt*™ system is used to investigate the NS-type sensors as shown in Figure 3.5.

Figure 3.4: The Humboldt™ Maturity Measurement System

The data logger (and the reader) in this system has 4-ports and hence can record data of maximum of 4 maturity sensors at a time. The reader operates with an internal battery. The thermocouple wires get the necessary power from the reader and do not require any additional power source.

3.4 Preliminary Testing and Development of Trial Curves

To become familiarize with the maturity equipment and to select the appropriate maturity function (Temperature-Time or Equivalent Age) for further research, few full scale experiments were conducted at the District Four and Six Materials Office, Davie during May-July 2004. Another purpose of these experiments was to investigate the effects of varying retarder doze on the maturity and compressive strength values.

FDOT Class II mix for bridge decks (mix #04-0703) was used in this set of experimentation. Three concrete mixtures were prepared with a normal retarder doze (8 oz), a reduced retarder doze (6 oz) and an enhanced retarder doze (10 oz). Sixteen cylinders were prepared for each concrete mixture. One cylinder was equipped with both types of maturity sensors. The cylinders were tested for compressive strengths at 1, 3, 7, 14 and 28 days and corresponding maturity values were recorded. Using the maturity and strength data, strength-maturity calibration curves were plotted and the effect of varying retarder dozes on the strength and maturity values was investigated.

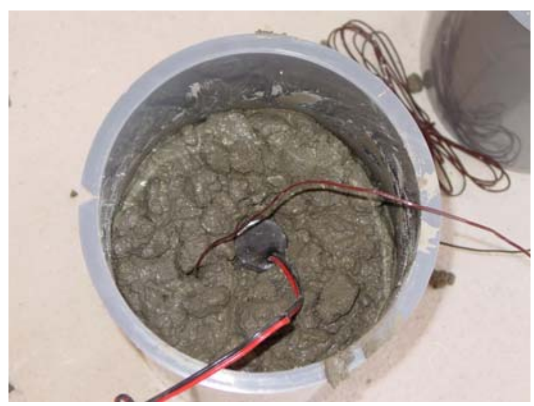



Figure 3.5: Installation of Maturity Sensors in the Trial Test Cylinders

The Temperature-Time Factor (TTF) was selected for calculating the maturity index. The main reasons for selecting the TTF were its simplicity, frequent use by other DOTs and the fact that the ambient temperature variations in Florida are not large and hence the effects of the curing temperature on the early-age strength are limited.

3.5 Development and Verification of the Strength-Maturity Calibration Curves

The strength-maturity calibration curves were prepared for the following concrete mixtures. The experimentation was conducted at the CSR Rinker Concrete Plant, Jupiter city. All the curves were verified by the CSR Rinker concrete plant personnel in the presence of FDOT Concrete Engineers.

1. FDOT mix #04-0803 (Class II Deck)
2. FDOT mix #04-0805 (Class II)
3. FDOT mix #04-0709 (Class IV Drill Shaft)
4. FDOT mix #04-0799 (Class IV)
5. FDOT mix #04-0808 (Class IV Drill Shaft)
6. FDOT mix #04-0857A (Class IV Drill Shaft with Delvo)
7. FDOT mix #04-0857-01A (Class IV Drill Shaft with Delvo)

The following concrete mixtures were selected for the I-95 mobility project: for drilled shafts, FDOT Class IV mix (#04-0857-01A) and for columns FDOT class II mix (#04-0805). The concrete mix design of both mixtures is depicted in Table 3.1.

TABLE 3.1: Concrete Mix Design of Selected Mixtures (per cu. yard)

ID	Mix Proportions	Measured Physical Properties
#04-0857-01A (Class IV)	Cement Type I: 478 lbs (217 kg) Fly ash: 257 lbs (117 kg) Coarse aggregates: 1621 lbs (736 kg) Fine aggregates: 1153 lbs (524 kg) Superplasticizer: 38.0 oz (1124 mL) Total water content: 296 lbs (134.5 kg) Slump range: 7-9 in. (180-230 mm) Design strength: 4000 psi (28 MPa)	Slump: 8.5 inch (216 mm) Air content: 3.6% Temperature: 87°F (30.5°C) Unit weight: 145 PCF (2285 kg/m^3)
#04-0805 (Class II)	Cement Type I: 457 lbs (208 kg) Fly ash: 115 lbs (52 kg) Coarse aggregates: 1716 lbs (780 kg) Fine aggregates: 1315 lbs (597 kg) Superplasticizer: 36.5 oz (1080 mL) Total water content: 257.9 lbs (117 kg) Slump range: 1.5-4.5 in. (40-115 mm) Design strength: 3400 psi (23 Mpa)	Slump: 2.5 inch (64 mm) Air content: 2% Temperature: 88°F (31°C) Unit weight: 140 PCF (2240 kg/m^3)

3.6 Installation of Maturity Sensors in Drilled Shafts and Columns

The experimental data were collected from a 6-lane highway concrete bridge which is currently under construction on I-95 near the Lake Worth exit, in West Palm Beach, Florida. This bridge is a part of the on-going I-95 mobility project. Figure 3.6 depicts different views of this project.

Figure 3.6a: A Longitudinal View of the Project

Figure 3.6b: A Transverse View of the Project

For selecting the most critical locations for the installation of sensors, the thermal gradients in drilled shafts and columns were studied. An earlier FDOT sponsored research indicated that the temperature was the maximum at the center of the structure (drilled shaft or column) and gradually reduces towards the sides (surface) (Ahmad and Azhar, 2004). It meant that the strength at the center would be higher than at the sides. To be on the conservative side, it was decided to install sensors at a distance of 2-4 inches from the formed sides. Along the length, sensors were installed at three critical locations as indicated by the same research. These locations were:

1. 3 ft (0.91 m) from top of the structure (hereafter termed as *top* sensors)
2. middle of the structure (hereafter termed as *middle* sensors)
3. 3 ft (0.91 m) from the bottom of structure (hereafter termed as *bottom* sensors)

Figure 3.7 shows a line diagram depicting the installation of sensors in the drilled shafts. A similar scheme was adopted in the columns. The dimensions of the drilled shaft are 5 ft diameter by 72 ft; and for columns are 3.5 ft diameter by 42 feet. The total number of maturity sensors and the data readers required for each type of structural element are given in the Appendix C.

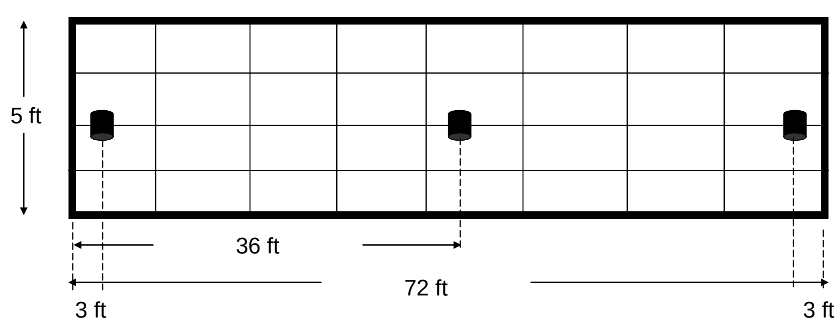


Figure 3.7: A Line Diagram Depicting the Sensors Installation Plan for Drilled Shafts

Both sensors were tied with the reinforcement to avoid displacement during concreting as shown in Figures 3.8a and 38.b. The sensors were not in direct contact with the reinforcing steel or formwork and installed while the reinforcement cages were on the ground. Great care was taken during the lifting of cages and placement of formwork (for columns) to avoid displacement of the sensors. Before the placement of concrete, a dry test was conducted to ensure that all sensors were in working condition.

Figure 3.8a: S-type and NS-type Sensors Tied Together to Measure Maturity at the Same Point

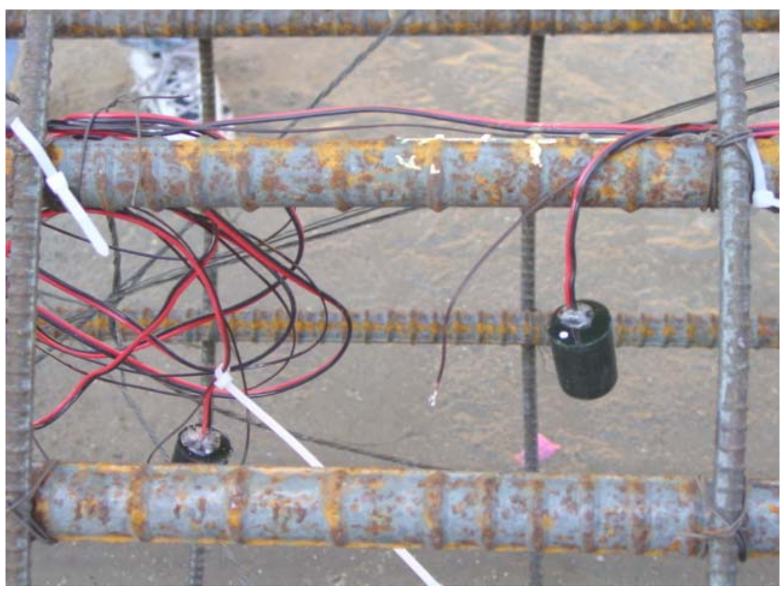


Figure 3.8b: Sensors were tied with the Reinforcement using Plastic Ties to Avoid Displacement during Concreting

Figure 3.8c: Sensors Wires Coming Out from the Scaffolding of a Column

Concrete was placed in drilled shafts and columns using the tremie pipe. Fifteen test cylinders per member were prepared to measure the compressive strength at ages of 1, 3, 7, 14 and 28 days in accordance with the existing FDOT specifications. One additional cylinder per member was also prepared and both types of maturity sensors were installed to collect the maturity data. These maturity data were first used for the re-verification of the strength-maturity calibration curves and then for the refinements of the calibration curves.

Initially, it was decided to cure concrete cylinders both in the field as well as in the laboratory to investigate the effect of curing conditions on the maturity and compressive strength values. However, this idea was dropped due to two reasons:1) It required frequent transportation of cylinders from the field to the laboratory and the contractor had limited man power to help the project team, 2) the ASTM specifications require curing under laboratory conditions only and hence field curing results may not be useful.

3.7 Measurement of the Maturity Index

After placement of concrete, maturity reader was immediately attached with the NS-type sensors to start recording the data. Since the S-type sensors record data on an internal memory chip, the reader can be attached at any time to read or download the data. Both types of maturity readers were set at their default datum temperatures which are 0°C for IntelliRock™ and -10°C for Humboldt™. As shown in the Eq (2.4), it is possible to convert the maturity index values from one datum temperature to another. This was the main reason of using the default datum temperatures so as to find out which datum temperature (0°C or -10°C) gives the most accurate indication of the compressive strength. As shown in chapter 4, at a later stage, maturity index values recorded from both types of maturity meters were converted with reference to a single datum temperature (i.e. 0°C) for comparison.

Figure 3.9: Data Recording from Sacrificial Sensors (IntelliRock™ System)

Figure 3.10: Data Recording from Non-Sacrificial Sensors (Humboldt™ System)

After 28 days of placement of concrete, the complete data were downloaded from both maturity readers and analyzed. The experimental results are illustrated and discussed in the following chapter.

Chapter 4

RESULTS AND DISCUSSION

4.1 Experimental Results

The experimental results of three phases of investigation are reported in this section. A brief discussion is provided along with the results while a more detailed discussion and comparison is made in section 4.2.

4.1.1 Preliminary Testing Results

The preliminary testing was performed on the FDOT Class II mix for bridge decks (mix #04-0703) with varying retarder dozes of 6 oz. (low), 8 oz. (normal) and 10 oz. (high). The physical properties of all the mixtures are shown in Table 4.1.

Table 4.1: Physical Properties of the Concrete Mixtures used in the Preliminary Investigation

Mix #	Date	FDOT Mix #	Retardar doze	Slump	Air	Density	Temp
			(oz)	(inch)	(%)	(PCF)	(F)
1*	18-May	#04-0703	8	1.25	3.25	144.43	84
2	25-May	#04-0703A&B	8	2.75	3.75	144.78	85
3	15-Jun	#04-0703C&D	6	0.5	2.5	144.68	96
4	13-Jul	#04-0703E&F	10	8.5	1.5	144.94	89

*Redone due to low slump

Designed slump with normal retarder doze = 3 inch
Allowable variation = 1 inch (2 -4 inch)

The maturity data were recorded using both types of maturity sensors (i.e. S-type and NS-type) and the corresponding compressive strengths were measured at ages of 1, 3, 7, 14, and 28 days. The results are summarized in the Appendix A.

The results indicate that reducing the retarder doze from standard amount of 8 oz. to 6 oz. did not have any impact on maturity or compressive strength values however it affected the workability of concrete (the slump was reduced from expected value of 3±1 inch to 0.5 inch only). Hence such retarder doze may not be appropriate in the field due to the workability concerns.

Increasing the retarder doze from 8 oz. to 10 oz. significantly reduced the maturity and compressive strength values. The slump was also increased to 8.5 inches, thereby increase the risk of segregation and bleeding. Hence this doze was also found not to be appropriate in the field. Finally it was decided to use the standard retarder doze of 8 oz. in the remaining concrete mixes.

The maturity data recorded from the S-type (IntelliRock™) and NS-type (Humboldt™) sensors are very consistent expect at few points. The discrepancy at these points was probably due to the disturbance of the Humboldt™ meter which was kept unprotected. In the future testing, it was made sure that the Humboldt™ meter is properly protected and remains undisturbed to ensure smooth recording of the maturity data.

Since the main purpose of this phase was to understand the operations of the maturity equipment, hence the results of this phase will not be further discussed.

4.1.2 Development of Strength-Maturity Calibration Curves

The strength-maturity calibration curves for the most commonly used FDOT concrete mixtures were prepared at the CSR Rinker Concrete Plant, Jupiter city. The curves were prepared using the S-type sensors only (the CSR Rinker concrete facility has only this type of equipment). All the curves were developed using a datum temperature of 0°C (as all the concrete mixtures contain Type I cement with no admixtures and were subjected to a curing range between 0°C to 40°C). The maturity index was recorded in term of Temperature-Time Factor (TTF).

The experimental data and the corresponding calibration curves are shown in Appendix B. These calibration curves are not approximated using a logarithmic or the parabolic function. The appropriate function can be selected by the Engineer depending on the curing conditions and the initial rate of strength gain.

All the calibration curves shown in the Appendix B are verified by the CSR Rinker concrete plant personnel in the presence of concrete engineers of the FDOT.

4.1.3 Re-verification of the Strength-Maturity Calibration Curves

The strength-maturity calibration curves of the concrete mixtures used in the drilled shafts (Mix # 04-0857-01A) and columns (Mix # 04-0805) were re-verified in the field. The purpose was to ensure that they are accurate enough to precisely estimate the in-place strength of concrete in these structural elements. Another purpose was to record any slightest modifications in the concrete mix design which could affect the shape of the strength-maturity calibration curves.

The re-verification data were collected from 4 sets of concrete cylinders taken in the field and cured under standard conditions. For each concrete mix (i.e. Class II or Class IV), two sets were prepared on two different days to account for the effects of variations in concrete batches and ambient temperature. Each set further contained 16 cylinders. Fifteen cylinders were tested for compressive strengths at 1, 3, 7, 14 and 28 days while one cylinder was used for maturity data collection using both types of maturity sensors. This practice was adopted to ensure that the calibration curves were accurate enough to give precise estimates of strength.

Figure 4.1 shows the calibration curve and re-verification points for drilled shafts while the Figure 4.2 illustrates the same for the columns. The solid line represents the original strength-maturity calibration curve while the two dotted lines represent the ±10% permissible range specified by ASTM C1074.

These strength-maturity calibration curves are best-fit curves plotted by using the Eq (2.3). This logarithmic trend line function is available in all spreadsheet programs and hence can be easily used. The regression coefficient R^2 must be larger than 0.95 to represent the best fit line. In this case, it is approximately 0.99 and hence represents an excellent fit.

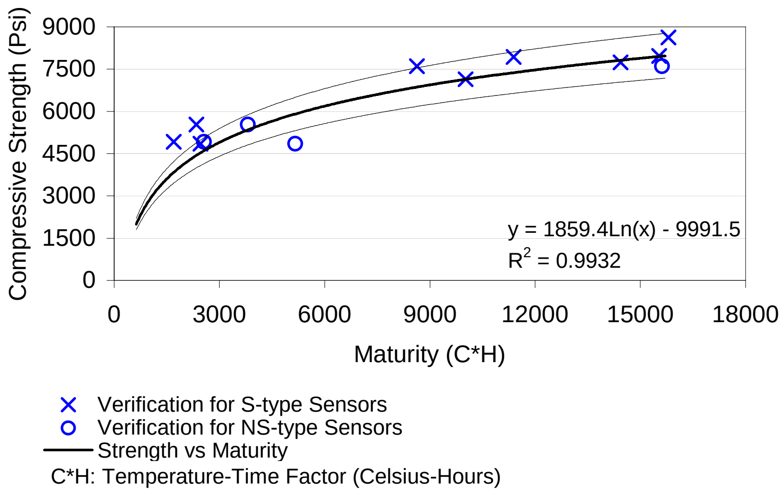


Figure 4.1: Strength-Maturity Calibration and Verification Curve for Drilled Shafts

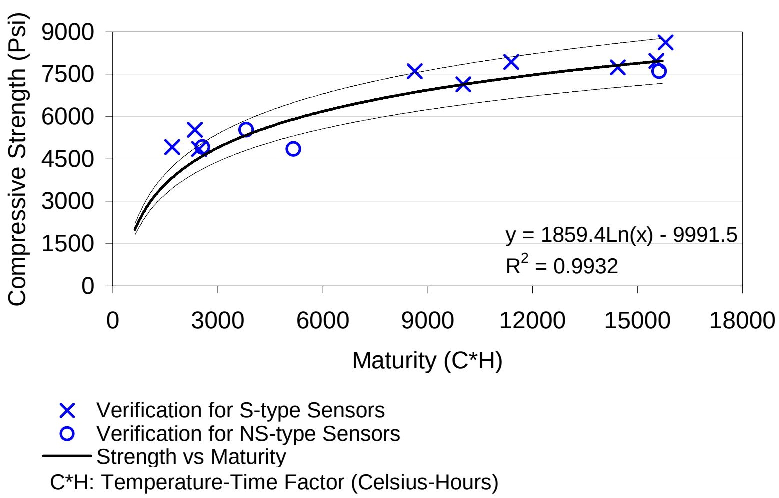


Figure 4.2: Strength-Maturity Calibration and Verification Curve for Columns

A quick look at Figures 4.1 and 4.2 indicates that all data fit within the permissible range of ±10% and hence these curves can be used for in-place concrete strength estimation with confidence.

As explained in the section 2.3.2, the re-verification data was used to further refine the strength-maturity calibration curves. The finally refined strength-maturity calibration curves which are used for the determination of in-place strength of concrete are shown in Figure 4.3.

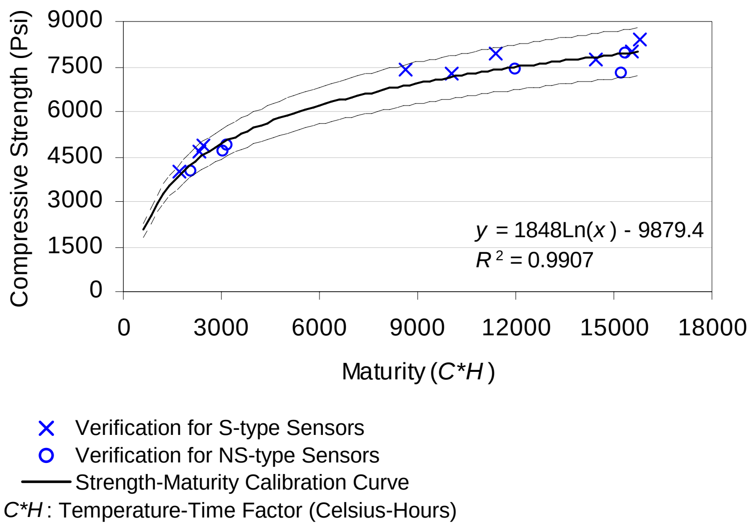


Figure 4.3: Final Strength-Maturity Calibration Curve for Drilled Shafts

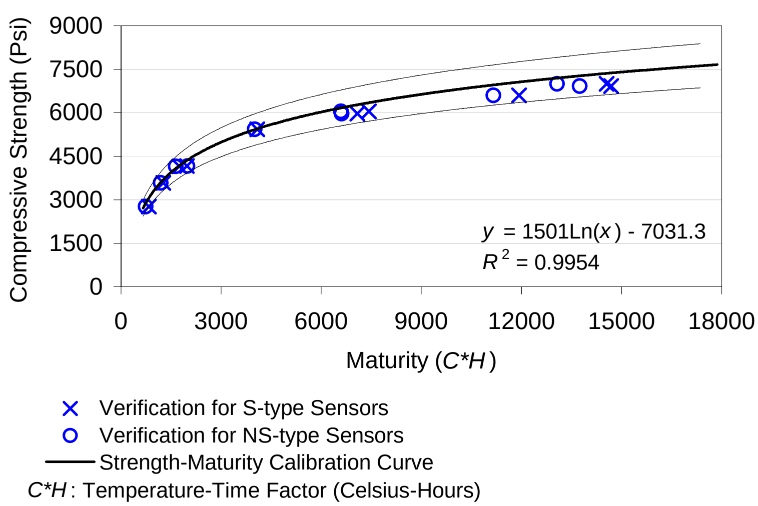


Figure 4.4: Final Strength-Maturity Calibration Curve for Columns

4.1.4 Measurement of the Maturity Index and the In-Place Concrete Strength

After the re-verification of the strength-maturity calibration curves, maturity sensors were installed in the drilled shafts and the columns for the determination of the maturity indexes in these structural elements at the specified age intervals as explained in the sections 3.6 and 3.7.

The maturity data collected from 3 drilled shafts and two columns are given in the Appendix D. As pointed out in the section 3.7, the IntelliRock™ equipment recorded the data using a default datum temperature of 0°C while the Humboldt™ meter recorded it using its default datum temperature of -10°C. Since the concrete mixtures for drilled shafts and columns were prepared using Type I cement with no admixtures and the concrete was cured under normal curing conditions, hence it was decided to normalize all maturity data for the datum temperature of 0°C. Equation 2.3 was used to normalize the maturity data from the datum temperature of -10°C to 0°C (i.e. the data recorded from the Humboldt meter™).

It is important to note that although cylinders testing were planned at 1, 3, 7, 14 and 28 days; the exact schedule could not be followed in some cases due to the weekends and other official holidays. However, it was made sure that the testing is performed as close as possible to the scheduled test dates.

4.2 Discussion

4.2.1 Comparison of Sacrificial (S-type) and Non-sacrificial (NS-type) Sensors

Both types of sensors were compared based on three criteria: *accuracy*, *cost* and *compatibility with field conditions*.

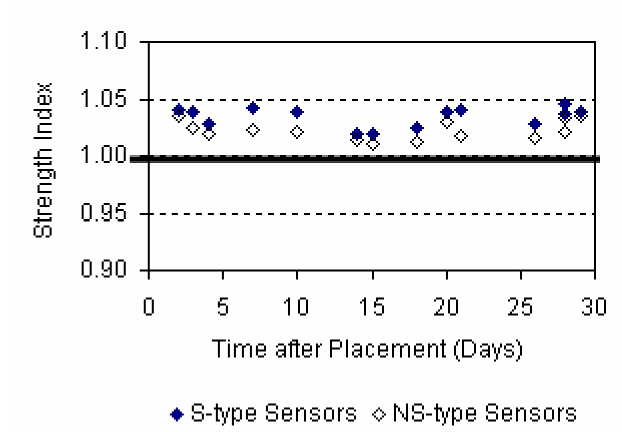
4.2.1.1 Accuracy

To compare accuracy, a parameter named *Strength Index* is calculated as defined below:

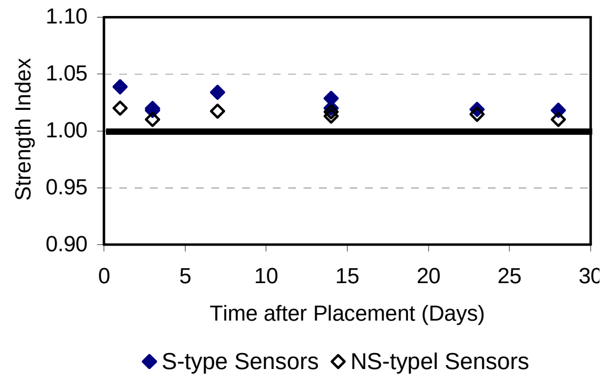
$$Strength\ Index = \frac{Estimated\ cylinder\ strength\ through\ strength - maturity\ curve\ at\ a\ given\ age}{Average\ cylinder\ strength\ obtained\ from\ the\ break\ tests\ at\ the\ same\ age} \quad (4.1)$$

The strength index was calculated for each set of concrete cylinders prepared from the concrete lots used for pouring the drilled shafts and columns. The values of the strength indices are plotted against the time after placement of concrete as shown in Figure 4.5. It is clear from the figure that the strength estimates from both types of sensors are very close to each other with a margin of error of ±2%. Hence as far as the accuracy is concerned, both types of sensors could be considered as equally accurate.

The Figure 4.5 also indicates that the estimated compressive strength values obtained from the maturity data are higher (minimum by 1.5% to maximum by 5%) than the compressive strength values obtained from the cylinder break tests. This implies that the maturity method overestimates the strengths by as much as 5%. This overestimation of strength may be due to the fact that the maturity method does not accurately incorporate the effect of early age curing temperature on the overall strength of concrete. The ASTM C1074-04 standard sets a permissible range of ±10% within which the maturity data may tolerate from the actual compressive strength obtained from the cylinder break tests. Since the reported data are well within this permissible range (i.e. within ±5), hence they can be considered as accurate enough to draw further conclusions.



(a) Data collected from 3 drilled shafts



(b) Data collected from 2 columns

Figure 4.5: Comparison for Accuracy between S-type and NS-type Sensors

4.2.1.2 Cost

There are two types of costs associated with the maturity measurement systems, *maturity readers cost* and the *sensors cost*. A cost comparison is shown in Figure 4.6. On the left, itemized costs of different items and on the right, a cost comparison based on the number of sensors required to simultaneously measure maturity index at different locations are shown. It should be noted that NS-type maturity meter can simultaneously record maturity index from four sensors but cannot be detached before the completion of the operation. Hence if the number of operational sensors is more than 4 during any particular time period, one maturity reader per four sensors would be required. The S-type maturity system on the other hand collects data on an internal memory chip and hence one reader is sufficient for the entire project or organization.

Item	S-type System	NS-type System
Readers Costs		
No of maturity readers required	1	1 per 4 sensors
Unit cost of maturity reader	$2700	$1520
Sensors Costs		
Unit cost of sensor	$38.40	$0.65/ft
Cost of 50 ft connecting wire	$0.50/ft	--*
Total cost of 1 sensor with 50 ft wire	$63.40	$32.50

* The NS-type sensors record maturity though thermocouples and the same wire could be extended to the maturity meter.

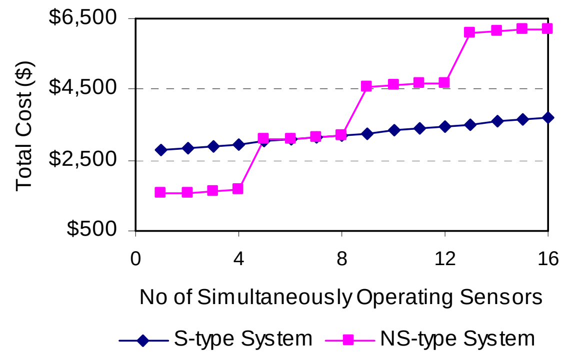


Figure 4.6: Costs Comparison of S-type and NS-type Sensors

The total cost comparison indicates that the NS-type sensors are economical if four or less sensors are simultaneously used to measure the maturity index. When the numbers of simultaneously operating sensors are from four to eight, both systems have almost the same cost. However when the number of simultaneously operating sensors exceeds eight then the S-type sensors becomes more cost effective. Thus eight simultaneously operating sensors can be considered as the breakeven point for cost comparisons.

4.2.1.3 Compatibility with Field Conditions

Both types of sensors have their own advantages and disadvantages in the field. S-type sensors are good for projects where site conditions are difficult and there is a danger of damage, theft and vandalism. These sensors record all data on a memory chip which operates with an internal battery (battery life is 3 months with 5 years shelf life). Hence they can be connected with the reader at any time to download the data. The NS-type sensors on the other hand require continuous attachment with the maturity reader. If the maturity reader lose power or becomes disconnected from the thermocouples the data can get lost.

The size of S-type sensor is approximately same as a 35 mm film canister which is a little larger than the maximum size of normally used aggregates. Hence these sensors are difficult to place at locations where the reinforcement is congested. Moreover, they should be tied with the reinforcement to avoid displacement or detachment during the placement of concrete. In drilled shafts or columns where there is often no middle reinforcement and concrete is placed through tremie pipes, such sensors cannot be installed in the *middle* portions. NS-type sensors on the other side consist of a thin thermocouple wire which can be placed at any location within the structure and chances of their displacement during the placement of concrete are modest.

4.2.2 Determination of Optimum Location of Sensors

4.2.2.1 Drilled Shafts

Figure 4.7 shows the estimated in-place strengths and internal temperature profiles of concrete determined through *top*, *middle* and *bottom* sensors installed in two 6 ft (1.83 m) diameter, 75 ft (22.9 m) deep drilled shafts. The data recorded through S-type sensors are reported here for simplicity and due to the reason that both sensors data are in close agreement. Also, the data recorded from three drilled shafts are found to be very consistent and average values are shown in the figure.

As predicted, the temperature profile indicated a peak during the first few days and then there was a gradual decrease in temperature. The strength development on the other hand, was rapid during the first two weeks and then gradually slowed down.

The figure indicated that *bottom* sensors estimate the lowest value of strength followed by *top* and *middle* sensors. The most probable reason could be the cooler ground temperature at the bottom of the shafts reduced the internal temperature of concrete. This was also obvious from the internal temperature profile of concrete. The maximum difference in estimated strengths lies between the *middle* and the *bottom* sensors and was found to be approximately 13%. Hence it is recommended to install maturity sensors near the bottom of drilled shafts for estimating the conservative or lower values of in-place concrete strength. From construction point of view, it may be easier to place sensors near the top portion of the drilled shaft (especially when the drilled shaft is very deep). In this situation, the decision should be based on the discretion of engineer and the local site conditions.

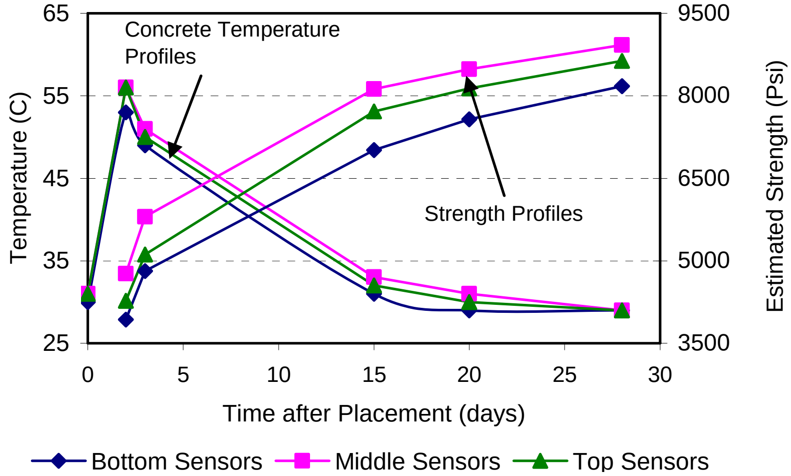


Figure 4.7: Effect of Sensors Location on Estimated Strength in Drilled Shafts

4.2.2.2 Columns

Figure 4.8 shows the estimated in-place strengths and internal temperature profiles recorded through *top*, *middle* and *bottom* sensors located in two circular columns each having a diameter of 3.5 ft (1.07 m) and length of 24 ft (7.31 m). Similar to drilled shafts, the average S-type sensors data from both columns are reported here.

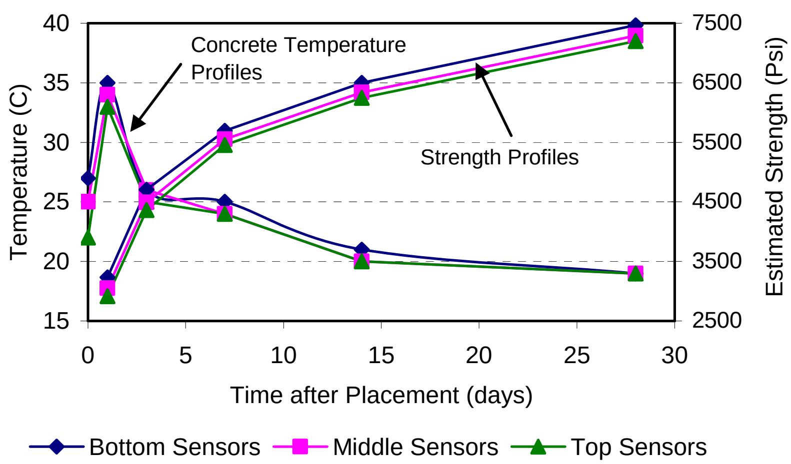


Figure 4.8: Effect of Sensors Location on Estimated Strength in Columns

Contrary to drilled shafts, the differences in estimated strengths determined through *top*, *middle* and *bottom* sensors were found to be within ±4% and hence may be considered as negligible. The top sensors recorded the minimum strength followed by middle and bottom sensors. The main reason could be the slightly lower ambient temperature around the top portion of the column. Though not mandatory due to negligible strength difference (i.e. ±4%), yet it is recommended to install sensors at the top portion of the column to estimate the lowest value of in-place strength.

4.3 Use of the Maturity Method for QA/QC

The purpose of the QA/QC is to certify the quality of concrete delivered at the jobsite and to ensure that the jobsite concrete has similar physical and mechanical characteristics as the design concrete. Traditionally, concrete cylinders are prepared at the jobsite by taking samples from the delivered concrete and compressive strength tests (also called the cylinder break tests or destructive tests) are performed at 1, 3, 7, 14 and 28 days to determine the compressive strength.

It has been demonstrated in sections 4.1 and 4.2 that the maturity method gives a fairly accurate estimation of the in-place compressive strength of concrete. Figures 4.9 and 4.10 depict a comparison of the compressive strengths obtained from the traditional cylinder break tests with the estimated compressive strength values obtained from the maturity data collected from the validation cylinders as well as from the sensors installed in the columns and drilled shafts (the average of the maturity values collected from the S-type and NS-type sensors are used to estimate the compressive strength). It is clear from both figures that the compressive strength values estimated from the maturity data are in close agreement with the actual compressive strengths obtained by breaking the cylinders. The difference in strengths at any given age is not more than 5% which is well within the permissible limit of ±10% as set by the ASTM C1074-04 standard. These data further support the conclusion that the maturity method can be used as a reliable technique for QA/QC of concrete.

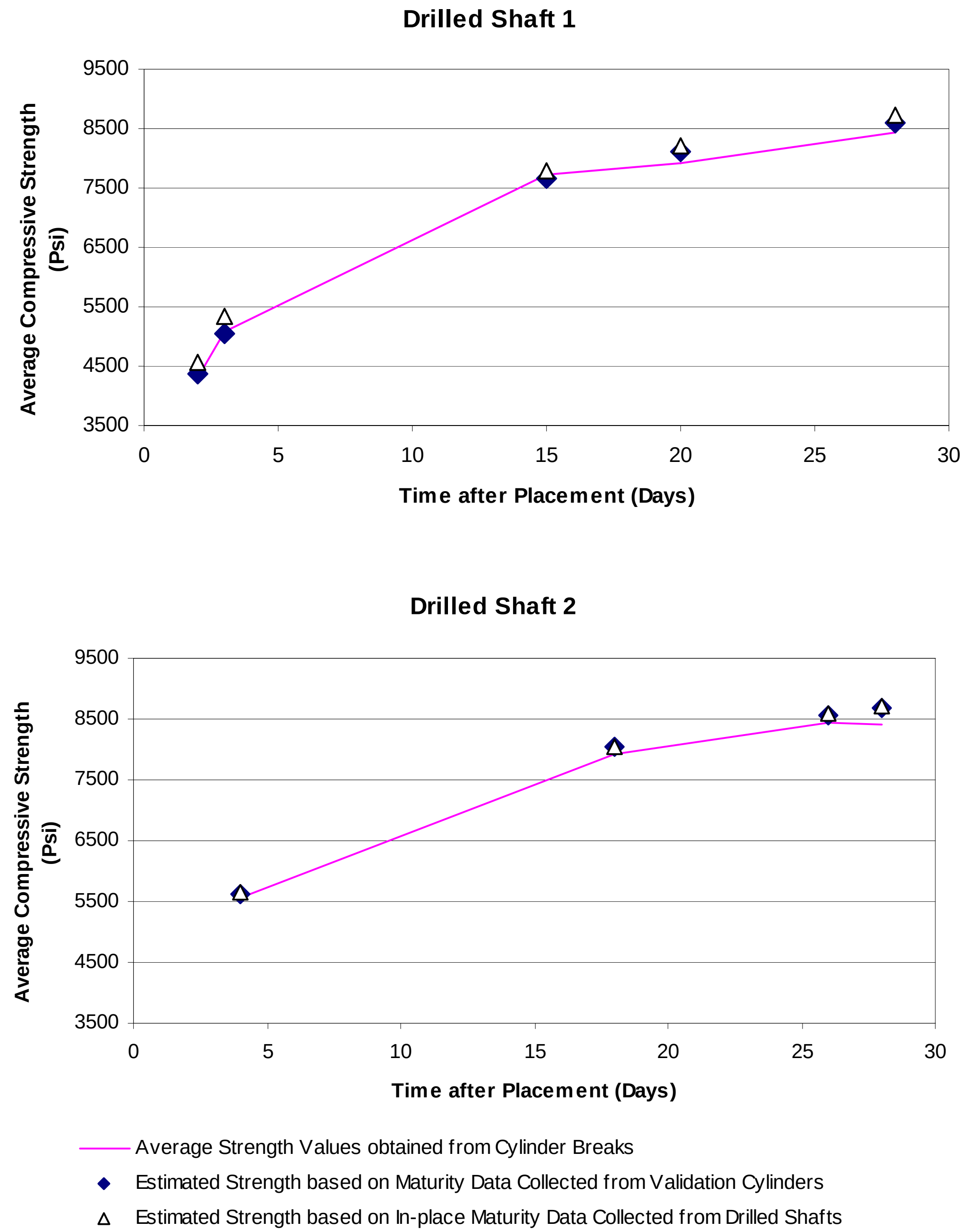


Figure 4.9: Comparison of the Compressive Strength Data of Drilled Shafts (Cylinder Breaks vs. Maturity Method)

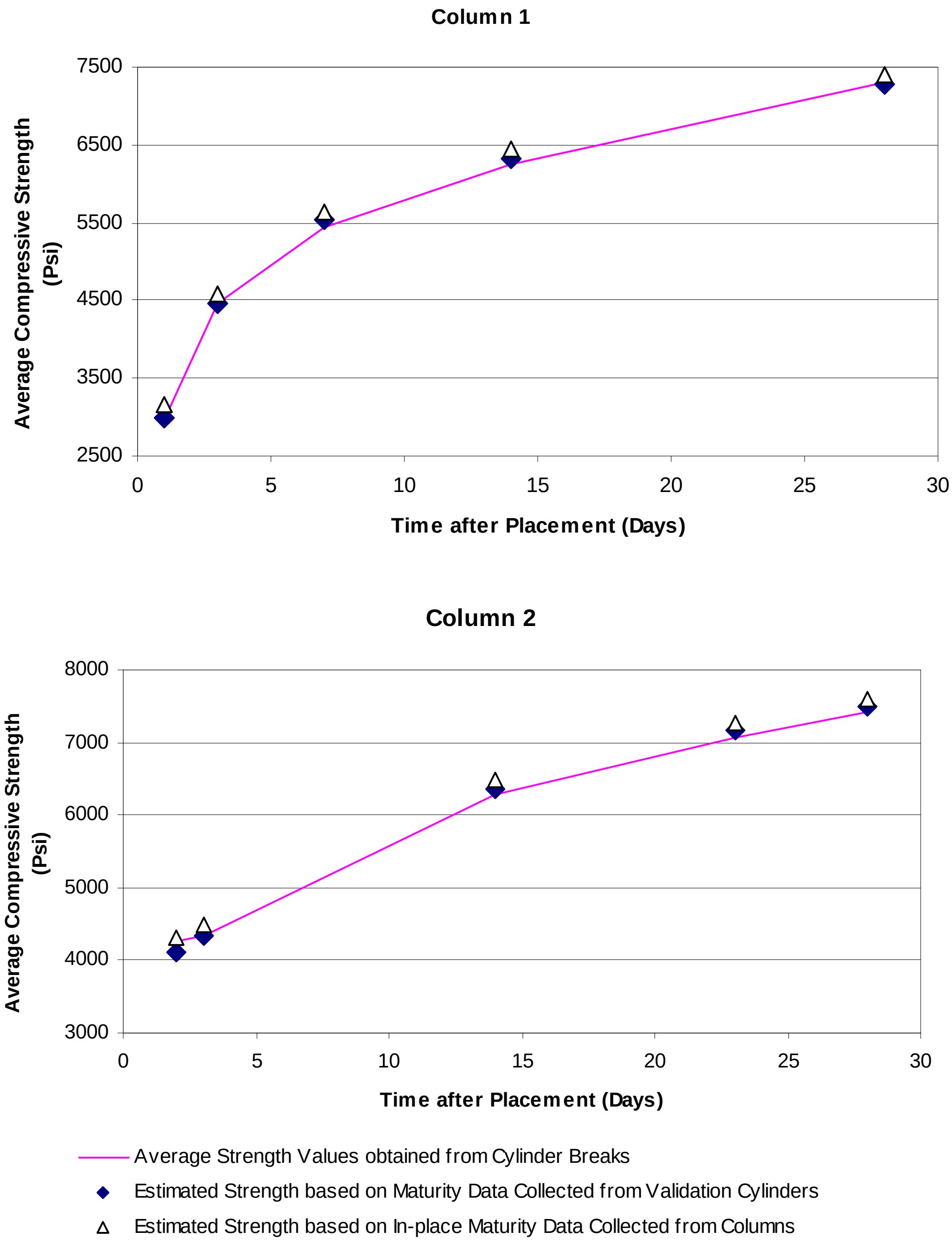


Figure 4.10: Comparison of the Compressive Strength Data of Columns (Cylinder Breaks vs. Maturity Method)

4.3.1 Proposed Changes in the Existing Specifications to Incorporate Maturity Method for QA/QC

This section outlines the proposed changes in the existing specification 346-9.1 to incorporate the use of the maturity method as an alternative strength measuring technique. The rationale behind each change in the specification is illustrated in the footnotes that follow the comparison table 4.2.

Table 4.2: Comparison between Existing and the Proposed Specifications

Existing Specification 346-9	**Proposed Specification**
346-9.1 …….cast a set of three QC cylinders for each LOT of structural concrete incorporated into the project……..The Department will …… cast a set of verification cylinders from a separate sample from the same load of concrete as the Contractor's QC sample. For each LOT verified by the Department, cast one additional cylinder from the same sample, and identify it as the QC "hold cylinder". The department will also cast one additional "hold" cylinder from each verification sample. All cylinders will be initially cured in the same curing facility. Transport the QC cylinders to the testing laboratory in the same time period the Department transports the Verification cylinders. Test the QC samples for compressive strength at the age of 28 days…….	For each LOT of structural concrete, cast two QC cylinder[(1)] with maturity probes. The Department shall …..cast two verification cylinder with maturity probes (from one of every four consecutive LOTS) from a separate sample from the same load of concrete as the Contractor's QC sample. For each LOT verified by the Department, cast two "hold cylinders" without maturity probes [(2)]. All cylinders shall be initially cured in the same curing facility. The maturity index of QC cylinder shall be determined at the age of 28 days (and/or at early ages, if required). Use this maturity index and estimate the strength from the Strength-Maturity curve. Use the same procedure for the verification cylinder. From one of every sixteen consecutive LOTS, cast three additional QC cylinders without maturity probes.[(3)]. Cure these cylinders under the same conditions as the cylinders with the maturity probes. Break the cylinders at 28 days. Use the strength data to revalidate the strength-maturity curve (i.e. strength tolerance must not be greater than ±10%). If there are deviations then the probable cause should be investigated. a. If the strength discrepancies are due to the problems with the batching procedures, corrective actions should be taken to ensure that the problems are not repeated. The tolerance in water-to-cementitious materials ratio should not be more than ±0.05. b. If the source of the observed differences cannot be readily determined, a new strength-maturity curve should be developed to account for any potential changes that may have occurred with the mixture components.

(1) It has been established by this research and earlier studies that the maturity data collected from the two cylinders are good enough to accurately estimate the strength of the concrete. The maturity data are based on the composition of the concrete mixture (i.e. heat of hydration) and are independent of the cylinders' casting defects such as improper compaction which may affect the compressive strength of the individual concrete cylinders during the cylinder breaks tests.

(2) Since the "hold cylinders" shall be used for verification purposes in case of any disputes, hence it is recommended to cast them without maturity probes to identify any errors which may occur as a result of malfunctioning of maturity sensors.

(3) The figure of "one of every 16 consecutive LOTS" is selected subjectively based on the premises that the deviations in the concrete materials may not happen very frequently. The presence of this clause will serve as a check to find any possible deviations and to refine the strength-maturity calibration curve accordingly.

4.3.2 Benefits of using the Maturity Method for QA/QC

The use of the maturity method shall reduce the number of concrete cylinders needed for QA/QC. Table 4.3 compares the number of concrete cylinders needed when using the existing specifications with the number of concrete cylinders required by using the proposed specifications.

Table 4.3: No of Concrete Cylinders required by using the Existing and the Proposed Specifications

Existing Specifications	Proposed Specifications
No. of cylinders required per four LOTS QC cylinders: 12 Verification cylinders: 3 Hold cylinders: 2	No. of cylinders required per four LOTS QC cylinders: 8 Verification cylinders: 2 Hold cylinders: 2
Total cylinders required: 17	Total cylinders required: 12

This comparison indicates that the current FDOT specification (346-9.1) requires at least 17 cylinders to be tested for direct compressive strength in the laboratory for every four consecutive LOTS. By successfully implementing the maturity method as a QA tool, this number will be reduced to 12, thereby resulting in 30% savings in laboratory testing costs and transportation charges.

The maturity testing of the QC and the verification cylinders can be reliably performed in the field (especially when the S-type sensors are used) and there is no need to transport the cylinders to the laboratory. This option will further reduce the transportation costs which are incurred as a result of transporting the cylinders from the field to the laboratory.

Moreover, prediction of strength can be made instantaneously at any given time. This will increase the speed of construction in fast-track projects, where the preceding activities (such as removal of formwork) are linked with the attainment of required level of strength.

Chapter 5

FINDINGS AND RECOMMENDATIONS

5.1 Summary of Findings

The findings of this study can be summarized as follows:

1. Both Sacrificial (S) and Non-sacrificial (NS) sensors produce equally accurate results. The choice between the two types should depend on their total cost and compatibility with field conditions. The NS-type sensors are economical when the number of simultaneously operated sensors is four or less. When this number exceeds four, the S-type sensors become more cost effective.

2. Sacrificial sensors are more secure than the non-sacrificial sensors. These sensors have least chances of data loss due to the power failure or breakage of wires. However, they could be displaced during the placement of concrete and hence cannot be installed at positions where no reinforcement is available to provide proper support.

3. The temperature gradient across the cross-section is lowest at the sides hence it is reasonable to install the sensors on the sides rather than in the middle portions. The sensors located in the middle of the structure have a greater chance of displacement during the placement of concrete.

4. The sensors must be installed at the bottom portion of drilled shafts and at the top portion of columns to record the conservative or lower strength values in the respective structural element.

5. The strength development in a concrete structure is not uniform. Hence for structures other than drilled shafts and columns, the sensors should be installed at regions where

internal temperature of concrete will be lowest, or regions where highest loads are expected.

5.2 Recommended Quality Assurance (QA) Protocol

As discussed in section 4.3, the rationale behind QA/QC is to verify that the concrete received at the site has similar properties as the design concrete. Based on the discussion done in section 4.3, the following QA protocol is recommended for the FDOT. The protocol is graphically depicted in Figure 5.1.

1. The contractor, with the help of the supplier, shall develop and verify strength-maturity relationships for each concrete mixture to be used in the field. Temperature-Time Factor (TTF) shall be used to calculate maturity index using a datum temperature of 0°C for normal strength concrete with Type I cement and no admixtures. The logarithmic trend line shall be used to plot the best fit strength-maturity curve. The curve should be approved by the FDOT.

2. For each LOT of structural concrete, the contractor shall cast two “QC cylinders” with maturity probes (sensors). The FDOT shall cast two “verification cylinders” with maturity probes from one of every four consecutive LOTS. For each LOT verified by the Department, two “hold cylinders” without maturity probes shall be cast. All cylinders shall be initially cured in the same curing facility.

3. The maturity index of QC cylinders shall be determined at the age of 28 days (and/or at early ages, if required). Use this maturity index and estimate the strength from the Strength-Maturity curve, developed in step 1. Use the same procedure for the verification cylinders.

4. From one of the every sixteen consecutive LOTS, three additional QC cylinders shall be cast. Cure these cylinders under the same conditions as the cylinders with the maturity probes and break them at 28 days. Use the strength data to revalidate the

strength-maturity curve (i.e. strength tolerance must not be greater than ±10%). If there are deviations then the probable cause should be investigated.

a. If the strength discrepancies are due to the problems with the batching procedures, corrective actions should be taken to ensure that the problems are not repeated. The tolerance in water-to-cementitious materials ratio should not be more than ±0.05.
b. If the source of the observed differences cannot be readily determined, a new strength-maturity curve should be developed to account for any potential changes that may have occurred with the mixture components.

5. For in-place strength determination, place maturity probes in the formwork prior to placement of concrete. The probes should be within two to four inches from any formed surface and should not touch the reinforcing steel or formwork. A minimum of two probes must be placed in each structural member or during each concrete placement. The recommended locations are *bottom* portions of drilled shafts and *top* portion of columns.

6. The 28-days strength and maturity data from cylinders may be used to refine the strength-maturity curve. It will help to prepare different sets of strength-maturity curves for the same concrete mix by incorporating the slight changes in different parameters such as changes in ambient temperature, slight variations in the w/c ratio, changes in retarder dose etc.

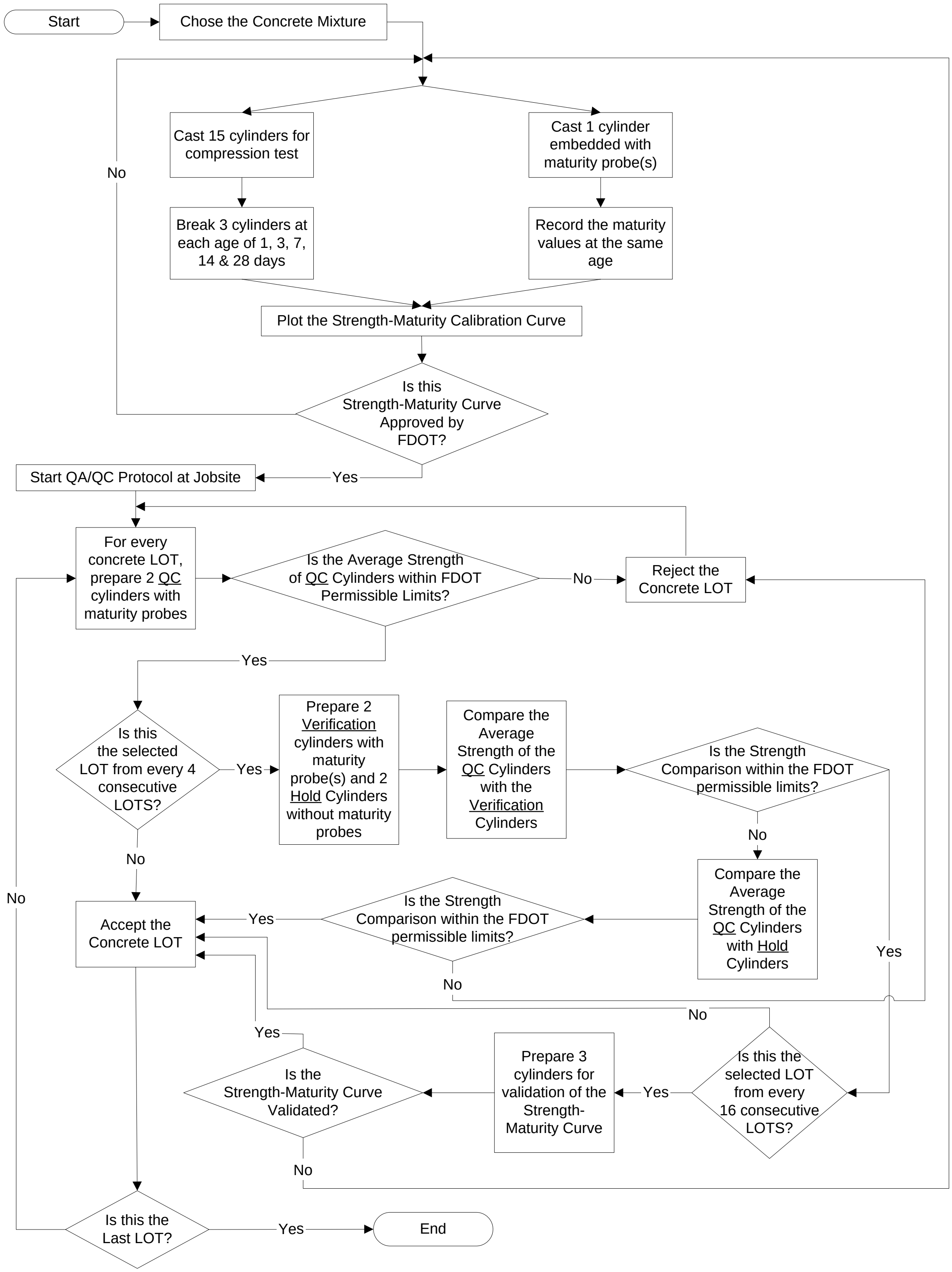


Figure 5.1: Graphical Illustration of the Proposed QA/QC Protocol

5.3 Future Studies

This research study investigated the use of the maturity method for the in-place strength determination of concrete and recommended a protocol to incorporate this method in the existing QA/QC procedure of the FDOT.

A continuation of this work is imperative in order to make conclusive recommendations. The following guidelines may serve as the basis of the future studies.

1. Other structural members such as bridge decks, pavement slabs, retaining walls, etc. should be tested to find the optimum location of maturity sensors in these structural elements.

2. The FDOT should maintain a data bank of maturity readings and corresponding strength values and refine the strength-maturity calibration curves on a continuous basis. The department may also prepare different sets of strength-maturity curves for the same concrete mix by incorporating the slight changes in different parameters such as changes in ambient temperature, slight variations in the w/c ratio, changes in retarder dose etc.

3. A database should be developed in any spreadsheet software such as Excel to allow easy maturity data entry and determination of in-place compressive strength.

4. A research study should be conducted to verify that the limitations of the maturity method, as discussed in section 2.2, do not affect the overall results in different field conditions. The researchers should conduct maturity testing at different ambient conditions and determine the effect of early-age strength gain on the over-all strength.

5. A separate study should be conducted to find the difference in the maturity values between the field-cured cylinders and the laboratory-cured cylinders.

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Appendix A

PRELIMINARY TESTING RESULTS

Table A.1: Maturity and Compressive Strength Results (IntelliRock™)

	Mix 1		Mix 2	
Days	Maturity (C*Hr)	Comp. Str.(Psi)	Maturity (C*Hr)	Comp. Str.(Psi)
0	0	0	0	0
1	725	4210	748	3080
4	2064	5370	2183	5203
7	4728	6557	5080	6723
14	9758	7553	9870	7890
28	19588	8190	19880	8990

	Mix 3		Mix 4	
Days	Maturity (C*Hr)	Comp. Str.(Psi)	Maturity (C*Hr)	Comp. Str.(Psi)
0	0	0	0	0
1	814	3850	1503	1200
4	2271	5367	2221	1990
7	5187	6550	9875	5127
14	10355	7720	14634	5810
28	19130	8697	19469	6407

Table A.2: Maturity and Compressive Strength Results (Humboldt™)

	Mix 1		Mix 2	
Days	Maturity (C*Hr)	Comp. Str.(Psi)	Maturity (C*Hr)	Comp. Str.(Psi)
0	0	0	0	0
1	633	4210	701	3080
4	1970	5370	2716	5203
7	3451	6557	4777	6723
14	8311	7553	9284	7890
28	15473	8190	18655	8990

	Mix 3		Mix 4	
Days	Maturity (C*Hr)	Comp. Str.(Psi)	Maturity (C*Hr)	Comp. Str.(Psi)
0	0	0	0	0
1	772	3850	693	1200
4	2839	5367	2703	1990
7	4896	6550	4649	5127
14	9839	7720	9197	5810
28	19398	8697	18179	6407

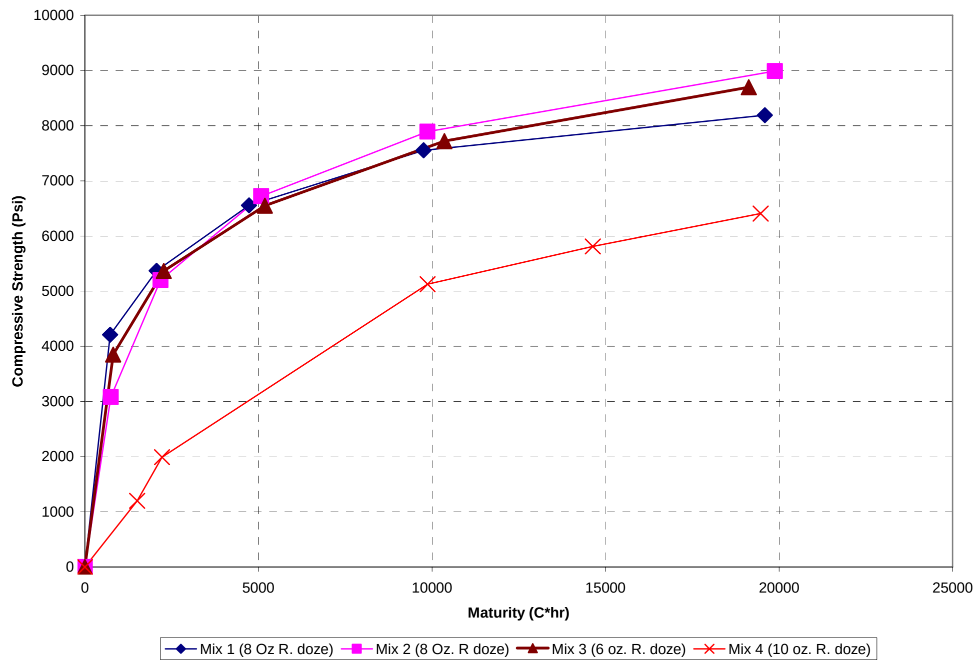


Figure A.1: Strength-Maturity Relationship for All Four Mixes

(Maturity data taken from the IntelliRock™ system)

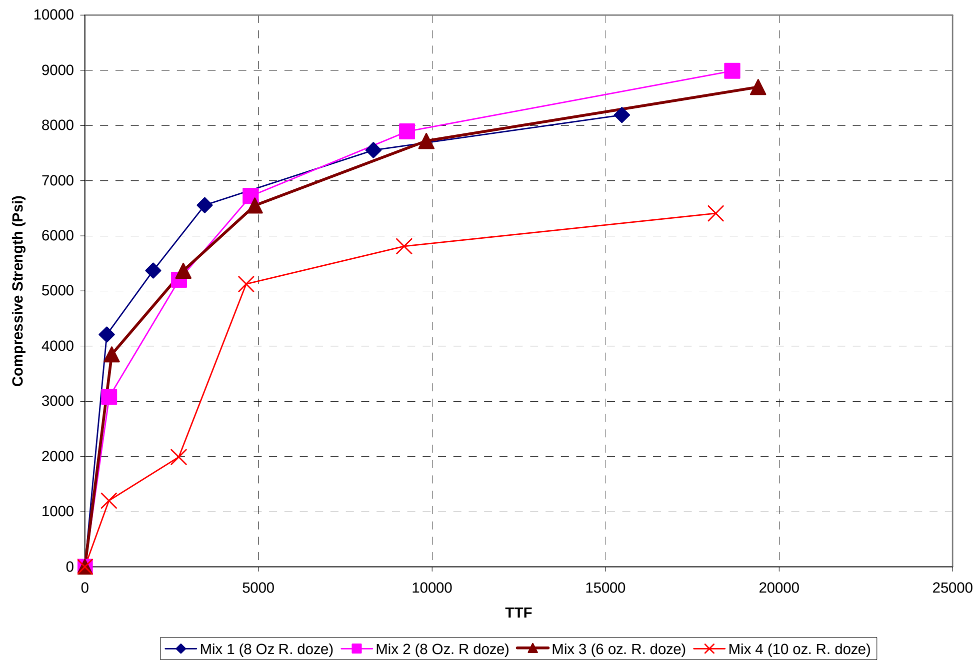


Figure A.2: Strength-Maturity Relationship for All Four Mixes

(Maturity data taken from the Humboldt™ System)

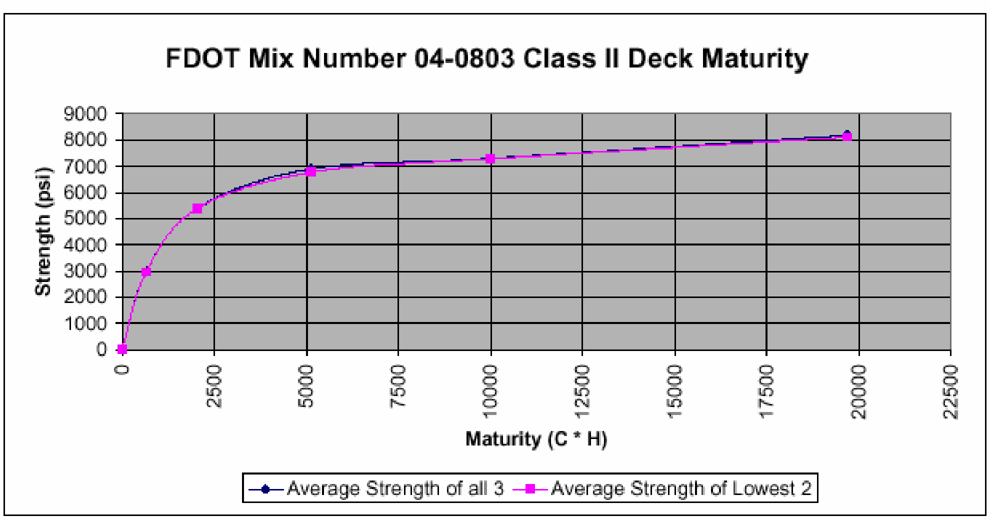
Appendix B

STRENGTH-MATURITY CALLIBRATION CURVES

A. Mix 04-0803

Trial Number:	2071	**Batch**	**Date:**	7/19/2004	**FDOT Mix Number:**	04-0803	
			Time:	11:45			
Intellirock							
Serial Number	**Date Activated**	**Time Activated**		**Description:**	Class II Deck		
2001868	7/20/2004	11:35					

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	7/20/2004	1	6	28.27	28.2	84,600	A	2990	663
B	7/20/2004	1	6	28.27	28.2	84,170	A	2980	
C	7/20/2004	1	6	28.27	28.3	83,700	A	2960	
D	7/22/2004	3	6	28.27	28.2	151,820	A	5370	2049
E	7/22/2004	3	6	28.27	28.05	153,060	C	5410	
F	7/22/2004	3	6	28.27	28.25	152,620	A	5400	
G	7/26/2004	7	6	28.27	28.15	196,670	C	6960	5125
H	7/26/2004	7	6	28.27	28.1	201,850	D	7130	
I	7/26/2004	7	6	28.27	28	186,270	D	6590	
J	8/2/2004	14	6	28.27	28	207,120	A	7330	10016
K	8/2/2004	14	6	28.18	28.1	207,210	C	7350	
L	8/2/2004	14	6	28.18	28	204,350	C	7250	
M	8/16/2004	28	6	28.27	27.75	234,240	A	8310	19689
N	8/16/2004	28	6	28.27	27.85	230,280	C	8170	
O	8/16/2004	28	6	28.27	27.8	226,770	C	8050	



B. Mix 04-0805

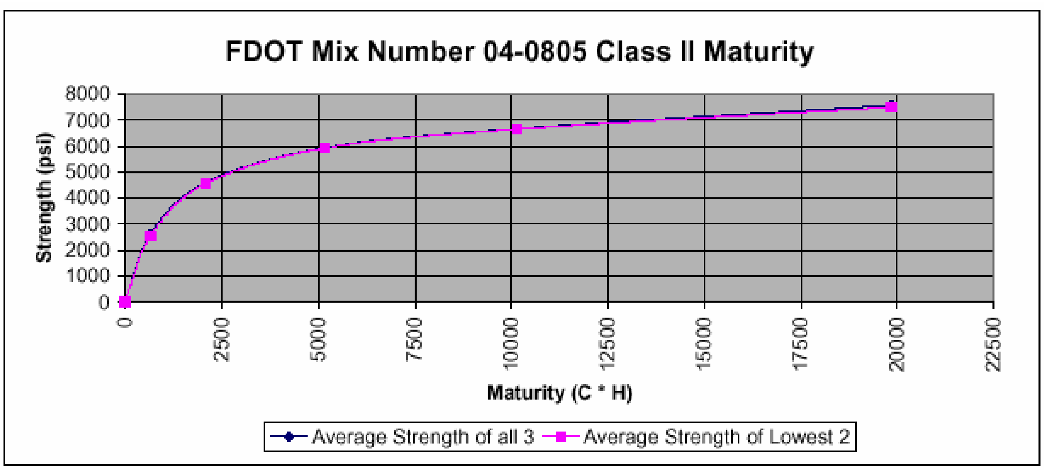
Trial Number: 2070 **Batch** **Date:** 7/19/2004 **Time:** 10:45 **FDOT Mix Number:** 04-0805

Intellirock

Serial Number	Date Activated	Time Activated
2003014	7/20/2004	11:35

Description: Class II

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
		0							0
A	7/20/2004	1	6	28.27	27.95	70,740	A	2500	658
B	7/20/2004	1	6	28.27	27.95	71,170	A	2520	
C	7/20/2004	1	6	28.27	27.95	78,260	A	2770	
D	7/22/2004	3	6	28.27	28.05	128,060	C	4530	2079
E	7/22/2004	3	6	28.27	28	130,890	C	4630	
F	7/22/2004	3	6	28.27	27.95	128,630	A	4550	
G	7/26/2004	7	6	28.27	27.85	169,270	A	5990	5183
H	7/26/2004	7	6	28.27	27.8	166,270	C	5880	
I	7/26/2004	7	6	28.27	27.8	168,360	A	5950	
J	8/2/2004	14	6	28.27	27.85	187,360	C	6630	10146
K	8/2/2004	14	6	28.18	27.7	187,200	C	6640	
L	8/2/2004	14	6	28.18	27.7	189,760	D	6730	
M	8/16/2004	28	6	28.27	27.6	209,620	B	7420	19862
N	8/16/2004	28	6	28.27	27.65	213,780	A	7560	
O	8/16/2004	28	6	28.27	27.65	218,560	A	7730	



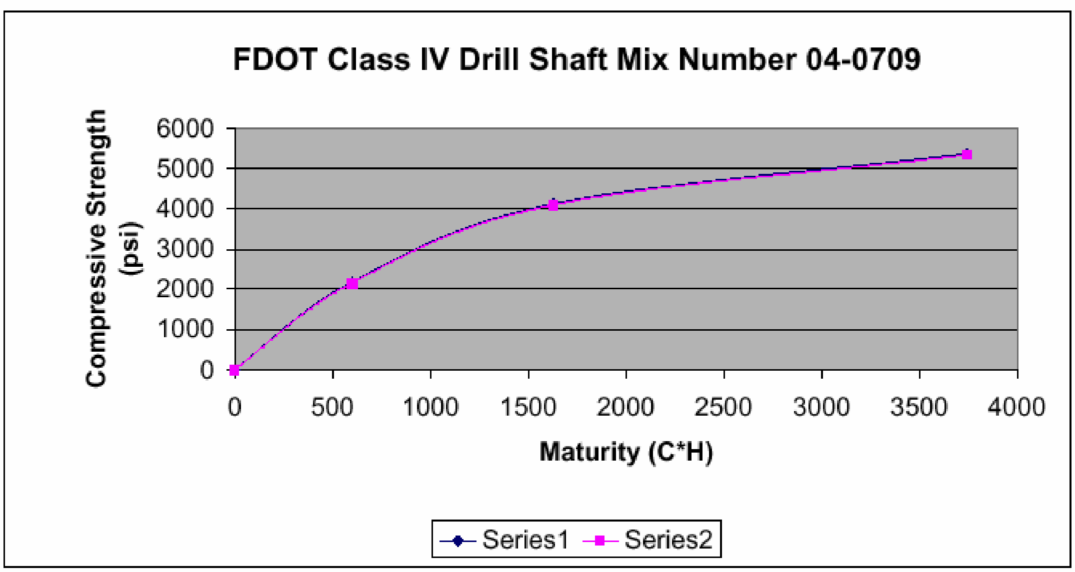
C. Mix 04-0709

Trial Number: 2365 **Batch** **Date:** 4/4/2005
Time: 8:30

Intellirock

Serial Number	Date Activated	Time Activated
2068557	4/4/2005	8:45

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	4/5/2005	1	6 x 12	27.99	27.1	59,880	A	2140	600
B	4/5/2005	1	6 x 12	27.99	27.2	60,250	A	2150	
C	4/5/2005	1	6 x 12	27.99	27.2	62,490	A	2230	
D	4/7/2005	3	6 x 12	28.09	27.85	117,100	A	4170	1628
E	4/7/2005	3	6 x 12	28.09	27.9	114,140	A	4060	
F	4/7/2005	3	6 x 12	28.09	27.8	116,090	A	4130	
G	4/11/2005	7	6 x 12	27.9	27.9	147,250	D	5280	3742
H	4/11/2005	7	6 x 12	27.95	27.9	150,440	A	5380	
I	4/11/2005	7	6 x 12	27.95	27.85	152,170	B	5440	
J	4/18/2005	14	6 x 12						
K	4/18/2005	14	6 x 12						
L	4/18/2005	14	6 x 12						
M	5/2/2005	28	6 x 12						
N	5/2/2005	28	6 x 12						
O	5/2/2005	28	6 x 12						



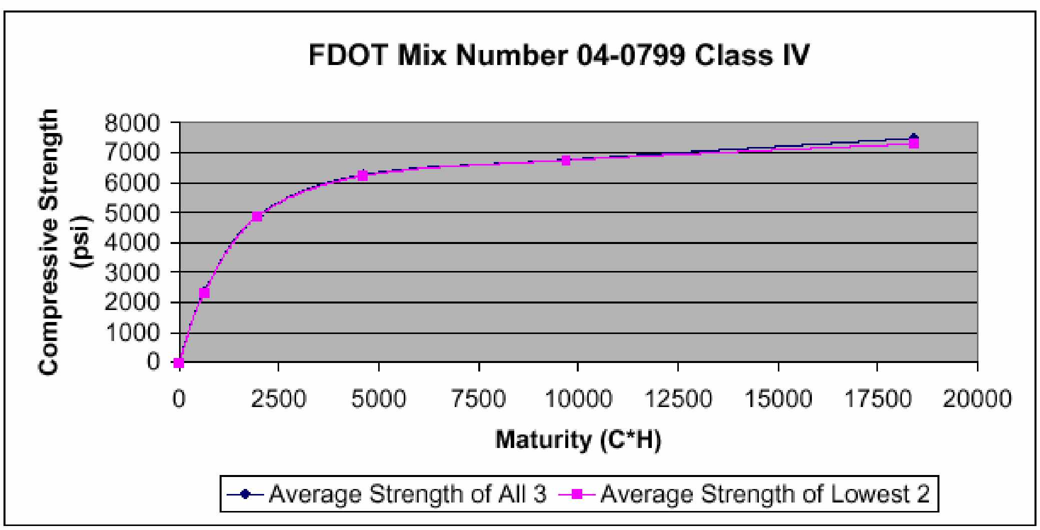
D. Mix 04-0799

Trial Number:	2141	**Batch**	**Date:**	9/20/2004	**FDOT Mix Number:**	04-0799
			Time:	10:40		

Intellirock

Serial Number	Date Activated	Time Activated	Description:
2001801	9/20/2004	11:15	Class IV

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	9/21/2004	1	6	28.086	27.1	65,200	A	2320	648
B	9/21/2004	1	6	28.086	27.2	68,880	A	2450	
C	9/21/2004	1	6	28.086	27.2	65,780	A	2340	
D	9/23/2004	3	6	28.18	27.1	138,750	A	4920	1980
E	9/23/2004	3	6	28.18	27.2	135,590	C	4810	
F	9/23/2004	3	6	28.18	27.2	139,060	A	4930	
G	9/28/2004	8	6	28.086	27.1	174,110	A	6200	4607
H	9/28/2004	8	6	28.086	27.15	175,360	A	6240	
I	9/28/2004	8	6	28.086	27.15	178,940	A	6370	
J	10/4/2004	14	6	28.086	27.2	191,090	A	6800	9694
K	10/4/2004	14	6	28.086	27.15	188,040	D	6700	
L	10/4/2004	14	6	28.086	27.15	190,810	A	6790	
M	10/18/2004	28	6	28.274	27.15	221,650	C	7840	18394
N	10/18/2004	28	6	28.274	27.1	206,790	D	7310	
O	10/18/2004	28	6	28.274	27.1	205,470	A	7290	



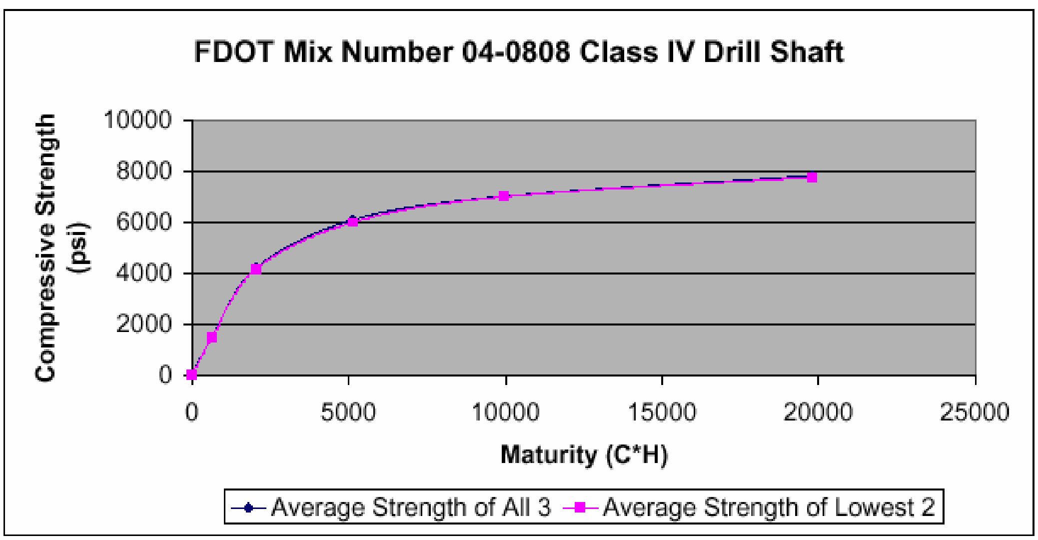
E. Mix 04-0808

Trial Number:	2073	**Batch**	Date:	7/20/2004	**FDOT Mix Number:**	04-0808
			Time:	11:35		

Intellirock

Serial Number	Date Activated	Time Activated	Description:	Class IV Drill Shaft
2001851	7/20/2004	11:35		

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	7/21/2004	1	6	28.27	27.7	42,900	A	1520	654
B	7/21/2004	1	6	28.27	27.75	43,980	A	1560	
C	7/21/2004	1	6	28.27	27.8	41,480	A	1470	
D	7/23/2004	3	6	28.27	27.85	120,940	A	4280	2044
E	7/23/2004	3	6	28.27	27.75	116,520	C	4120	
F	7/23/2004	3	6	28.27	27.95	118,250	C	4180	
G	7/27/2004	7	6	28.18	27.8	170,120	A	6040	5132
H	7/27/2004	7	6	28.18	27.7	167,180	C	5930	
I	7/27/2004	7	6	28.18	27.85	177,130	A	6290	
J	8/3/2004	14	6	28.27	27.65	199,720	C	7070	9966
K	8/3/2004	14	6	28.27	27.65	195,640	A	6920	
L	8/3/2004	14	6	28.27	27.7	199,740	A	7070	
M	8/17/2004	28	6	28.27	27.8	223,760	C	7920	19806
N	8/17/2004	28	6	28.27	27.8	220,800	C	7810	
O	8/17/2004	28	6	28.27	27.7	218,270	A	7720	



F. Mix 04-0857A

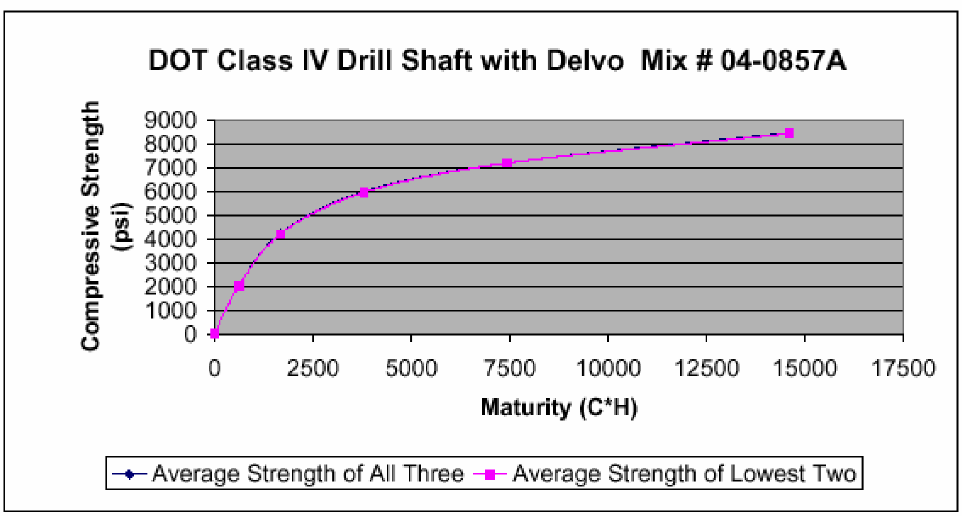
Trial Number: 2304 **Batch** **Date:** 2/15/2005

Mix Number: 04-0857A **Time:** 12:40

Intellirock

Serial Number	Date Activated	Time Activated
2001842	2/15/2005	12:50

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	2/16/2005	1	6	27.9	28	55,450	A	1990	622
B	2/16/2005	1	6	27.9	27.85	55,920	A	2000	
C	2/16/2005	1	6	27.9	28.05	55,390	A	1990	
D	2/18/2005	3	6	27.9	28.05	117,610	A	4220	1684
E	2/18/2005	3	6	27.9	27.9	119,230	A	4270	
F	2/18/2005	3	6	27.9	28	116,300	A	4170	
G	2/22/2005	7	6	27.9	27.95	116,110	D	5950	3796
H	2/22/2005	7	6	27.9	28.1	165,770	A	5940	
I	2/22/2005	7	6	27.9	28.1	167,910	A	6020	
J	3/1/2005	14	6	27.9	28.15	199,660	A	7160	7453
K	3/1/2005	14	6	27.9	28.05	201,150	A	7210	
L	3/1/2005	14	6	27.9	28.05	201,010	C	7210	
M	3/15/2005	28	6	27.9	28.1	238,510	A	8550	14613
N	3/15/2005	28	6	27.9	28.05	236,210	A	8470	
O	3/15/2005	28	6	27.9	28.05	233,990	A	8390	



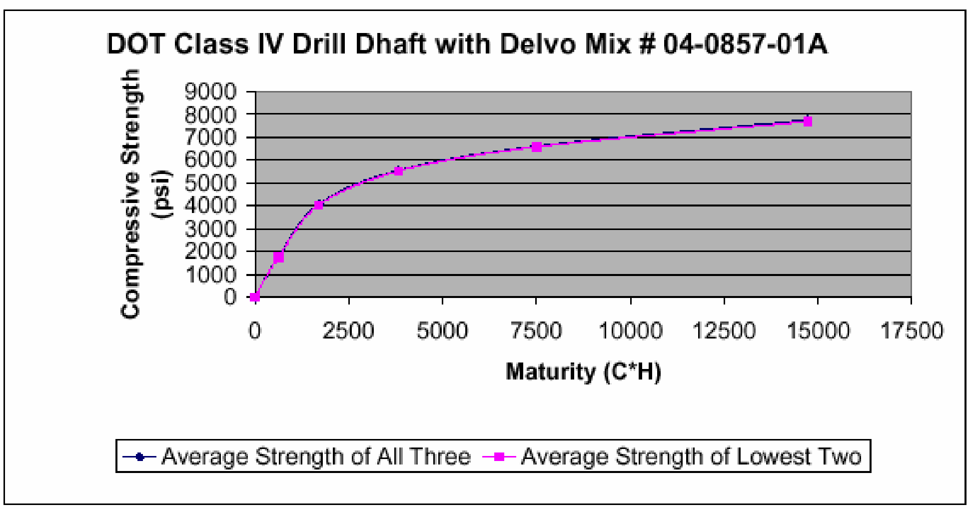
G. Mix 04-0857-01A

Trial Number:	2305	**Batch**	**Date:**	2/15/2005
Mix Number:	04-0857-01A		**Time:**	10:35

Intellirock

Serial Number	Date Activated	Time Activated
2001564	2/15/2005	10:50

Cylinder Number:	Test Date	Test Age	Size	Area	Weight (g)	Total Load	Break Type	PSI	Maturity Reading (C*H)
A	2/16/2005	1	6	27.99	27.85	49,750	A	1780	631
B	2/16/2005	1	6	27.99	27.8	52,310	A	1870	
C	2/16/2005	1	6	27.99	27.8	48,600	A	1740	
D	2/18/2005	3	6	27.9	27.8	113,180	D	4060	1701
E	2/18/2005	3	6	27.9	27.9	100,430	C	3960	
F	2/18/2005	3	6	27.9	27.8	116,040	A	4160	
G	2/23/2005	8	6	27.9	27.9	152,870	D	5480	3813
H	2/23/2005	8	6	27.9	27.95	157,030	C	5630	
I	2/23/2005	8	6	27.9	27.95	154,370	D	5530	
J	3/1/2005	14	6	27.9	27.95	184,890	A	6630	7506
K	3/1/2005	14	6	27.9	28	186,230	A	6680	
L	3/1/2005	14	6	27.9	27.9	182,340	A	6540	
M	3/15/2005	28	6	27.9	28	214,170	A	7680	14712
N	3/15/2005	28	6	27.9	27.9	224,100	A	7890	
O	3/15/2005	28	6	27.9	28	214,610	C	7690	



Appendix C

EQUIPMENT DETAILS

<u>IntelliRock™</u>

For Field Data

Structural member	Drilled Shaft	Column	Deck
No. of members being tested	3	3	3
No. of data logging points/Mbr	4	4	4
Total	12	12	12

Total data loggers needed for field testing = 36

For Cylinders

Curing Conditions	Field Curing	Lab. Curing
Cylinders for 3 Shafts	1 x 3 = 3	1 x 3 = 3
Cylinders for 3 Columns	1 x 3 = 3	1 x 3 = 3
Cylinders for 3 Decks	1 x 3 = 3	1 x 3 = 3
Total cylinders	9	9

Total data logger required for cylinders = 18

<u>IntelliRock™ Equipment Purchase – Summary</u>

1. Data logger required = 36 + 18 = 56 or make it 60
2. Wire length for each logger = 100 ft
3. IntelliRock 2 device = 1
4. Splicer kit

For each type of structural member, 16 cylinders will be cast. Fifteen cylinders will be tested for compressive strength at 1, 3, 7, 14 and 28 days. The last cylinder will be used to install data loggers.

No. of cylinder molds required (with lids) = 16 x 9 x 2 = 288 or make it 300

HUMBOLDT™

HUMBOLDT meter will be used to gather data up to 28 days for each type of the structural member. The reason for selecting 28 days is to reuse the equipment. The price of one Humboldt maturity meter is around $1400. If the data is recorded for 56 days, then more maturity meters will be required which may cross the top line of the budgeted amount.

For Field Data

Structural member	Drilled Shaft	Columns	Deck
No. of members being tested	3	3	3
No. of data logging points/Mbr	4	4	4
Data logging channels needed	12	12	12
Humboldt Meter needed	3	3 (reused)	3 (reused)

Total HUMBOLDT meters needed = 3

For Cylinders

Structural member	Drilled Shaft	Columns	Deck
No. of specimen	3	3	3
Cylinders/Curing conditions	2	2	2
Data logging channels needed	6	6	6
Humboldt Meter needed	2	2 (reused)	2 (reused)

1. Total HUMBOLDT meters required = 5 -1 (already bought) = 4
2. Number of wires = 36 + 18 56 ≈ 60
3. Length of each wire = 100 ft

Overall Summary

Device	IntelliRock	HUMBOLDT
Data loggers with 100 ft wire	60	--
Meters	1	4
Spliced wires (100 ft)	--	60
Cylinders with lids	300	
Splicer kit	1	--

Appendix D

MATURITY INDEXES AND ESTIMATED IN-PLACE CONCRETE STRENGTHS

Drilled Shaft 1 (Casting Date: 05-03-2005)

Data Recorded from S-Type Sensors (IntelliRock™ System)
Default Datum Temperature = 0°C

Age	Temperature-Time Function (TTF)				TTF Readings from Test Cylinders (°C-hours)	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	0	0	0	0	0	0
2	2280	2463	2521	2421	1701	4920
3	3511	3749	3790	3683	3343	5537
15	NA*	14955	14349	14652	13628	7610
20	NA*	18772	17897	18335	18387	7934
28	NA*	24545	23367	23956	22802	8627

* The data could not be collected due to the malfunctioning of the sensors.

Data Recorded from NS-Type Sensors (Humboldt™ System)
Default Datum Temperature = -10°C
Normalized Datum Temperature = 0°C

Age	Temperature-Time Function (TTF in °C-hours)^				TTF Readings from Test Cylinders (°C-hours)^	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	0	0	0	0	0	0
2	1787	2798	2148	2244	2561	4920
3	1589	4877	3373	3280	3811	5537
15	9388	17002	13673	13354	15615	7610
20	12659	20677	17116	16817	18158	7934
28	17496	26175	22397	22023	22421	8627

* TTF values are converted from -10°C to 0°C

Drilled Shaft 2 (Casting Date: 05-05-2005)

Data Recorded from S-Type Sensors (IntelliRock™ System)
Default Datum Temperature = 0°C

Age	Temperature-Time Function (TTF)				TTF Readings from Test Cylinders (°C-hours)	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	0	0	0	0	0	0
4	4543	4927	4489	4653	4459	5254
18	17211	17764	16233	17069	17021	7137
26	23130	23678	21973	22927	24436	7740
28	24522	25069	23365	24319	25540	7967

Data Recorded from NS-Type Sensors (Humboldt™ System)
Default Datum Temperature = -10°C
Normalized Datum Temperature = 0°C

Age	Temperature-Time Function (TTF in °C-hours)^				TTF Readings from Test Cylinders (°C-hours)^	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	0	0	0	0	0	0
4	4344	4914	4128	4462	5161	5254
18	16124	17245	15422	16264	19590	7137
26	21338	22848	20925	21704	20043	7740
28	22616	24192	22269	23026	22378	7967

^ TTF values are converted from -10°C to 0°C

Drilled Shaft 3 (Casting Date: 08-08-2005)

Data Recorded from S-Type Sensors (IntelliRock™ System)
Default Datum Temperature = 0°C

Age	Temperature-Time Function (TTF)				TTF Readings from Test Cylinders (°C-hours)	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	NA*	0	NA*	0	0	0
7	NA	5732	NA	5732	5586	7640
10	NA	7476	NA	7476	7549	8610
14	NA	9683	NA	9683	10051	8700
21	NA	13558	NA	13558	13684	9290
29	NA	18005	NA	18005	18250	9730

* The data could not be collected due to the malfunctioning of the sensors.

Data Recorded from NS-Type Sensors (Humboldt™ System)
Default Datum Temperature = -10°C
Normalized Datum Temperature = 0°C

Age	Temperature-Time Function (TTF in °C-hours)^				TTF Readings from Test Cylinders (°C-hours)^	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	NA*	0	NA*	0	0	0
7	NA	5604	NA	5604	5646	7640
10	NA	7281	NA	7281	7485	8610
14	NA	9393	NA	9393	9815	8700
21	NA	13076	NA	13076	13248	9290
29	NA	17245	NA	17245	17925	9730

^ TTF values are converted from -10°C to 0°C

Column 1 (Casting Date: 02-22-2005)

Data Recorded from S-Type Sensors (IntelliRock™ System)
Default Datum Temperature = 0°C

Age	**Temperature-Time Function (TTF in °C-hours)**				**TTF Readings from Test Cylinders (°C-hours)**	**Average Compressive Strength from Cylinders (Psi)**
	Bottom	**Middle**	**Top**	**Average**		
0	0	0	0	0	0	0
1	801	852	883	845	830	2670
3	2160	2261	2284	2235	1974	3764
7	4483	4601	4624	4569	4077	5034
14	7747	7857	7872	7825	7422	5847
28	14709	14941	14938	14863	14547	6367

Data Recorded from NS-Type Sensors (Humboldt™ System)
Default Datum Temperature = -10°C
Normalized Datum Temperature = 0°C

Age	**Temperature-Time Function (TTF in °C-hours)^**				**TTF Readings from Test Cylinders (°C-hours)^**	**Average Compressive Strength from Cylinders (Psi)**
	Bottom	**Middle**	**Top**	**Average**		
0	0	0	0	0	0	0
1	809	827	764	800	978	2670
3	2116	2156	2041	2104	2711	3764
7	4350	4364	4204	4306	5685	5034
14	7422	7392	7204	7339	9950	5847
28	14034	13928	13709	13890	13068	6367

^ TTF values are converted from -10°C to 0°C

Column 2 (Casting Date: 03-01-2005)

Data Recorded from S-Type Sensors (IntelliRock™ System)
Default Datum Temperature = 0°C

Age	Temperature-Time Function (TTF in °C-hours)				TTF Readings from Test Cylinders (°C-hours)	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	NA*	0	0	0	0	0
2	NA	1450	1470	1460	1262	3078
3	NA	1945	1946	1946	1742	3350
14	NA	7550	7487	7519	7076	4374
23	NA	12843	12744	12794	11931	5794
28	NA	16160	16062	16111	14690	6022

* The data could not be collected due to the malfunctioning of the sensors.

Data Recorded from NS-Type Sensors (Humboldt™ System)
Default Datum Temperature = -10°C
Normalized Datum Temperature = 0°C

Age	Temperature-Time Function (TTF in °C-hours)^				TTF Readings from Test Cylinders (°C-hours)^	Average Compressive Strength from Cylinders (Psi)
	Bottom	Middle	Top	Average		
0	NA*	0	0	0	0	0
2	NA	1932	2063	1998	1191	3078
3	NA	2748	2196	2472	1641	3350
14	NA	8249	6933	7591	6613	4374
23	NA	13471	12295	12883	11161	5794
28	NA	16807	15389	16098	13743	6022

^ TTF values are converted from -10°C to 0°C
* The data could not be collected due to the malfunctioning of the sensors.

Appendix E

SUPPLIMENTARY SPECIFICATIONS FOR THE MATURITY METER METHOD (DEVELOPED FOR I-95 MOBILITY PROJECT)

(REV 10-20-03)

SECTION 346 (of the Supplemental Specifications) is expanded by the following:

346-12 Maturity Method Research

346-12.1 General: Furnish maturity meters and their corresponding data loggers sufficient in quantity to meet the calibration and testing requirements. Two brands of maturity meters, namely, the IntelliRock and the Humboldt shall be used to develop two different sets of curves, one for each brand of meter. Test results from the maturity method are not to be considered for the acceptance of any structure, but are to be used only in determining the validity of the maturity method as part of an ongoing research project.

Develop and verify in-place strength and strength-maturity relationships in accordance with ASTM C-1074. Use a datum temperature of $0^{o}C$ in development of the strength-maturity curves. In developing the concrete mix design, use tolerances set forth by FDOT specifications. Ensure that the water-to-cementitious materials ratio does not exceed the required target value for each design mix by +/- 0.05. No structural concrete shall be poured on the project until the strength-maturity curves and methodology have been submitted and approved by the Engineer and approved. Mix designs, testing methodology and strength-maturity curves should be submitted to the Engineer for approval within 45 days of Notice to Proceed.

Any changes to the approved concrete design mix, other than the allowed tolerances, and including material source, shall require development of a new concrete strength-maturity relationship curve.

When the strength-maturity relationship is not verified to within 10% of the corresponding strength as established by the concrete strength-maturity relationship curve, maturity testing for that element shall be discontinued until a new curve is developed.

Test results from the above maturity method are not to be considered for the acceptance of any structure, but are only to be used in determining the validity of the maturity method as part of an ongoing research project.

346-12.2 Placement of Sensors:

(a) Place temperature sensors (also known as probes) into the formwork prior to placement of concrete. The exact locations for placing the sensors shall be selected by the Engineer and will vary between structural elements.

(b) Place sensors within two to four inches from any formed surface or at mid-depth of the section for sections less than four inches. (NOTE: Sensors may be tied to reinforcing steel, but should not be in direct contact with the reinforcing steel or formwork.)

(c) Sensors should be placed in six drilled shafts, six columns and six bridge decks pour. Each structural element (shafts, columns, and decks) must have at least eight sensors per device (IntelliRock & Humboldt), installed at different locations as directed by the Engineer. The sensors will be provided by the Department.

(d) Sensor placement within each structural element shall be selected by the Engineer. The Engineer will select locations throughout each structural element to maximize sampling and data points, rather than for ease of placement. Sensors will be placed along the middle, bottom and top of proposed drilled shafts and columns, and along the top and bottom of decks, which may require additional wiring to connect readers at accessible locations, or it may require the use of special equipment to provide access for the readers to the sensors.

(e) Sensors shall be placed on structural elements (shafts, columns, and decks) selected by the Engineer. The Engineer will select the structural elements to be instrumented at different times within the Contractor's schedule, in order to record data from each structural element at different ambient temperatures and weather conditions. This will require multiple mobilizations by the Contractor of technical support personnel.

346-12.3 Payment: All costs associated with Maturity Method Research shall be included with affected concrete pay items.