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RESEARCH

2009-26

Demonstration of Concrete Maturity Test Process on the TH-694/ TH-35E Interchange - Unweave the Weave

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Based on the data from the pilot project and preliminary tasks, maturity curves are sensitive to small changes of 10 lb/yd^3 of cementitious material. It was also found that a maturity datum temperature of 0 °C was too high. Strength continued to increase even when the concrete fell below this temperature. Further studies of 15 projects over the next three years will further increase Mn/DOT’s knowledge and experience with the maturity method. Included is an overview of the maturity function utilized by the data loggers.</td></tr>
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EXECUTIVE SUMMARY

Minnesota's early spring, mid-summer and late fall construction seasons present highly variable curing conditions such that a simple set of rules for opening the pavement to traffic may not be adequate. A maturity protocol will allow a more precise identification of the time when sufficient strength has been gained such that the pavement can be opened for certain uses. This way, traffic can be regulated to protect the integrity of the pavement while simultaneously streamlining construction operations by avoiding excessive initial cure periods. The overall goal of this research initiative is to develop maturity strength curves for the majority of the paving mixes used by Mn/DOT and test maturity meter implementation on several projects to observe potential difficulties/successes with their use.

An implementation project was carried out on the TH-694/TH-35E interchange otherwise known as the Unweave the Weave project. This was one of the first Mn/DOT projects to test the implementation of maturity meters in a field setting. Field implementation on this project helped to show the potential benefits and weaknesses of using maturity data loggers. Included with this information is a preliminary analysis of the maturity function utilized by the data loggers on the Unweave the Weave project in calculating maturity.

A Maturity Work Plan was developed in three tasks.

1) Field demo at MnROAD
2) Lab study
3) Implement on paving project(s)

Task 1 included a field demonstration of the installation and monitoring of data loggers in a test slab at MnROAD. Task 2 included monitoring of data loggers during trial mixing at AET and establishing maturity strength curves. Task 3 included placements of maturity data loggers in the concrete paving of the Unweave the Weave project and subsequent download and examination of maturity data. This report summarizes the finding of all three tasks.

Based on the data from the Unweave the Weave project and preliminary tasks, maturity curves are sensitive to small changes of 10 lb/yd^3 of cementitious material. It was also found that a maturity datum temperature of 0 ˚C was too high. Strength continued to increase even when the concrete fell below this temperature.

The Unweave the Weave project (SP 6280-304) is the first of many projects to become a testing ground for the development of Mn/DOT's maturity protocol. The Mn/DOT Concrete Pavement Office and Mn/DOT Concrete Research Section plan to study 15 more Mn/DOT construction projects over the 2009 to 2011 paving seasons.

INTRODUCTION

Although the maturity concept for nondestructively measuring in-situ strength of concrete pavements has seen widespread use in many state DOTs [1], the Minnesota Department of Transportation has had limited experience with it. The maturity concept uses the time/temperature history of concrete to develop a maturity strength curve that is specific to a mix. Once this curve has been established, the strength of the mix can be determined from the maturity (non-destructively). Since maturity strength curves are specific to a mix, there is a need to establish them for the high-pozzolan/supplementary cementitious materials (SCM) and low water/cement-ratio (w/cm) mixes used by Mn/DOT. High performance concrete pavement (HPCP) mixes incorporating fly ash (pozzolan) substitutions up to 30% and slag (SCM) substitutions up to 35% by mass of cement, which are common in Minnesota, increase the durability of concrete but decreases the rate of strength gain. This means that curing takes longer and therefore ambient air conditions have a greater influence on the strength gain than faster setting mixes containing no pozzolans. Efforts of the Mn/DOT Concrete Research Section and the Concrete Pavement Office are therefore being made toward the development of maturity curves for these mixes.

An in-house field test was conducted on portions of the pilot project during paving which included inserting maturity data loggers and downloading the information through a reader. Test specimens of the trial mixes prepared at AET labs used in the Unweave the Weave project were cast and monitored prior to the start of paving activities. However, a more broad approach to field-experimentation needs to be conducted in order to develop a more comprehensive representation of maturity curves. This will involve further maturity activities on many Mn/DOT paving projects.

Development of maturity-strength protocols for high cement replacement and low w/cm mixes will allow early and long-term strength predictions simply by monitoring the maturity functions of the concrete and ambient conditions during hydration. Currently the only Mn/DOT specification for determining concrete strength based on its time/temperature history is Table 2401-1 in the Bridge Construction Section of the 2005 Mn/DOT Standard Specifications for Construction. Table 2401-1 provides a method to determine strength gain in structural concrete based on the concrete surface temperature and does not make adjustments for differences in cementitious materials, admixtures and mix proportions. This-approach is currently inadequate for predicting the strength of high cement replacement or low w/cm ratio concrete. Costly mistakes associated with improper joint sawing which can cause “Sliver Spalling” or random cracking and pre-mature form stripping and loading of concrete structures and pavements because of inadequate concrete strength will be alleviated through the use of a maturity protocol. Applicable maturity-strength curves for these mixes will enable Mn/DOT to better determine opening times based on performance requirements and anticipated ambient conditions.

A maturity protocol would use the established relationship between strength and maturity for concrete paving mixes and then use this information to more accurately determine opening times for concrete pavements. Traditional methods of making and testing beams or cylinders have several disadvantages:

- Due to the exothermic nature of the cement hydration reaction, as the volume of concrete placements increases, the core temperature and temperature differential of the core to exterior increases.

- Cylinders and beams made according to ASTM C 31 are not consolidated in the same way as concrete placed using a slipform paver.

- Destructive methods such as coring are time, labor, and fiscally intensive.

While cylinders and beams will still be made to verify strength, significantly less testing will be needed when a maturity protocol is implemented. While it is not the intention to specify the time at which concrete joints will be sawed, the maturity protocol can be used to determine the strength at which contractors typically saw joints.

The TH-694/ TH-35E interchange otherwise known as Unweave the Weave, project SP 6280-304, was the first of many projects to become a testing ground for the development of Mn/DOT's maturity protocol. The Mn/DOT Concrete Pavement Office and Mn/DOT Concrete Research Section plan to study 15 more Mn/DOT construction projects over the 2009 to 2011 paving seasons.

Research Process

A Maturity Work Plan (Appendix A) was developed to separate the maturity research into three tasks.

1) Field demo at MnROAD
2) Lab study (American Engineering Testing, AET)
3) Implement on paving project(s)

Task 1 included a field demonstration of the installation and monitoring of data loggers in a test slab at MnROAD. Task 2 included monitoring of data loggers during trial mixing at the AET concrete batching lab and establishing strength maturity cures for the trial batches. Task 3 included placements of maturity data loggers in the concrete paving of the Unweave the Weave project and subsequent download and examination of maturity data. In the future, maturity data loggers will be placed on other projects as well; however, this report covers only the maturity tasks completed for the Unweave the Weave project during fall 2006 and 2007.

Paving with high cement replacement and low w/cm ratio mix designs typically used by Mn/DOT present unique difficulties during the variable and extreme ambient conditions present during early spring, late fall, and mid summer construction seasons. A critical part of these difficulties include the decision of when to open the pavement for construction traffic or public use. Proper implementation of a maturity protocol will help to streamline these decisions by opening the pavement to traffic earlier than current guidelines allow if sufficient strength is indicated by the maturity function. Similarly, the pavement maturity may indicate that sufficient strength has not been attained, and traffic can then be diverted until the pavement reaches the proper maturity. As such, the overall goal of this research initiative is to develop maturity strength curves for the majority of the paving mixes used by Mn/DOT and test maturity meter implementation on several projects to examine their implementation in a real world setting.

Objective

The main objective of this report is to determine if slight variations in a concrete mix design change the resulting strength maturity relationship. This objective was achieved by:

- Instrumentation of a typical Mn/DOT project with data loggers to monitor maturity of the concrete.
- Correlation of maturity values with flexural strength and compressive strength.
- Examination of the degree of variability of maturity between mix designs with various pozzolanic substitutions and cement/aggregate content.
- Development of maturity strength data for typical Mn/DOT mixes.

Background

The maturity function is used as a non-destructive way of estimating concrete strength at different ages. Concrete's strength depends not only on the curing time, but also on the temperature of the concrete while it's curing. Maturity refers to the time temperature history of the concrete. The heat generated due to cements' exothermic hydration reaction as well as the ambient temperature of the air effects the rate at which concrete gains strength. The warmer the concrete, the faster it gains strength [2]. Since the rate of strength gain in concrete is dependent on its time temperature history, if this history is known, it can be used to accurately predict the strength of concrete. Two equations are accepted by the American Standards for Testing and Materials (ASTM) [3] to calculate concrete strength from time temperature history: the Nurse-Saul and the Arrhenius equation with the former being the more popular due to its simplicity [2].

The Arrhenius equation is based on the equivalent maturity of the concrete as compared to concrete cured at a specific temperature, usually taken as 20˚C or 23˚C. Essentially, the age of the concrete is scaled to be greater or less based on whether the actual temperature history of the concrete acts to increase or decrease the rate of the reaction [1]. This exponential relationship between temperature and maturity is given by Equation 1.

$$t_e = \sum \exp - Q\left(1/T_a - 1/T_s\right)\Delta T \qquad (1)$$

Where t_e is the equivalent age at a specified temperature T_s, Q is the activation energy divided by the gas constant K, T_a is the average temperature of concrete during time interval Δt, T_s is the specified temperature, and Δt is the time interval [2]. The Nurse-Saul equation uses a linear relationship between maturity and temperature and is given by Equation 2.

$$M(t) = \left(T - T_0\right)\Delta t \qquad (2)$$

Where M(t) is the maturity at age t, Δt is the time interval, T is the average concrete temperature during the time interval, and T_0 is the datum temperature. The datum temperature is the temperature below which the concrete ceases to gain strength and is typically taken as between 0˚C and -10˚C. While an exponential relationship between temperature and maturity is more accurate, the Nurse-Saul function is more popular because it is a simple linear relation [2]. Once maturity data and the corresponding flexural or compressive strength data are obtained, a maturity strength curve can be developed. The two equations most widely used to predict strength based on maturity are the strength-logarithm of maturity relationship and hyperbolic strength-maturity relationship with the former most commonly used because of its simplicity and the later because of its theoretical basis [1].

The strength-logarithm equation follows the form:

$$S = B \cdot \ln(M) + A \tag{3}$$

Where S is the flexural or compressive strength, M is the maturity, and A, B are regression constants. The hyperbolic model follows the form:

$$S = \frac{S_u \cdot K \cdot (t - t_0)}{1 + K \cdot (t - t_0)} \tag{4}$$

Where S is concrete strength, t is the test age, S_u is the limiting strength, t_0 is the age when strength development is assumed to begin, and K is the rate constant. The rate constant K is the rate of strength gain at a specific temperature and is found by the procedure described in ASTM C 1074 [3].

Report Organization

This chapter provided an introduction to the maturity method and how it would be implemented on a paving project. Chapter 2 of this report discusses the preliminary tests at MnROAD and AET that were completed to familiarize Mn/DOT personnel with the maturity method. Chapter 3 presents the results from the Unweave the Weave project and conclusions are included in Chapter 4.

TEST SLAB AND TRIAL BATCHING

Task 1, at MnROAD, provided a primer on how to install and read the data loggers. The information gained from Task 1 was used to implement Task 2, instrumentation of the trial batching tests performed at AET; this step provided specific data relating to several of Mn/DOT's paving mixes. Finally, all of the information gathered from Tasks 1 and 2 was used to implement Task 3, collection of maturity data on the Unweave the Weave project.

Demonstration of Maturity Protocol on MnROAD Test Slab

To demonstrate the Intellirock data logger and reader device, a test slab measuring 8x8 ft by 8 in. was constructed at MnROAD in October 2006. Engius provided a demonstration of installing and reading the Intellirock data loggers. The Intellirock device used the Nurse-Saul equation to calculate maturity. This primer also introduced the concept of the datum temperature and how the resulting data might be affected by it. During the process of the demonstration, fresh concrete was brought in and placed within the slab form. Three data loggers were embedded in the slab; one at the center and two at the edges. Two other data loggers where used, one in a cylinder and the other was left in air to measure the surrounding air temperature. The maturity data was downloaded from the data loggers 28 days after placement.

Cores from the slab at the locations of the maturity loggers and cylinders, that were lab cured, were then tested at 14, 21, and 28 days. The time temperature history of the slab, cylinder, and air is shown in Figure 1 as measured by the embedded maturity loggers. The temperature of the cylinder was much higher than the slab and surrounding air because 24 hours after casting, it was moved to a climate controlled laboratory. As shown in Figure 2, temperature of the cylinder stabilized after it was brought into the laboratory for curing. The measured temperatures inside the slab were higher than the ambient air temperature for the first six days due to heat of hydration, after six days the slab temperature was similar to the surrounding air temperature as shown in Figure 3. The low temperatures in the slab were due to a sudden drop in temperature when the trial slab froze. During days 20 to 28 the temperatures in the slab vary up to 5 ˚C from the edge to center.

The maturity time relationship at three different datum temperatures of 0, -5, and -10 ˚C is shown in Figure 4 along with the compressive strength of cores taken from the slab. As shown in the top plot, for a datum temperature of 0 ˚C, the concrete maturity did not increase from day 21 to day 28 but the compressive strength of the cores did. This suggests that a lower datum than 0 ˚C should be used because that datum temperature is the temperature below which strength gain ceases. The plots for datum temperature of -5 and -10 ˚C correspond better with the compressive strength data. Since the maturity as calculated by the Nurse-Saul equation depends on the datum temperature, more tests are needed to establish what temperature should be used. The Iowa DOT uses -10 ˚C as their datum temperature [1]. Based on this trial, -10 ˚C is a reasonable datum temperature.

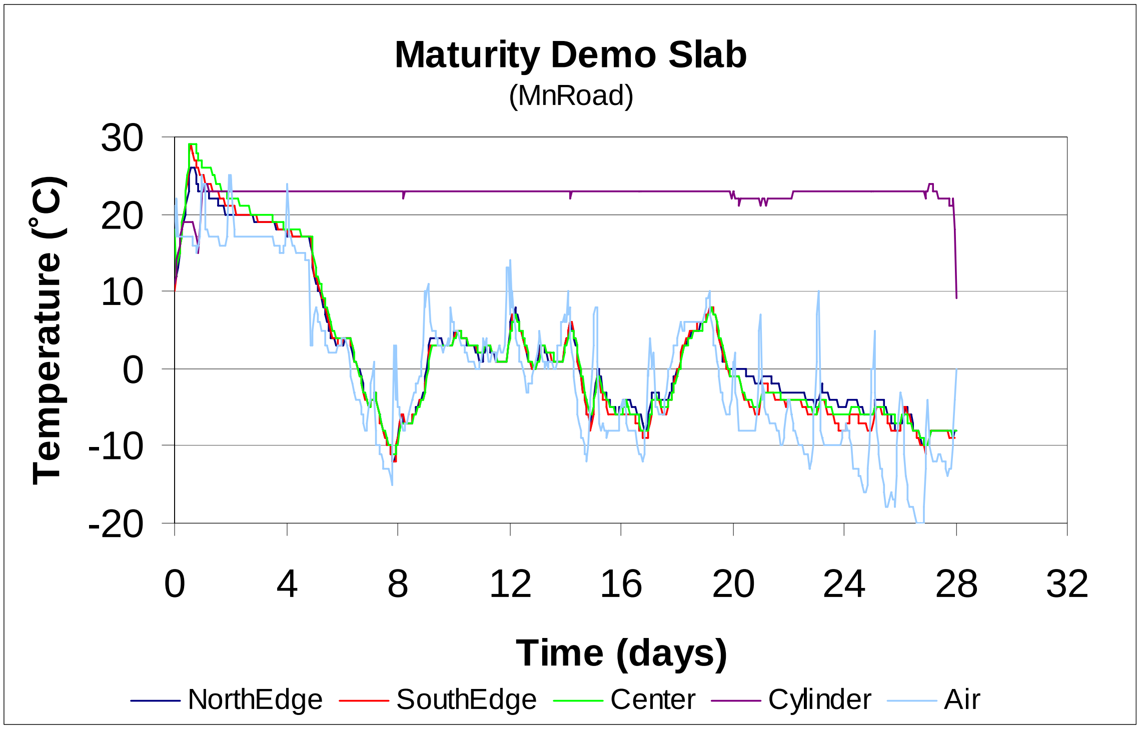

FIGURE 1 Time temperature history of the three slab locations, cylinders, and air surrounding the trial slab.

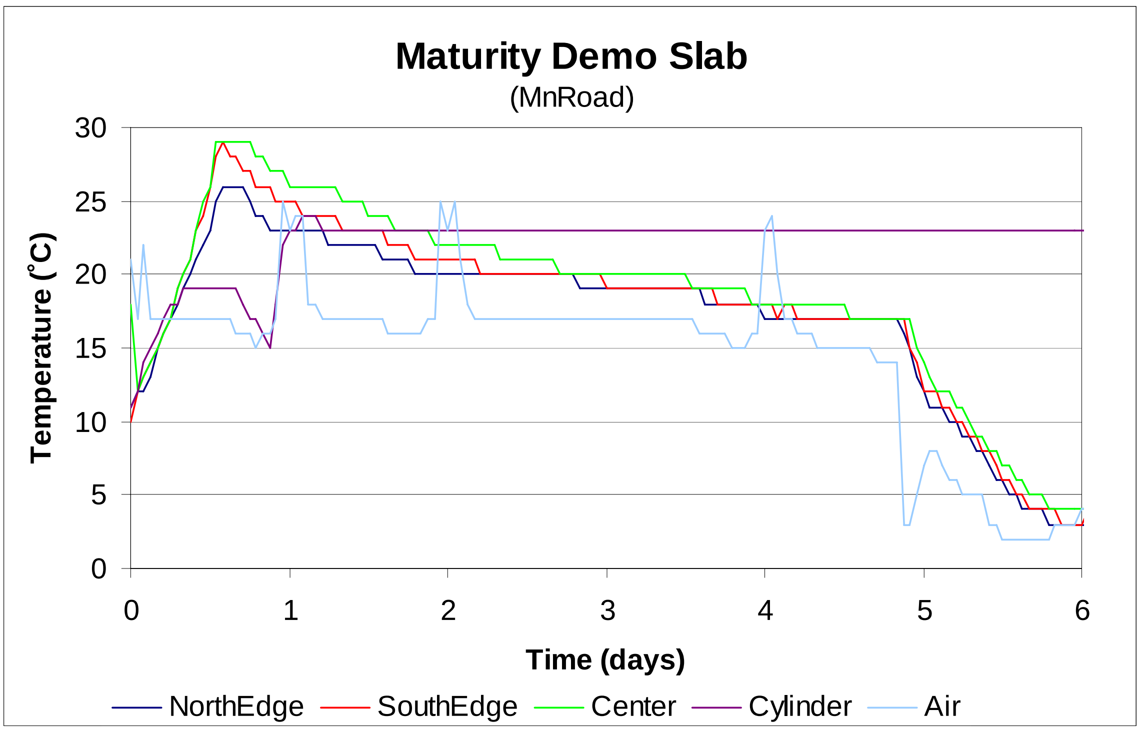

FIGURE 2 First six days time temperature history of the three slab locations, cylinders, and air surrounding the trial slab.

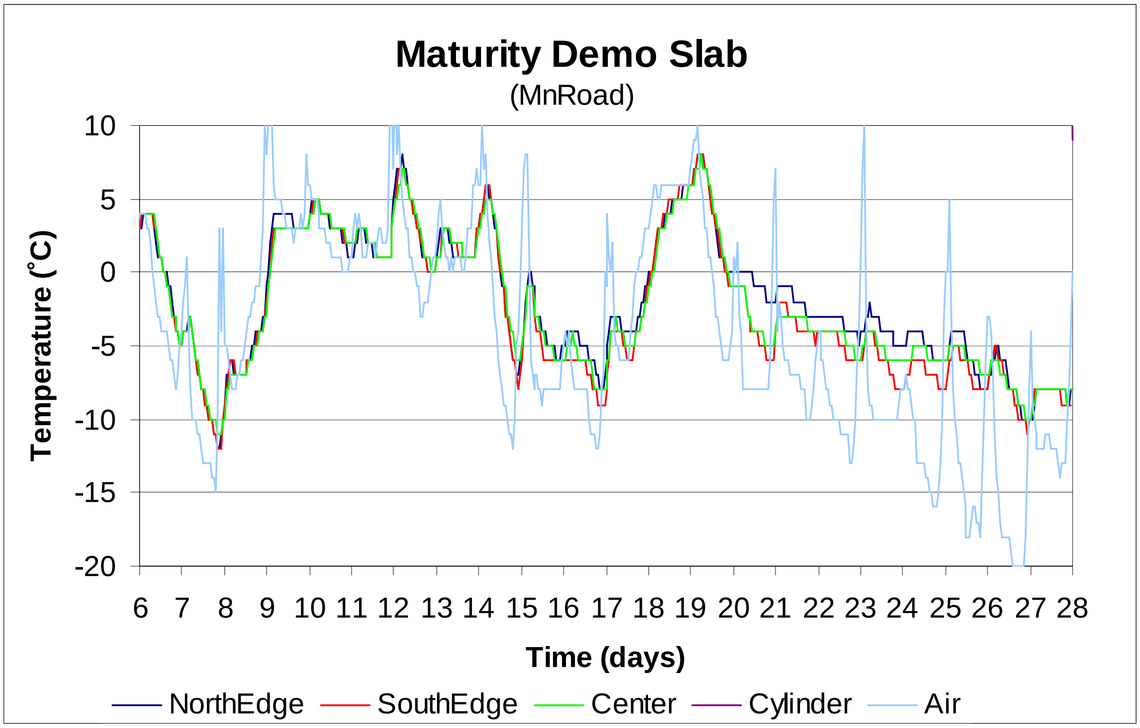

FIGURE 3 Time temperature history days six to 28 of the three slab locations, cylinders, and air surrounding the trial slab.

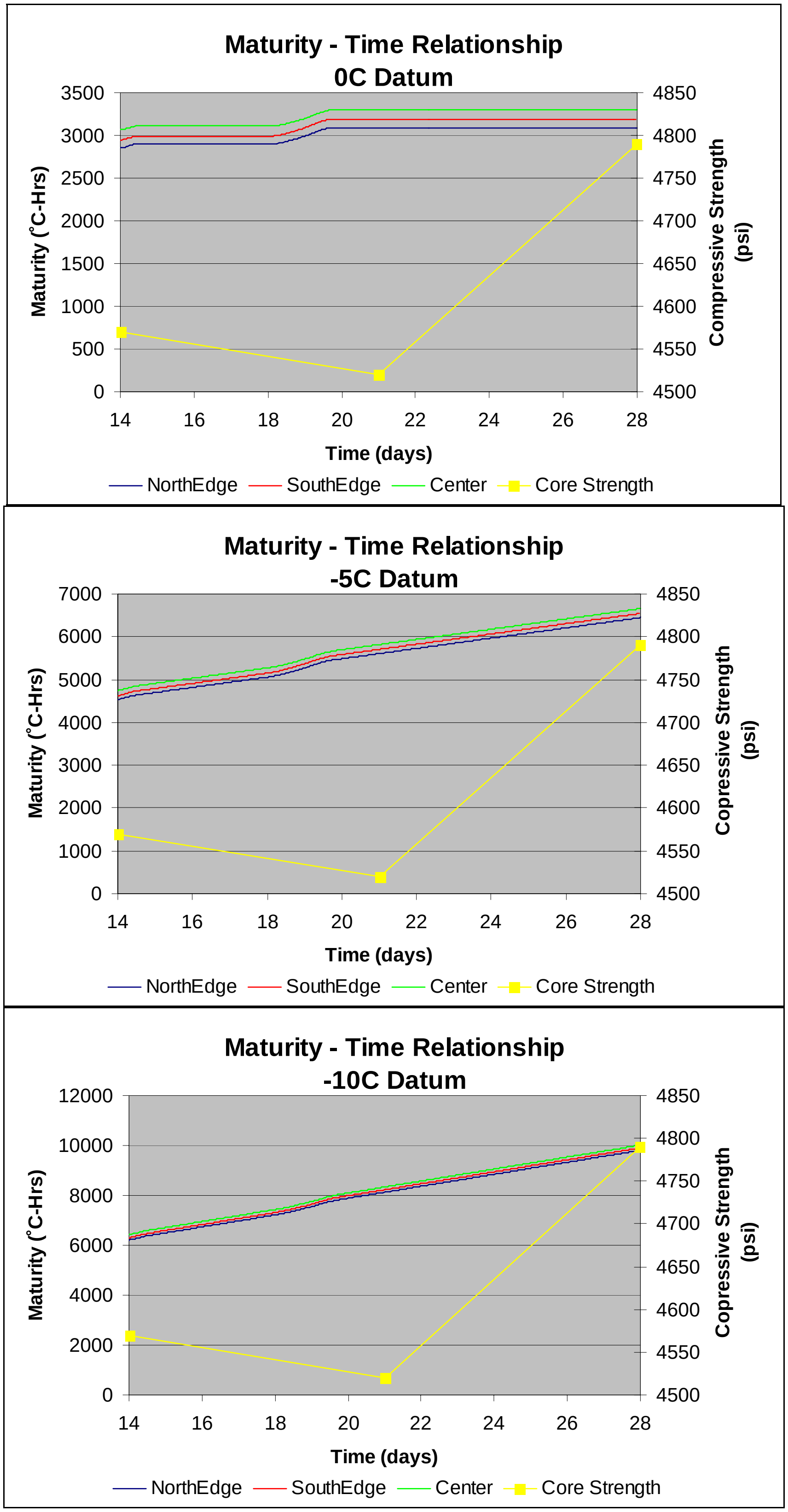

FIGURE 4 Maturity time relationships at 0, -5, and -10 ˚C.

AET Trial Mixing
Trial mixing of the proposed mix design to be used on the Unweave the Weave project was done at American Engineering Testing. To adequately characterize the shape of the maturity-strength curves, flexural strength was tested at 1, 2, 3, 5, 7, and 28 days and compressive strength was tested at 1, 3, 5, 7, 14, and 28 days. In addition to the standard test specimens required, the following test specimens were fabricated from each trail mix:

1 - Flexural beam with a maturity meter installed
2 - 6 x 12 cylinders with maturity meters installed
8 - Additional flexural beams to be broken at 1, 2, 3 and 5 days (sets of 2)
4 - Additional compressive strength cylinders broken at 5 and 14 days (sets of 2)

Mn/DOT supplied the maturity sensors and the readers. A total of four mixes were batched and tested, using two cements, Lafarge Davenport and Mylaki, and two fly ashes, Portage and Coal Creek. Each mix contained 410 lbs of cement, 175 lbs fly ash, and 211 lbs water giving a 0.36 w/cm ratio and 30% fly ash replacement.

The strength maturity curves for flexural and compressive strength of all four trial mixes are shown in Figure 5 for flexural and Figure 6 for compressive strength. Although each mix used the same mix proportions, there was a unique curve for each combination of cement and fly ash. The resulting logarithmic equations for each maturity strength curve are shown in Table 1. The maturity values for each mix at a flexural strength of 350 psi and compressive strength of 3000 psi are shown in Table 2. An important observation to note is that the maturity strength curves based on compressive strength are not the same as the curves based on flexural strength.

All the maturity values measured for these mixes were based on a datum of -10°C. For proper comparison with these lab mixes, all subsequent maturity measurements of the job mix should use the same datum (-10°C). The cement and the fly ash both influence the maturity-strength relationship, and each mix will have a unique maturity-strength curve. Although, of the two cements and two fly ashes used, the maturity-strength curves differed only slightly. As maturity is further studied, a better perspective will be gained on how dramatically the maturity – strength relationship can vary when different mix parameters change and under different curing conditions.

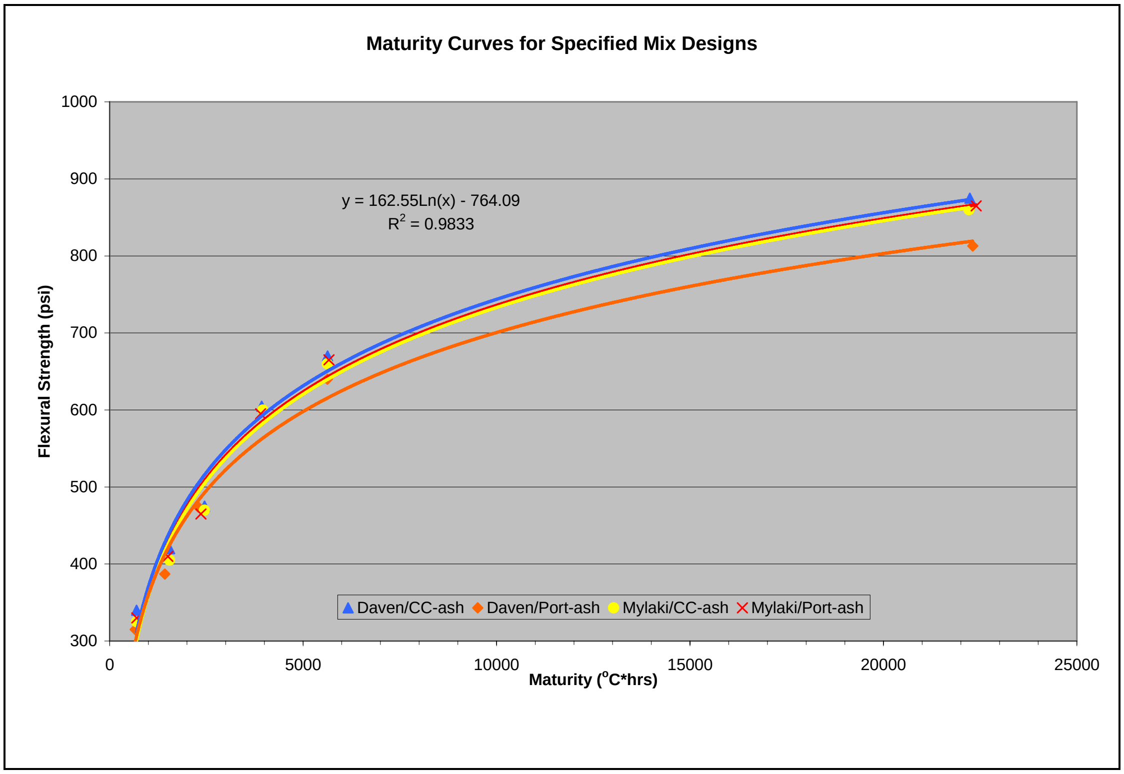

FIGURE 5 AET trial batching maturity flexural strength curves.

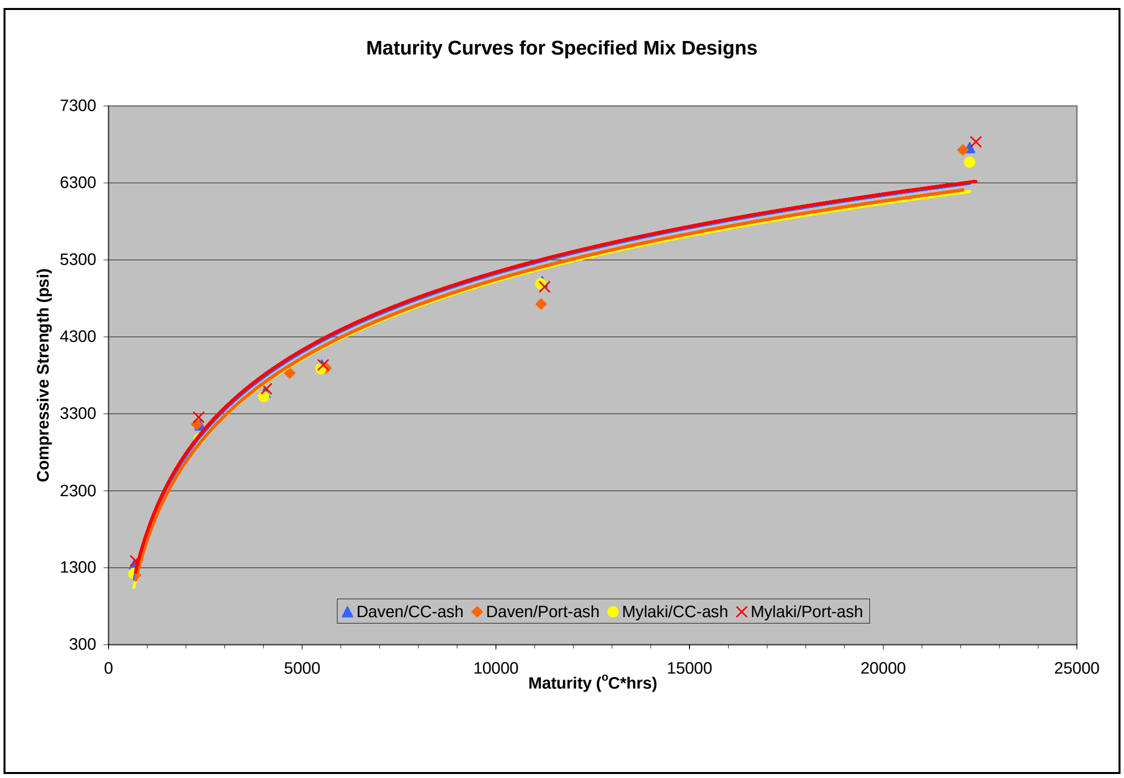

FIGURE 6 AET trial batching maturity compressive strength curves.

TABLE 1 Maturity Strength Equations For AET Trial Batches

Mix	Flexural Strength Equation	R^2
Daven/CC-ash	*Flexural Strength* = 162.18·**Ln**(*Maturity*) - 750.05	0.9816
Daven/Port-ash	*Flexural Strength* = 147.98·**Ln**(*Maturity*) - 662.39	0.9899
Mylaki/CC-ash	*Flexural Strength* = 162.55·**Ln**(*Maturity*) - 764.09	0.9833
Mylaki/Port-ash	*Flexural Strength* = 162.02·**Ln**(*Maturity*) - 756.46	0.9846
Mix	**Compressive Strength Equation**	R^2
Daven/CC-ash	*Compressive Strength* = 1467.6·**Ln**(*Maturity*) - 8393.6	0.9705
Daven/Port-ash	*Compressive Strength* = 1470.2·**Ln**(*Maturity*) - 8495.9	0.9579
Mylaki/CC-ash	*Compressive Strength* = 1458.9·**Ln**(*Maturity*) - 8411.0	0.9808
Mylaki/Port-ash	*Compressive Strength* = 1463.3·**Ln**(*Maturity*) - 8336.2	0.9612

* Maturity values based on -10 ˚C datum

TABLE 2 Maturity at Specific Compressive and Flexural Strengths

Mix	Compressive Strength 3000 psi	Flexural Strength 350 psi
Daven/CC-ash	2150 °C-hr	882.6 °C-hr
Daven/Port-ash	2060 °C-hr	935.8 °C-hr
Mylaki/CC-ash	2380 °C-hr	947.5 °C-hr
Mylaki/Port-ash	2020 °C-hr	924.4 °C-hr

* Maturity values based on -10 ˚C datum

MATURITY IMPLEMENTATION

A general meeting regarding the maturity meters was held on August 24, 2006 involving Mn/DOT Maplewood Lab personnel, Mn/DOT Unweave Engineers and Inspectors, and Contractor representatives. General maturity information and Mn/DOT's preferred method of placement of the maturity data loggers was discussed and clarified. Sixteen data loggers were eventually placed during several separate paving events of the late summer and fall months of 2006 and 2007. Most of the maturity data loggers placed in the paving were still accessible to download after their 28-day data collection window had passed. The shortest data collection period recorded was 15 days, and only 3 of the maturity data loggers were lost before any data could be retrieved from them.

Project inspectors tied the maturity data loggers to the dowel bar baskets. Once placed, the data loggers were initialized just before or just after the paving machine passed to begin the collection of time-temperature data. Most of the data loggers were placed such that their wires would protrude from the sides of the paving slab. It was often necessary to splice additional wire lengths to the data loggers to relocate the wire ends to an area where they would not be buried or damaged by continuing construction operations. The locations of the maturity data loggers placed during 2006 and pictures of installation are shown in Appendix C.

Maturity data was frequently downloaded during the initial days after paving, and approximately every 7-14 days thereafter to maintain a current database in lieu of potential damage or burial of the maturity meter wires. Furthermore, the field inspectors of the Unweave the Weave project periodically download the maturity data. Frequent download of the maturity data during the first days after initiation was important because Mn/DOT's primary objective in these maturity tasks was to evaluate maturity behavior during the critical hours when flexural strengths were approaching values that allowed for some amount of traffic loading.

Data Collection and Analysis

The data loggers placed in the Unweave the Weave project provided continuous maturity data for the 28 day period that they were programmed to remain active. Beams to be tested for flexural strength were cast at every location where a maturity data logger was placed. Once the beams had cured for 24 hours at the location they were cast, the beams were removed from the mold and placed in a water bath near the project construction trailers located on the southeast quadrant of the intersection of I-694 and TH-61. The water bath was not temperature controlled, and water temperature was subject to outdoor ambient temperatures for the entire curing period until the beams were broken. Figures 7 and 8 show the average daily air temperatures at the project site for the 2006 and 2007 paving periods respectively. In general, beams were tested for flexural strength at 2, 3, or 4 days; and also at 7 and 28 days. Davenport cement and Coal Creek Fly Ash was used in all concrete mixes in the Unweave the Weave project, see Appendix D for the concrete mix designs used on the project. Table 3 summarizes the four mix designs that were instrumented with maturity loggers. As shown in the table, each mix design is very similar.

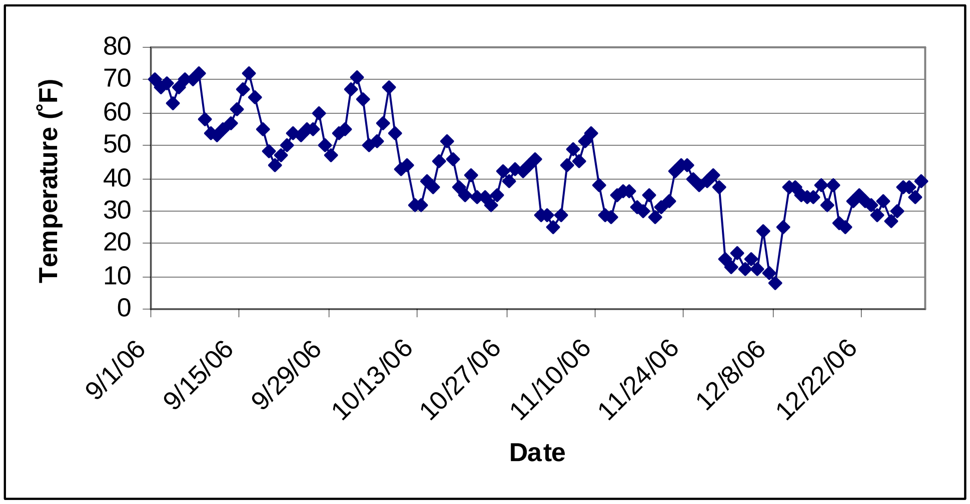

FIGURE 7 St. Paul air temperatures for the 2006 paving period.

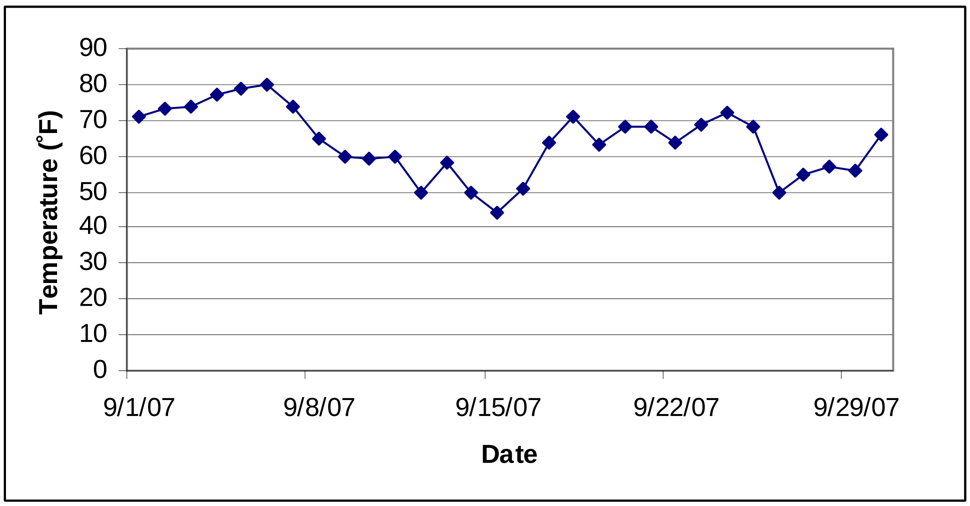

FIGURE 8 St. Paul air temperatures for the 2007 paving period.

TABLE 3 Concrete Mix Designs Instrumented With Data Loggers on Unweave the Weave

Component	3A21-8	3A41-6	3A21-5	3A21-4
Water (lb/yd^3)	193	216	211	205
Cement (lb/yd^3)	400	420	410	400
Fly Ash (lb/yd^3)	150	180	175	170
Sand (lb/yd^3)	1133	1094	1104	1115
CA #1 (lb/yd^3)	220	213	215	217
CA #2 (lb/yd^3)	1071	1034	1044	1053
CA #3 (lb/yd^3)	724	699	706	713
AEA (oz/100 lb cement)	4	4	4	4
w/cm	0.35	0.36	0.36	0.36
% Fly Ash Sub. (%)	27	30	30	30

The locations, maturity data, flexural strength, and concrete mix design for each maturity meter is shown in Table 4. The maturity strength curves for all four concrete mixes that were instrumented with maturity meters are shown in Figure 9. Although each mix used the same cement, fly ash, and similar mix proportions, there are large differences in the resulting maturity curves. As expected, mix 3A21-8 had the highest 28-day strength and followed a much different maturity curve than the other three mixes which had slightly higher w/cm ratio's and higher fly ash replacements. What was not expected is the large difference for such small mixture variations. Mix 3A41-6 had the lowest 28-day strength but since only three data points were obtained for this mix, no conclusions can be drawn.

Figure 10 shows the maturity curves for mix 3A21-5 for both the AET trial batching and the beams made during the Unweave the Weave project. As shown in the figure, the curves are very different even though -10 °C was used as datum for both curves. One reason for this difference is that while the cement, fly ash, and w/cm ratio's used were the same, there could have been differences in the aggregates and chemical admixtures used. Since the maturity meters were placed in the pavements and not the beams, and the beams were cured in a water tank, the most probable reason for the differences in maturity curves is differences in curing temperatures and conditions. In a large mass concrete placement the heat of hydration of the concrete increases the temperature that the concrete experiences (Figure 2). Since maturity is a function of temperature, this increases the maturity of the concrete. Since the beams have a much smaller volume than the pavement, they are affected more by ambient temperatures at early ages. This means that the beams were not at the same maturity as the pavement, and therefore had lower strength. In the future, maturity meters may need to be installed in the beams as well as the pavement to monitor any differences in curing conditions.

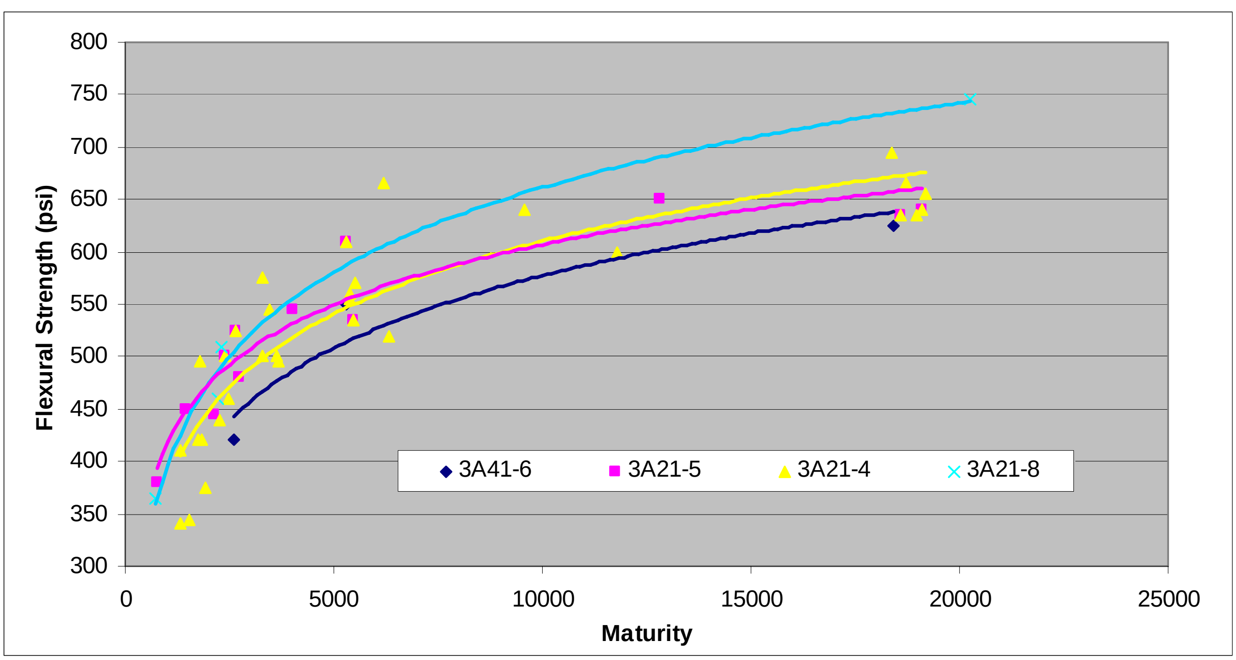

FIGURE 9 Maturity curves for concrete mix designs used on the Unweave the Weave project.

TABLE 4 Maturity Logger Locations and Data

Maturity Meter ID	Station	Beam ID	Date Made	Mix Number	Date Tested	Age (days)	Maturity (^oC*hr)	Modulus of Rupture (psi)
4049561	WB694 2022+30	3A	09/05/06	3A21-5	09/12/06	7	4035	545
		3B			10/03/06	28	12837	650
		3C			09/06/06	1	762	380
		3D			09/07/06	2	1472	450
		3E			09/08/06	3	2150	445
		3F			09/09/06	4	2714	480
		3G			---	---	---	---
4049830	SB35E 1035+10 3' RT	4A	09/08/06	3A21-4 or 5	09/15/06	7	5479	535
		4B			10/06/06	28	18609	635
		4C			09/11/06	3	2629	525
		4D			---	---	---	---
4049556	SB35E 1047+00	5A	09/08/06	3A21-4 or 5	09/15/06	7	5284	610
		5B			10/06/06	28	19099	640
		5C			09/11/06	3	2398	500
		5D			---	---	---	---
4049825	CR E, SW Ramp HOV 105+50 14' LT	6A	09/11/06	3A21-4	09/18/06	7	5369	560
		6B			10/09/06	28	18705	665
		6C			09/13/06	2	1523	345
		6D			09/13/06	2.50	1911	375
4049829	CR E, SW Ramp acc. ln. 95+00	7A	09/12/06	3A21-4	09/19/06	7	5520	570
		7B			10/10/06	28	18966	635
		7C			09/16/06	4	3289	500
		7D			---	---	---	---
4049555	SB35E 1035+10 12' RT	8A	09/13/06	3A21-4	09/20/06	7	5365	555
		8B			10/11/06	28	19191	655
		8C			09/16/06	3	2468	460
		8D			---	---	---	---
4049832	CR E, SW Ramp 100+50 LT	9A	09/13/06	3A41-6	09/20/06	7	5283	550
		9B			10/11/06	28	18423	625
		9C			09/16/06	3	2600	420
		9D			---	---	---	---
4049831	CR E, SW Ramp 102+75 RT Taper	10A	09/14/06	3A21-4	09/21/06	7	6334	520
		10B			10/12/06	28	18388	695
		10C			09/16/06	2	1751	420
4049812	NB35E 804+00 12'-36' RT	12A	10/10/06	3A21-4	10/17/06	7	3660	495
		12B			11/07/06	28	---	615
		12C			10/12/06	2	1316	340
		12D			10/12/06	2	1316	410
4049526	35E 1025+46	63A	9/12/2007	3A21-8	9/15/07	3	2230	460
		63B			10/10/07	28	20247	746
4049520	2083+85	64A	9/12/2007	3A21-8	9/15/07	3	2320	510
4049610	2082+70	67A	9/14/2007	3A21-8	9/15/07	1	746	364

*Maturity datum of 0 ˚C used

TABLE 4 Maturity Logger Locations and Data (Cont.)

Maturity Meter ID	Station	Beam ID	Date Made	Mix Number	Date Tested	Age (days)	Maturity (^{o}C*hr)	Modulus of Rupture (psi)
4049589	NB35E to 694 814+00 LT	15A 15B 15C 15D	10/13/06	3A21-4	10/20/06 11/10/06 10/17/06 ---	7 28 4 ---	3628 11797 2246 ---	500 600 440 ---
4049587	SB35E 1032+75 CL-24' LT	17A 17B 17C	10/16/06	3A21-4	10/23/06 11/13/06 10/19/06	7 28 3	3473 6217 1814	545 665 495
4049811	SB35E to EB694 1034+58 (Ramp SB35E 31+05)	19A 19B 19C 19D	11/06/06	3A21-4	11/13/06 12/04/06 11/09/06 ---	7 28 3 ---	3305 9576 1824 ---	575 640 420 ---

*Maturity datum of 0 ˚C used

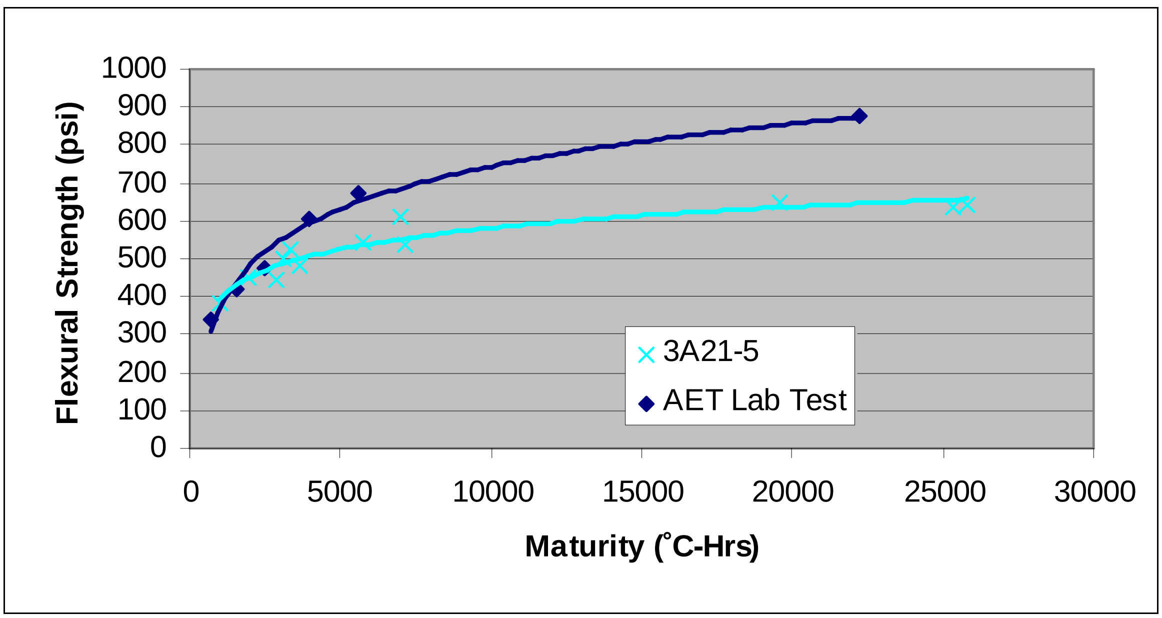

FIGURE 10 Laboratory and field maturity curves for mix 3A21-5.

Recommendations for Further Field Implementation

This report encompasses the maturity tasks completed in preparation to and including the Unweave the Weave project. Through cooperation of Mn/DOT Maplewood Lab personnel, Mn/DOT Inspectors and Engineers, and Contractors/Subcontractors on the project, the maturity tasks performed were largely successful, and 15 of the 21 maturity data loggers originally placed in the concrete remained available for download after the 28-day data collection period had expired.

The primary factors related to the success of the implementation of the fieldwork tasks on the Unweave the Weave project include, but are not limited to:

- Communication with the primary concrete paving inspector
- Proper documentation of paving operations and activities
- Proper documentation, and mapping, of the locations of maturity data loggers
- Marking the location of data loggers clearly on the pavement
- Frequent download of the maturity data
- Relocation of the data download wires when construction activities encroached on their original location
- Consistent beam casting/curing technique and documentation of such
- Consistent strength testing technique and documentation

Several difficulties with implementing the maturity tasks on this project include, but are not limited to:

- Confirming the exact time of a paving event
- Placing data loggers near areas where many construction activities might occur simultaneously, making the relocation of data logger wires to a safe area difficult
- Finding the field location of a data logger as landmarks change and station laths are lost due to the construction progression
- Placing maturity data logger wires in areas where they will not be damaged or buried

As with any field procedure, proper documentation and field notes are an essential component to successful completion of field tasks. Accuracy in documenting the location of the maturity meter is of utmost importance because often it is difficult to spot the data wires protruding from the side of the pavement. Large markings in bright paint on the top surface of the pavement are extremely helpful. On the Unweave the Weave project, data wires were often temporarily lost just after paving, and also during subsequent shoulder grading operations. As a result it was common to extend the wires beyond the paved shoulder so that they would not be lost when the shoulder was paved/graded.

A potential solution to the problem with locating the wires is to implement wireless maturity data loggers on future construction projects. This will eliminate any problems with losing valuable data due to buried, damaged, or cut data wires.

CONCLUSIONS

An implementation project was carried out on the TH-694/ TH-35E interchange (SP 6280-304) otherwise known as the Unweave the Weave project. This was one of the first Mn/DOT projects to test the implementation of maturity meters in a field setting. Field implementation on this project helped to show the potential benefits and weaknesses of using maturity data loggers. The preliminary tasks for this project included a field demo at MnROAD and a lab study.

The MnROAD field demonstration included the installation and monitoring of data loggers in a test slab. The lab study included monitoring of data loggers during trial mixing at AET and establishing maturity strength curves for combinations of two different cements and fly ashes. The final task included placements of maturity data loggers in the concrete paving of the Unweave the Weave project and subsequent download and examination of maturity data. This report summarizes the finding of all three tasks.

Based on the trial slab at MnROAD, it is recommended that -10 °C be used as the datum temperature. The trail mixing at AET showed that for identical mix proportions, different cements and fly ashes produce different maturity curves. The maturity curves for flexural and compressive strength for a mix were also different with mixes gaining flexural and compressive strength at different rates of maturity gain. Maturity meters installed at the Unweave the Weave project showed that for small changes in cementitious content (10 lbs/yd^3) or mix proportions with w/cm ratio constant, there are differences in the resulting maturity strength curves.

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2. Mohsen, J.P., Roach, B.L., and Kessinger, D.T. (2004). "Maturity Method Applied to Highway Construction," *Transportation Research Record*, Washington, D.C., pp. 79-85.

3. Standard Practice for Estimating Concrete Strength by the Matruity Method. *ASTM C 1074 -04*, ASTM International, West Conshohocken, PA.

4. Rajesh, C. and Carino, N. J. (1991). "Rate Constant Functions for Strength Development of Concrete," *ACI Materials Journal*, Vol. 88, No. 1, January-February, pp. 74-83.

APPENDIX A

Maturity Work Plan

Developing Maturity-Strength Curves for High-pozzolan/High SCM Mixes and Low Water/Cementitious Ratio

Proposed Work Plan

Problem Statement: The maturity factor is used as a non-destructive way of estimating the concrete strength at different ages. Maturity-strength curves can be used to estimate when to saw joints and when a pavement can be open to traffic. Maturity-strength curves are common for many standard PC concrete mixes; however few are available for the high-pozzolan/SCM (supplementary cementing materials) substitution and low w/cm (water/cement-ratio) mixes often used by MN/DOT. In addition, the development of strength in these mixes is strongly influenced by ambient temperatures which make early- or late-season paving with these mixes susceptible to problems and difficult to predict when to saw joints and open pavement to traffic. Use of high-pozzolan/SCM mixes is limited and often avoided, especially in late- or early-season paving, because of the strong and often unpredictable influence of ambient temperature during paving and curing.

Benefits: If maturity-strength curves are available for high-pozzolan or high-SCM and low w/cm mixes that represent a variety of ambient conditions then early and long-term strengths can be predicted simply by monitoring the temperature of the concrete and ambient conditions during hydration. This will help prevent costly problems related to unpredicted delays in joint sawing and opening time, raveling and cracking at the joints when not cut at the proper time, or opening before adequate strength has developed. Applicable maturity-strength curves will enable the use of these mixes during early and late season paving and enable MN/DOT to optimize mix selection based on performance requirements and anticipated ambient conditions.

Introduction and Background: The strength development in concrete is directly related to the hydration of the cement. As the cement hydrates the strength increases. The hydration process is an exothermic reaction, releasing heat as the cement hydrates and concrete hardens and gains strength. The heat released over time can be measured and related to the strength that developed. Therefore, the strength of concrete can be considered a function of the total heat released over time or written as $\sum$ (time interval x temperature). This summation is called the maturity and expressed in units of degree C-hours.

The maturity factor is influenced by ambient conditions such as temperature, relative humidity (RH), and wind during placement and hydration/curing. Maturity also is influenced by mix parameters such as type of cement, use of pozzolans, SCM, and w/cm. All of these factors can influence the hydration process, and subsequent temperatures and the strength gains of the concrete. Each combination of ambient conditions and mix properties could potentially result in a unique strength-maturity curve.

Maturity curves are often developed in the lab for a given mix and used to predict strength gain in the field. For standard OPC concrete mixes this may be adequate in many situations. However, the hydration process in high-pozzolan and/or SCM mixes with low w/cm is very sensitive to ambient temperatures. Ambient lab conditions may not adequately represent many field conditions, and could result in significantly different maturity-strength curves inaccurately predicting strength gains in the field, especially with early- and late-season paving.

Objective: **The goal of this study is to develop maturity-strength curves that represent the majority of mixes used in MN/DOT paving projects at paving conditions typical for Minnesota, especially in the late fall and early spring. To achieve this, the hydration temperatures of several mixes placed during demo project(s) and paving projects will be monitored using IntelliRock thermocouple devices.**

Thermocouple devices will be placed in several locations and levels within the slab, per manufacturer's recommendations. Several cylinder and beam specimens will be cast from the same paving mix as the demo slab or pavement. At least one cylinder and one beam will be fitted with thermocouple devices. Specimens will be cured in the field, alongside the pavement slab and treated in a similar manner as the slab. Specimens will be tested for compressive and flexural strength in compliance with ASTM/AASHTO standard test procedures at 1, 3, 7, 14 and 28 days.

On several projects additional cylinders and beams will be fabricated from the paving mix, with at least one cylinder and one beam fitted with thermocouples devices. These extra specimens will be moist cured in laboratory conditions and tested at the same time intervals as field cured specimens to compare maturity-strength relationships of the same mix but under field vs. lab conditions. Also, on several projects cores will be taken from the slabs and tested for compressive strength at the same intervals as the cylinders. Maturity-strength curves will be developed from testing the cores and compared to curves developed on the strengths of the cylinders.

Task 1 - Demo
A 6ft x 6ft x 10in slab will be poured in the late fall out at the MnRoad site using a 3U18 mix and low w/cm. Thermocouple devices will be placed in several locations and levels within the slab, near the edge, near the center and approximately 1 ft from the edge. Where possible devices will be placed at 3 different depths within the slab:1) at 1-inch below the surface, 2) at mid-depth 3) 1-inch above the bottom of the slab.

From the same mix as the slab, cylinder specimens will be poured. Thermocouple devices will be place at 3 levels within at least one cylinder: 1) 1-inch below the surface, 2) in the center of the cylinder and 3) 1-inch above the bottom of the cylinder. The cylinders will remain in the field and cured under similar conditions as the slab.

At specified intervals (ideally at 1, 3, 7, 14 and 28 days) field cured specimens will be tested for compressive strength. At the same time intervals cores shall be taken at least 1ft away from the edge of the slab, noting the exact location, and then tested for compressive strength. All cores shall be sealed in plastic and carefully transported to the lab, especially at early ages when strength is not well developed. Cores shall be retrieved from areas near the thermocouple devices but in such a way as to not damage the instruments. The instrumented cylinder specimen(s) shall not be tested until the final day.

Ambient temperatures, RH and wind speed will be monitored for the duration of the testing. If desired strengths are not achieved in the field specimens within 28 days then specimens and cores will continue to be tested at 42 and 56 days, or until ambient temperatures consistently fall to -10°C (14°F) the temperature at which hydration is halted. If temperatures consistently fall below this critical level then the remaining specimens will finish curing in the lab at 0°C (32°F) and tested at 42 and 56 days.

Maturity-strength curves will be developed for a combination of the following temperature and strength conditions:

Table 1. Temperature and strength conditions

Temperature	Strengths
Slab (one curve for each location in the slab)	Cores
Slab (one curve for each location in the slab)	Cylinder – field cured
Cylinder (field cured)	Cores
Cylinder (field cured)	Cylinder - field

Benefits: The demo will provide good training and practice on how to place the devices in new concrete, both slabs and test specimens. It will provide an opportunity on how to read the devices and develop maturity-strength curves from the data. It will provide insight on best placement techniques and where to place the devices both in the slab and test specimens to provide the most useful data. It will demonstrate how the maturity-strength curves based on slab temperatures and core strengths relates to maturity-strength curves based on cylinder temperatures and strengths.

Task 2 – Lab study

To better understand how extreme ambient conditions may influence the maturity of various high pozzolan/SCM mixes with low w/cm a lab study will be pursued prior to the 2006 construction season. Several mixes will be developed and tested in the lab monitoring the heat of hydration and testing the strength at specified intervals. Curing will take place in simulated environmental extremes that are expected to influence the strength development. The environmental chamber will be used to simulate extreme summer ambient conditions that might be experienced during summer and a refrigerator will be used to simulate late/early season paving.

Specimens primarily used for testing will be 4 x 8 cylinders. Two cylinders will be instrumented from each batch. Compressive strength tests will be performed at regular intervals similar to that proposed in Task 1. A test matrix of mix designs will be developed in conjunction with the Concrete Unit. At least one thermocouple will be used to monitor the air temperature and RH measurements will occur when possible.

As a control, for comparison, each mix will have specimens cured in the moist room at standard temperatures and least one OPC concrete mix, without pozzolans or SCM will be cured at higher temperatures, at lower temperatures and in a standard moist room.

Benefits: Task 2 will allow for testing a variety of high-pozzolan/SCM mixes with Mn/DOT's typical low w/cm. Preliminary maturity-strength curves will be developed that will then be corrected or validated during Task 3, field paving. We will begin to develop an understanding on how temperature extremes influence maturity and the strength development and how best to measure it. It should provide some background knowledge that will aid in choosing mixes for Task 3 and optimize the use of the thermocouple devices.

Task 3 – Early- and Late-Season, and Mid-Summer (High Temperature) Paving

The process will be similar to Task 1 in that slabs and cylinders will be placed, monitored and tested, but exact methodology will be refined based on what is learned from task 1 and 2. Unlike task 1, the slab will be actual paving projects and the mixes actual pavement mixes. The exact placement of the thermocouples and days for strength testing may be adjusted pending results of Tasks 1 and 2.

Benefits: Task 3, performed using knowledge acquired during Tasks 1 and 2, will allow a comparison between the maturity-strength curves for actual paving versus field cured and lab cured high-pozzolan/SCM with low w/cm. Once defined and correlated, the maturity-strength curves from the paving and cylinders may eventually be used for Mn/DOT paving projects to provide an accurate representation of pavement strength so that sawing operations and subsequent reopening of the road for public use can be done in a timely manner, without adverse effects on the concrete.

APPENDIX B

Trial Slab Figures and Pictures

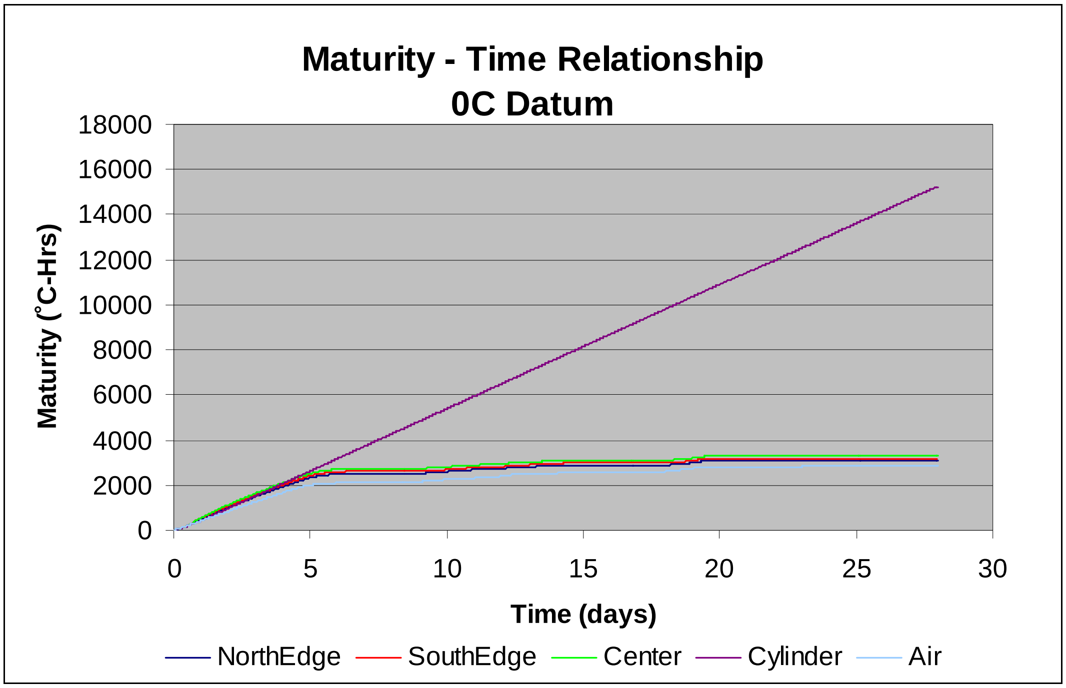

FIGURE B1 Maturity time relationship for test slab.

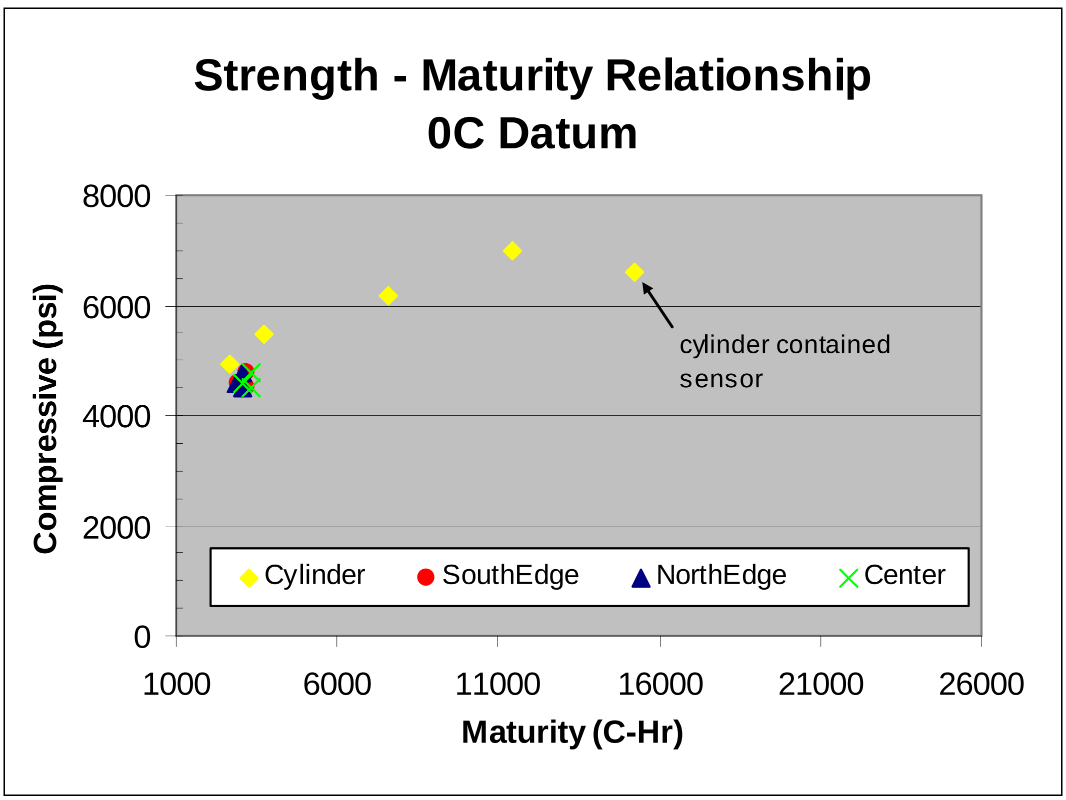

FIGURE B2 Trial slab strength maturity relationship for 0˚C datum.

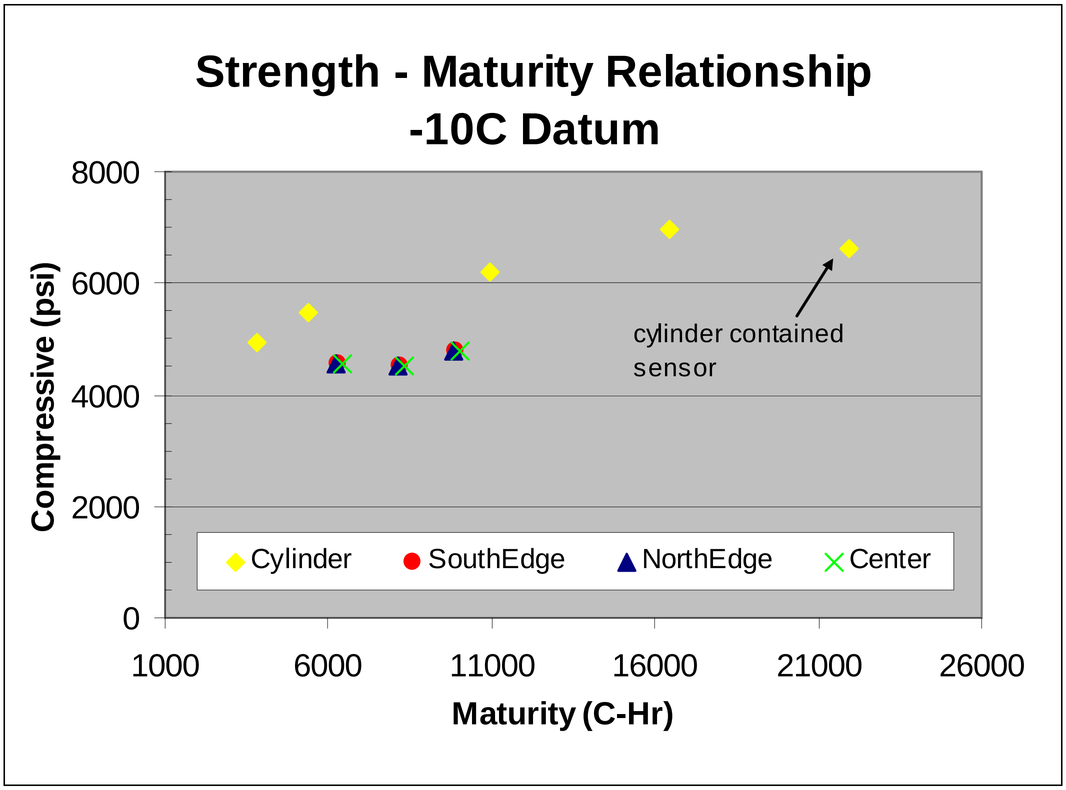

FIGURE B3 Trial slab strength maturity relationship for -10˚C datum.

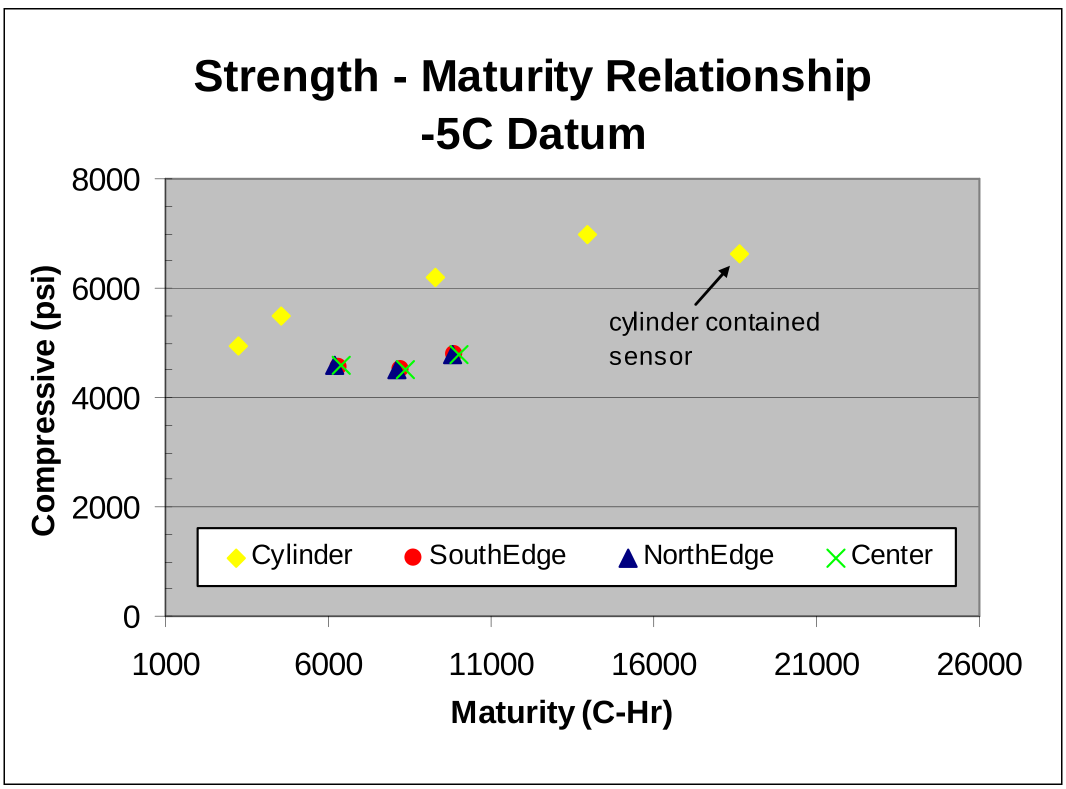

FIGURE B4 Trial slab strength maturity relationship for -5˚C datum.

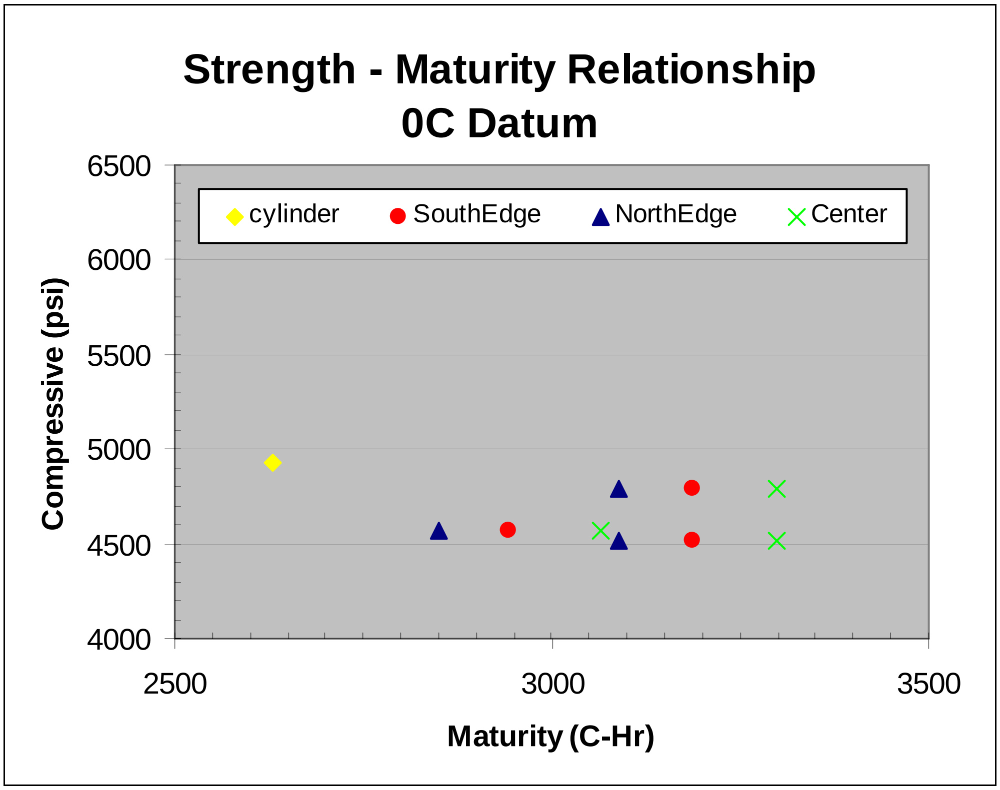

FIGURE B5 Close up of trial slab strength maturity relationship for 0˚C datum.

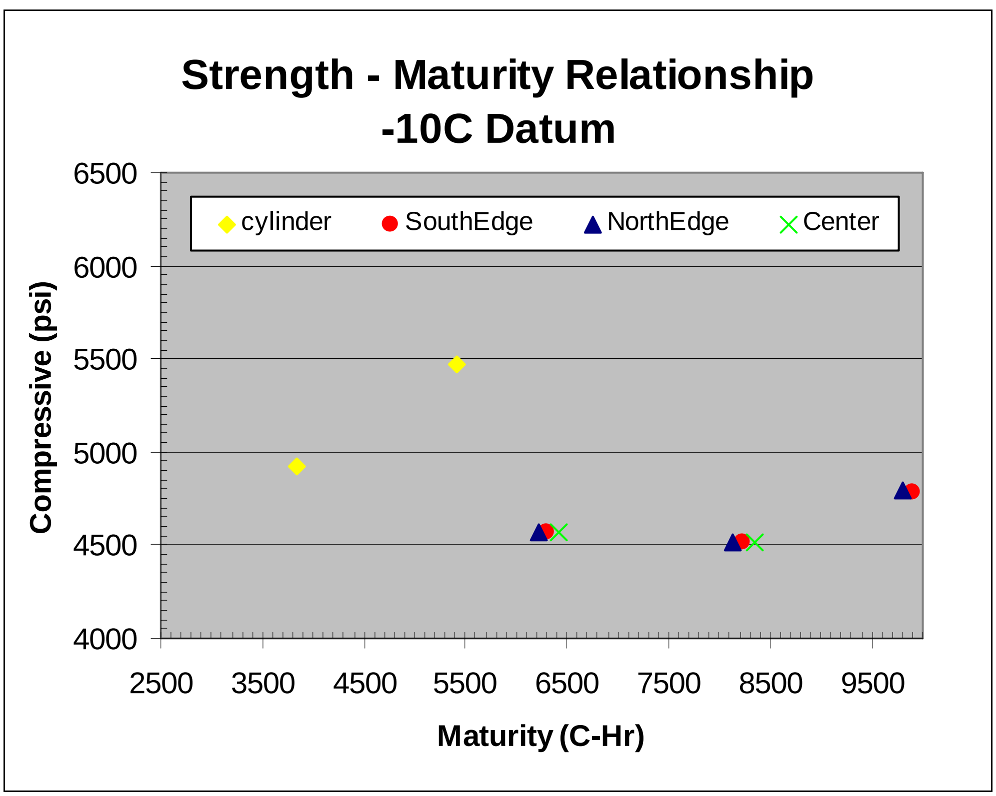

FIGURE B6 Close up of trial slab strength maturity relationship for -10˚C datum.

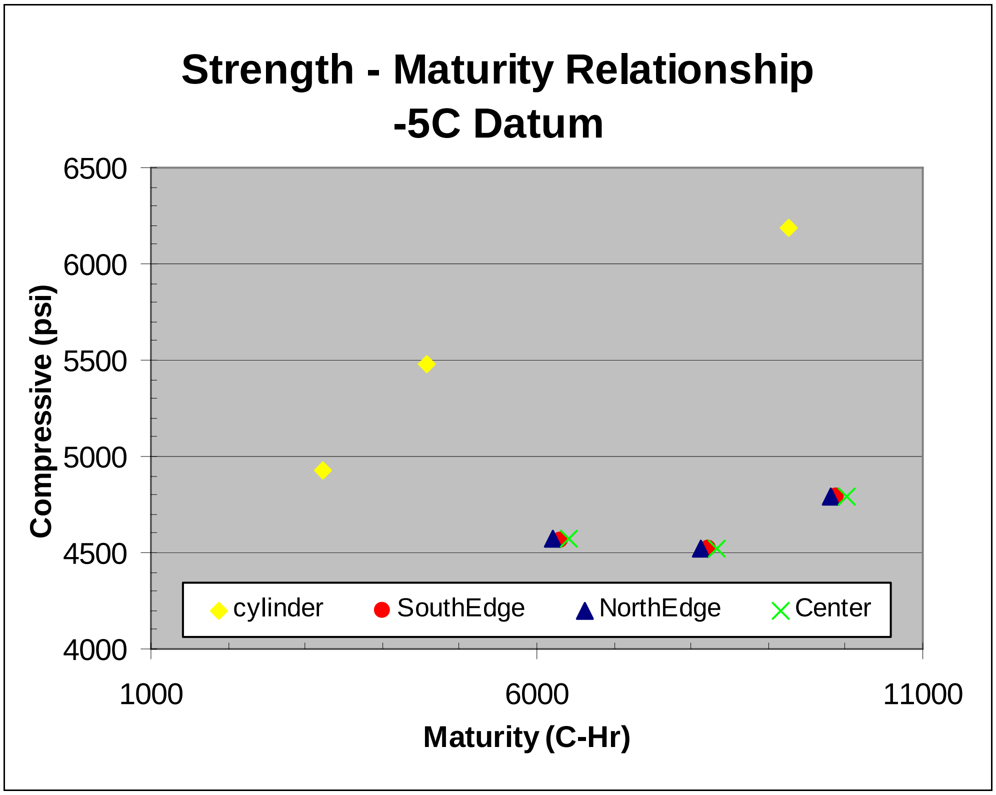

FIGURE B7 Close up of trial slab strength maturity relationship for -5˚C datum.

FIGURE B8 MnROAD trial slab.

FIGURE B9 Placement of edge maturity meter in MnROAD trial slab.

FIGURE B10 Placement of maturity meter in cylinders.

FIGURE B11 Maturity meter wire protruding out side of test slab.

FIGURE B12 Placement of maturity meter in center of test slab.

FIGURE B13 Maturity data logger.

APPENDIX C

Data Logger Locations and Pictures

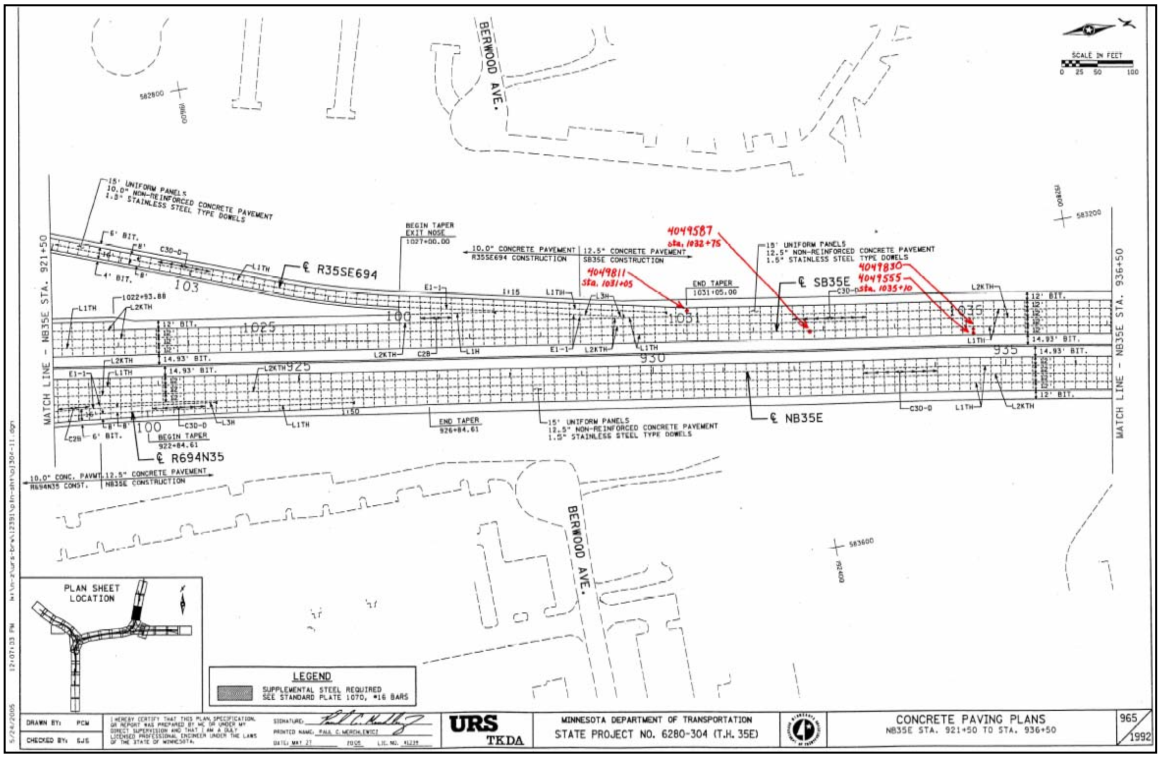

FIGURE C1 Location of data loggers 4049811, 4049587, 4049830, and 4049555.

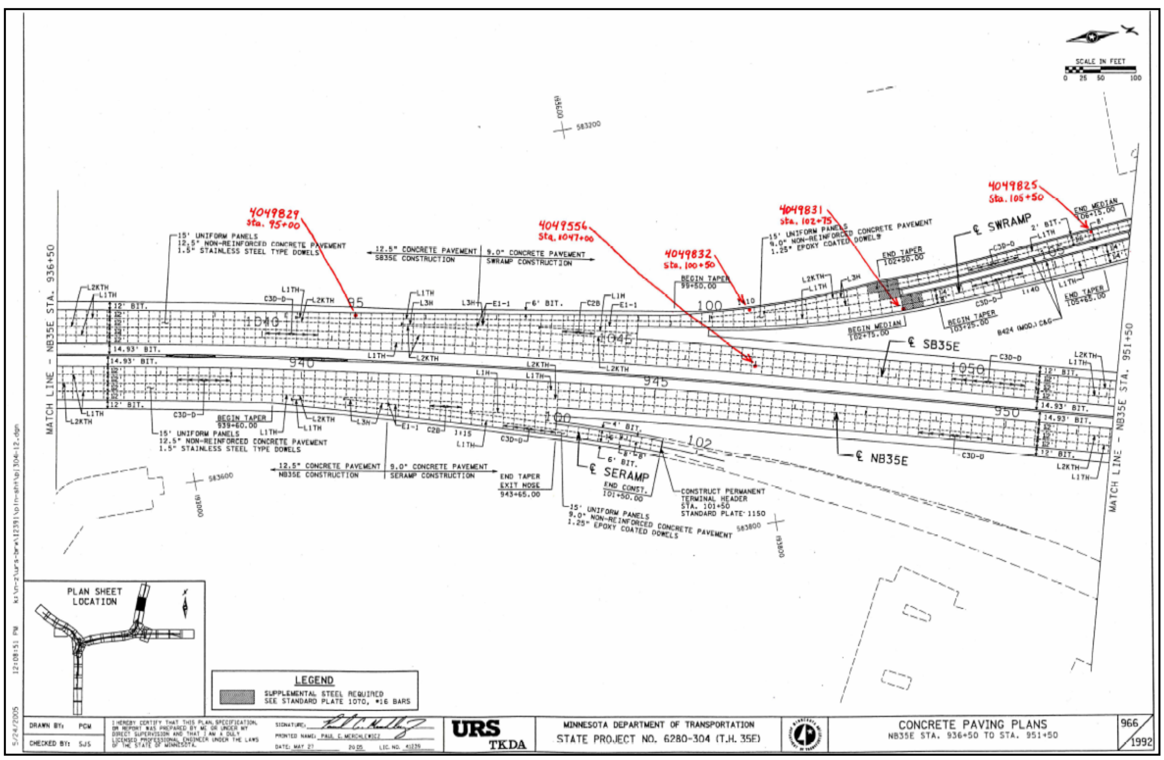

FIGURE C2 Location of data loggers 4049829, 4049556, 4049832, 4049831, and 4049825.

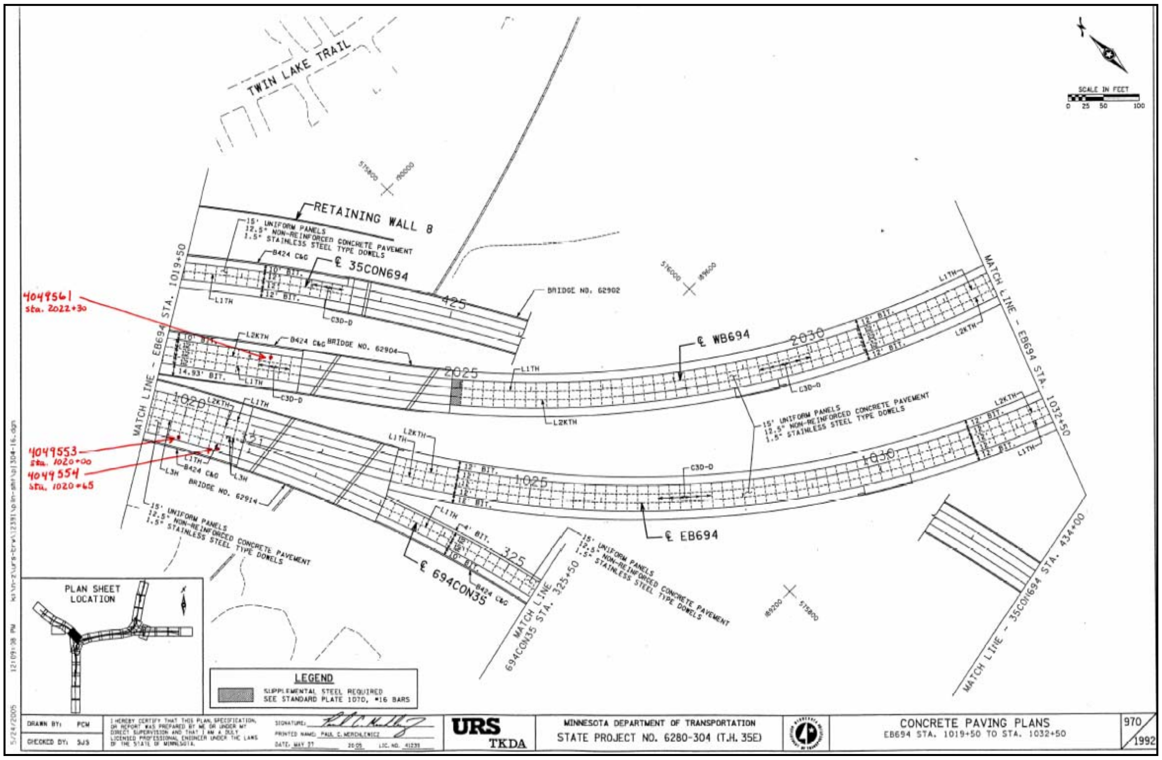

FIGURE C3 Location of data loggers 4049561, 4049553, and 4049554.

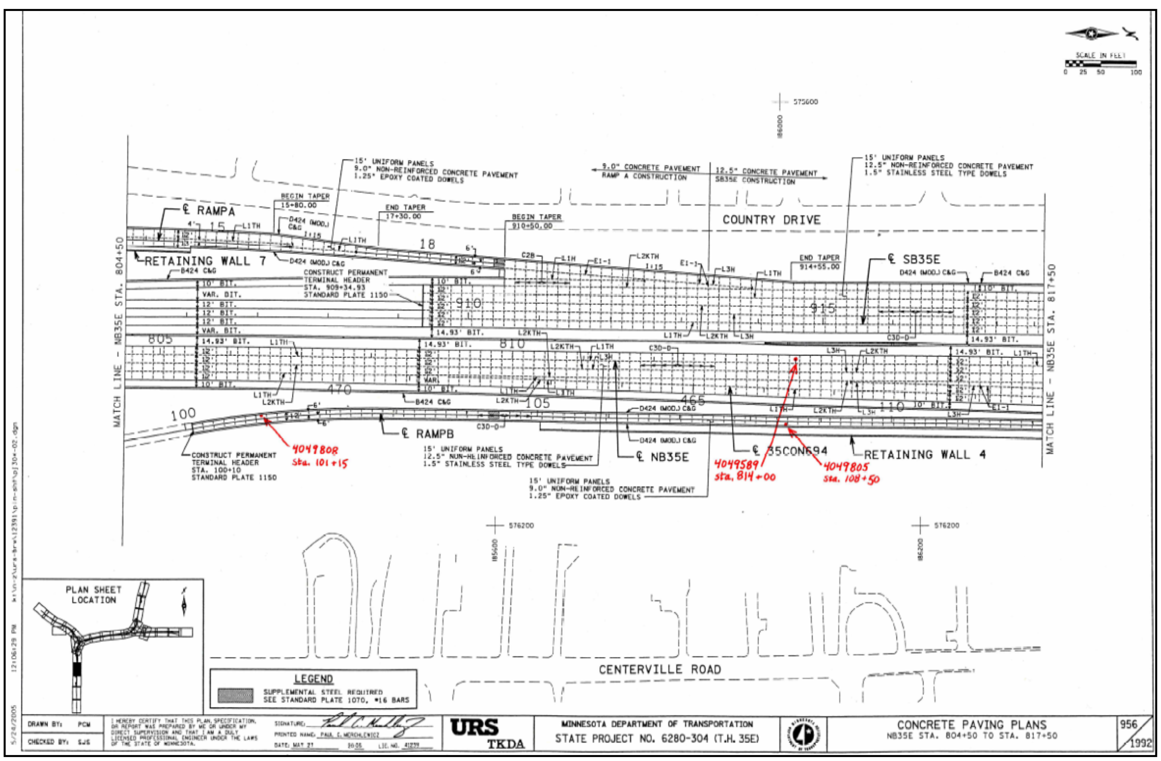

FIGURE C4 Location of data loggers 4049808, 4049589, and 4049805.

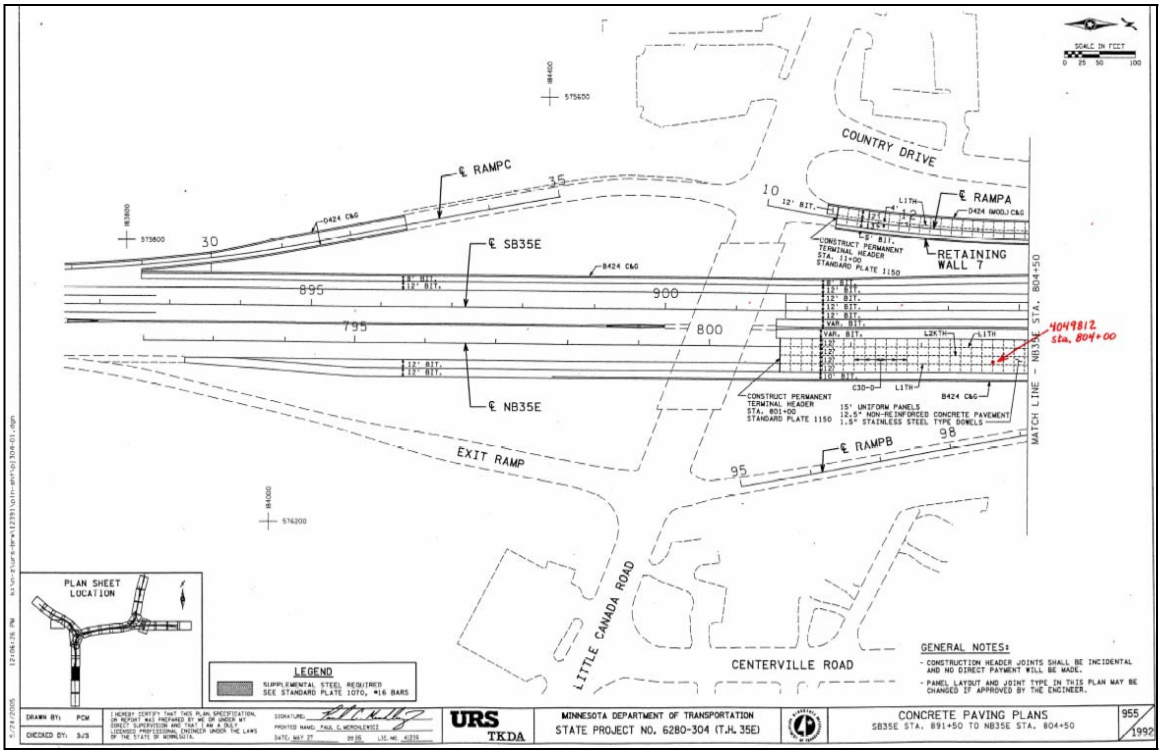

FIGURE C5 Location of data logger 4049812.

FIGURE C6 Pictures of sensor instalation on Unweave the Weave project.

APPENDIX D

Unweave the Weave Mix Designs

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Troy Vrieze Phone: 651-257-5019

Firm Name: Shafer Contracting Co.

Agency Engineer/Inspector: Mn/DOT T. Krier S.P. 6280-304 TH 35E/694

	CA #1	CA #2	CA #3	Sand
Pit Number	113004	182004	182004	182001
Pit Name	Al St. Croix	Agg. Ind. LL	Agg. Ind. LL	Al Nelson
Nearest Town				
Size	FA-2	3/4"	1-1/2"	—
Specific Gravity	2.68	2.67	2.67	2.62
Absorbtion (Provided by MN/DOT)	0.015	0.014	0.014	0.010

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Lafarge	Headwaters	—
Mill/Power Plant	Davenport	Coal Creek	—
Type/Class	Type I	Class C/F	—
Specific Gravity	3.15	2.55	—

Proposed Mix Designs

MN/DOT Mix Number	#1 3A21	#2 3A21	#3 3A41	—
Water (lbs/C.Y.)	205	210	216	—
Cement (lbs/C.Y.)	400	410	420	—
Fly Ash (lbs/C.Y.)	170	175	180	—
Other Cementitious (lbs/C.Y.)	—	—	—	—
w/cm Ratio	0.36	0.36	0.36	—
Sand (Oven Dry, lbs/C.Y.)	1117	1106	1096	—
CA #1 (Oven Dry, lbs/C.Y.)	216	215	213	—
CA #2 (Oven Dry, lbs/C.Y.)	1053	1044	1034	—
CA #3 (Oven Dry, lbs/C.Y.)	713	706	700	—
% Air Content	7	7	7	—
Admix. # 1 (oz/100 # CM)	4	4	4	—
Admix. # 2 (oz/100 # CM)	—	—	—	—

The above mixes are approved for use, contingent upon satisfactory site performance and continuous acceptability of all material sources, by:

JKXYaH 6/13/06

Concrete Engineering Specialist DATE

Comments:

FIGURE D1. Mix designs 3A21-1, 3A21-2, and 3A41-3.

Mix #
1,2,3

JMF748
Job Mix Formula

Unweave the Weave
S.P.6280-304

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	pea	3/4-	1.5"		SAND						
PROPORTION, %	7.00%	34.00%	23.00%		36.00%		100.00%				
2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1"	100.0	100.0	58.0		100.0		90	± 5	85	95	10
3/4"	100.0	98.0	14.0		100.0		80	± 5	75	85	11
1/2"	100.0	68.0	1.0		100.0		66	± 5	61	71	13
3/8"	100.0	36.0	0.0		100.0		55	± 5	50	60	11
#4	87.0	6.0	0.0		100.0		44	± 5	39	49	11
#8	14.0	1.0	0.0		86.0		32	± 4	28	36	12
#16	4.0	0.0	0.0		60.0		22	± 4	18	26	10
#30	1.0	0.0	0.0		29.0		11	± 4	7	15	11
#50	0.0	0.0	0.0		5.0		2	± 3	0	5	9
#100	0.0	0.0	0.0		1.0		0	± 2	0	2	1
#200	0.0	0.0	0.0		1.0		0.4	± 1.6% max	0.0	2.0	0

Workability Factor
(% passing #8)
32

Coarseness Factor
(% retained above 3/8" / % retained above #8)
66

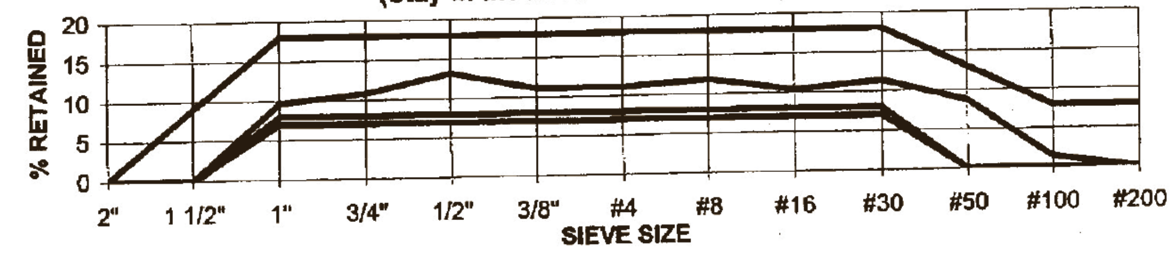

FIGURE D2 Job mix formula and aggregate gradation for mix designs 3A21-1, 3A21-2, and 3A41-3.

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Greg C. Pelkey Phone: 651-257-5019

Firm Name: Shafer Contracting Co.

Agency Engineer/Inspector: Mn/DOT T. Krier S.P. 6280-304 TH 35E/694

	CA #1	CA #2	CA #3	Sand
Pit Number	113004	13004	182004	182001
Pit Name	Al St Croix	Al St Croix	Agg. Ind. Lt.	Al Nelson
Nearest Town				
Size	FA-2	3/4"	1-1/2"	——
Sp. G. & Abs. (Provided by Mn/DOT)	2.66/0.015	2.88/0.014	2.67/0.014	2.82/0.010

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Lafarge	Lafarge	——
Mill/Power Plant	Davenport	Coal Creek	——
Type/Class	Type I	Class F	——
Specific Gravity	3.15	2.55	——

Propsed Mix Designs

MN/DOT Mix Number	#4 3A21	#5 3A21	#6 3A41
Water (lbs/C.Y.)	205	211	216
Cement (lbs/C.Y.)	400	410	420
Fly Ash (lbs/C.Y.)	170	175	180
Other Cementitious (lbs/C.Y.)	——	——	——
w/cm Ratio	0.36	0.36	0.36
Sand (Oven Dry, lbs/C.Y.)	1115	1104	1094
CA #1 (Oven Dry, lbs/C.Y.)	217	215	213
CA #2 (Oven Dry, lbs/C.Y.)	1053	1044	1034
CA #3 (Oven Dry, lbs/C.Y.)	713	706	699
% Air Content	7	7	7
Admix. # 1 (oz/100 # CM)	4	4	4
Admix. # 2 (oz/100 # CM)	——	——	——

The above mixes are approved for use, contingent upon satisfactory site performance and c acceptability of all material sources, by:

Maria Masten 8/21/2006

(Asst. Concrete Engineering Specialist) DATE

FIGURE D3. Mix designs 3A21-4, 3A21-5, and 3A41-6.

[illegible] mixes 4-6

Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	FA-2	3/4-	3/4+		Sand						
PROPORTION, %	7.00%	34.00%	23.00%		36.00%		100.00%				
2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1"	100.0	100.0	58.0		100.0		90	± 5	85	95	10
3/4"	100.0	99.0	14.0		100.0		80	± 5	75	85	10
1/2"	100.0	67.0	1.0		100.0		66	± 5	61	71	14
3/8"	100.0	42.0	0.0		100.0		57	± 5	52	62	9
#4	87.0	5.0			100.0		44	± 5	39	49	13
#8	14.0	1.5			86.0		32	± 4	28	36	11
#16	4.0				60.0		22	± 4	18	26	11
#30	1.0				29.0		11	± 4	7	15	11
#50	0.0				5.0		2	± 3	0	5	9
#100	0.0				1.0		0	± 2	0	2	1
#200	0.0				1.0		0.4	± 1.6% max	0.0	2.0	0

Workability Factor
(% passing #8)
32

Coarseness Factor
(% retained above 3/8" / % retained above #8)
63

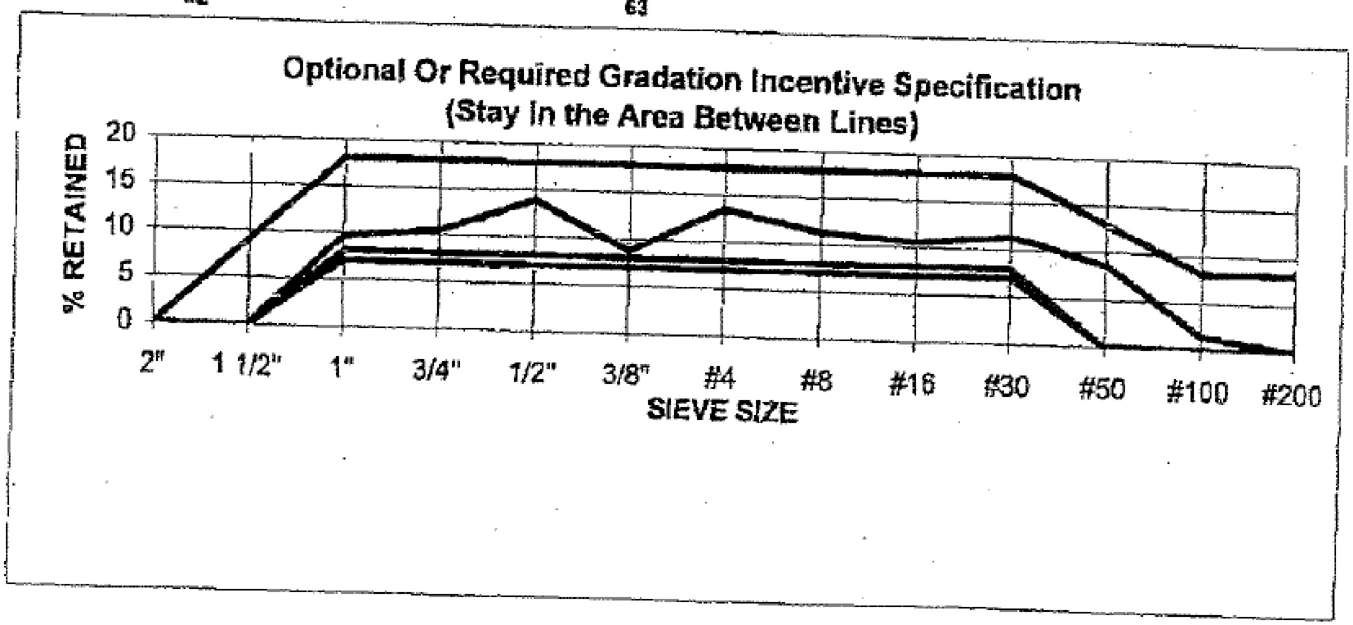

FIGURE D4 Job mix formula and aggregate gradation for mix designs 3A21-1, 3A21-2, and 3A41-3.

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Greg C. Peikey Phone: 651-257-5919

Firm Name: Shafer Contracting Co.

Agency Engineer/Inspector: Mn/DOT T. Krier S.P. 6280-304 TH 35E/694

	CA #1	CA #2	CA #3	Sand
Pit Number	113004	13004	162004	182001
Pit Name	Al St Croix	Al St Croix	Agg. Ind. LL	Al Nelson
Nearest Town				
Size	FA-2	3/4"	1-1/2"	—
Sp. G. & Abs. (Provided by MN/DOT)	2.66/0.015	2.60/0.014	2.57/0.014	2.62/0.010

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Lafarge	Lafarge	—
Mill/Power Plant	Davenport	Coal Creek	—
Type/Class	Type I	Class F	—
Specific Gravity	3.15	2.55	—

Propsed Mix Designs

MN/DOT Mix Number	#7 3A21	#8 3A21	#9 3A21
Water (lbs/C.Y.)	189	193	196
Cement (lbs/C.Y.)	400	400	400
Fly Ash (lbs/C.Y.)	140	150	160
Other Cementitious (lbs/C.Y.)	—	—	—
w/cm Ratio	0.35	0.35	0.35
Sand (Oven Dry, lbs/C.Y.)	1140	1133	1127
CA #1 (Oven Dry, lbs/C.Y.)	222	220	218
CA #2 (Oven Dry, lbs/C.Y.)	1078	1071	1064
CA #3 (Oven Dry, lbs/C.Y.)	729	724	720
% Air Content	7	7	7
Admix. # 1 (oz/100 # CM)	4	4	4
Admix. # 2 (oz/100 # CM)	—	—	—

The above mixes are approved for use, contingent upon satisfactory site performance and c acceptability of all material sources, by:

Maria Masten 5/1/2007

Concrete Materials Specialist DATE

FIGURE D5 Mix designs 3A21-7, 3A21-8, and 3A21-9.

Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	FA-2	3/4-	3/4+		Sand						
PROPORTION, %	7.00%	34.00%	23.00%		36.00%		100.00%				
2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1"	100.0	100.0	58.0		100.0		90	± 5	85	95	10
3/4"	100.0	99.0	14.0		100.0		80	± 5	75	85	10
1/2"	100.0	67.0	1.0		100.0		66	± 5	61	71	14
3/8"	100.0	42.0	0.0		100.0		57	± 5	52	62	9
#4	87.0	5.0			100.0		44	± 5	39	49	13
#8	14.0	1.5			86.0		32	± 4	28	36	11
#16	4.0				60.0		22	± 4	18	26	11
#30	1.0				29.0		11	± 4	7	15	11
#50	0.0				5.0		2	± 3	0	5	9
#100	0.0				1.0		0	± 2	0	2	1
#200	0.0				1.0		0.4	± 1.6% max	0.0	2.0	0

Workability Factor (% passing #8): 32

Coarseness Factor (% retained above 3/8" / % retained above #8): 63

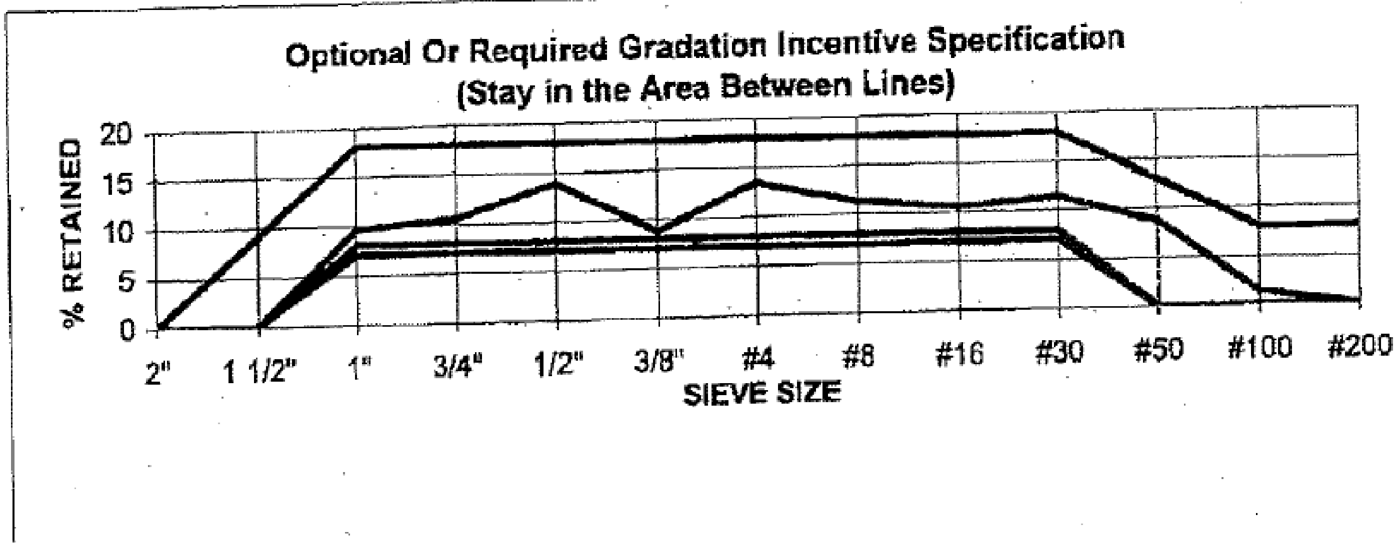

FIGURE D6 Job mix formula and aggregate gradation for mix designs 3A21-7, 3A21-8, and 3A21-9.

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Greg C. Pelkey Phone: 651-257-6019

Firm Name: Shafer Contracting Co.

Agency Engineer/Inspector: Mn/DOT T. Krier S.P. 8280-304 TH 35E/694

	CA #1	CA #2	CA #3	Sand
Pit Number	13004	13004	71041	82001
Pit Name	Al St Croix	Al St Croix	Agg. Ind. ER	Al Nelson
Nearest Town				
Size	FA-2	3/4"	1-1/2"	—
Sp. G. & Abs. (Provided by Mn/DOT)	2.66/0.015	2.66/0.014	2.75/0.009	2.62/0.010

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Lafarge	Lafarge	—
Mill/Power Plant	Davenport	Coal Creek	—
Type/Class	Type I	Class F	—
Specific Gravity	3.15	2.55	—

Propsed Mix Designs

MN/DOT Mix Number	#10 3A21	#11 3A21	#12 3A21
Water (lbs/C.Y.)	189	193	196
Cement (lbs/C.Y.)	400	400	400
Fly Ash (lbs/C.Y.)	140	150	160
Other Cementitious (lbs/C.Y.)	—	—	—
w/cm Ratio	0.35	0.35	0.35
Sand (Oven Dry, lbs/C.Y.)	1147	1140	1133
CA #1 (Oven Dry, lbs/C.Y.)	287	285	283
CA #2 (Oven Dry, lbs/C.Y.)	1115	1108	1102
CA #3 (Oven Dry, lbs/C.Y.)	638	633	629
% Air Content	7	7	7
Admix. # 1 (oz/100 # CM)	4	4	4
Admix. # 2 (oz/100 # CM)	—	—	—

The above mixes are approved for use, contingent upon satisfactory site performance and c acceptability of all material sources, by:

Maria Masten 10/4/2005

DATE

FIGURE D7 Mix designs 3A21-10, 3A21-11, and 3A21-12.

jmf/48.xls Mixes 10-12

Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	FA-2	3/4-	3/4+		Sand						
PROPORTION, %	9.00%	35.00%	20.00%		36.00%		100.00%				
2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1"	100.0	100.0	48.0		100.0		90	± 5	85	95	10
3/4"	100.0	99.0	3.0		100.0		80	± 5	75	85	9
1/2"	100.0	67.0	0.2		100.0		68	± 5	63	73	12
3/8"	100.0	42.0	0.0		100.0		60	± 5	55	65	9
#4	87.0	5.0			100.0		46	± 5	41	51	14
#8	14.0	1.5			86.0		33	± 4	29	37	13
#16	4.0				60.0		22	± 4	18	26	11
#30	1.0				29.0		11	± 4	7	15	11
#50	0.0				5.0		2	± 3	0	5	9
#100	0.0				1.0		0	± 2	0	2	1
#200	0.0				1.0		0.4	± 1.6% max	0.0	2.0	0

Workability Factor (% passing #8): 33

Coarseness Factor (% retained above 3/8" / % retained above #8): 60

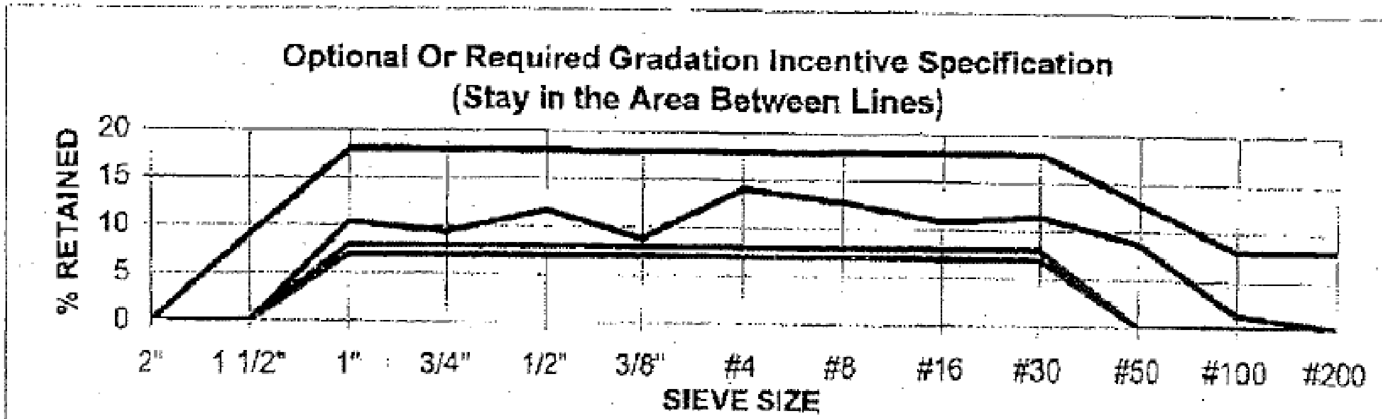

FIGURE D8 Job mix formula and aggregate gradation for mix designs 3A21-10, 3A21-11, and 3A21-12.

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Troy Vrieze | Phone: 651-257-5019

Firm Name: Shafer Contracting Co.

Agency Engineer/Inspector: MnDOT Tom Krier | S.P. 6280-304

	CA #1	CA #2	CA #3	Sand
Pit Number	13004	13004	71041	82001
Pit Name	AI St. Croix	AI St. Croix	Agg. Ind. ER	AI Nelson
Nearest Town				
Size	3/4"	3/4"	1-1/2"	—
Specific Gravity	2.66	2.66	2.75	2.62
Absorbtion (Checked by MnDOT)	0.015	0.014	0.009	0.010

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Lafarge	Lafarge	—
Mill/Power Plant	Davenport	Coal Creek	—
Type/Class	Type I	Class F	—
Specific Gravity	3.15	2.55	—

Propsed Mix Designs

MN/DOT Mix Number	#13 3A41
Water (lbs/C.Y.)	210
Cement (lbs/C.Y.)	420
Fly Ash (lbs/C.Y.)	180
Other Cementitious (lbs/C.Y.)	—
w/cm Ratio	0.35
Sand (Oven Dry, lbs/C.Y.)	1106
CA #1 (Oven Dry, lbs/C.Y.)	275
CA #2 (Oven Dry, lbs/C.Y.)	1073
CA #3 (Oven Dry, lbs/C.Y.)	615
% Air Content	7
Admix. #1 (oz/100 # CM)	3 to 5
Admix. #2 (oz/100 # CM)	—

The above mixes are approved for use, contingent upon satisfactory site performance and continuous acceptability of all material sources, by:

[signature] 10/24/07 DATE

FIGURE D9 Mix design 3A21-13.

Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	3/8"	3/4"	1 1/2"		SAND						
PROPORTION, %	9.00%	35.00%	20.00%		36.00%		100.00%				
2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0		100.0		100	± 5	95	100	0
1"	100.0	100.0	48.0		100.0		90	± 5	85	95	10
3/4"	100.0	99.0	3.0		100.0		80	± 5	75	85	9
1/2"	100.0	67.0	0.2		100.0		68	± 5	63	73	12
3/8"	100.0	42.0	0.0		100.0		60	± 5	55	65	9
#4	87.0	5.0	0.0		100.0		46	± 5	41	51	14
#8	14.0	1.5	0.0		86.0		33	± 4	29	37	13
#16	4.0	0.0	0.0		60.0		22	± 4	18	26	11
#30	1.0	0.0	0.0		29.0		11	± 4	7	15	11
#50	0.0	0.0	0.0		5.0		2	± 3	0	5	9
#100	0.0	0.0	0.0		1.0		0	± 2	0	2	1
#200	0.0	0.0	0.0		1.0		0.4	± 1.6% max	0.0	2.0	0

Workability Factor (% passing #8): 33

Coarseness Factor (% retained above 3/8" / % retained above #8): 60

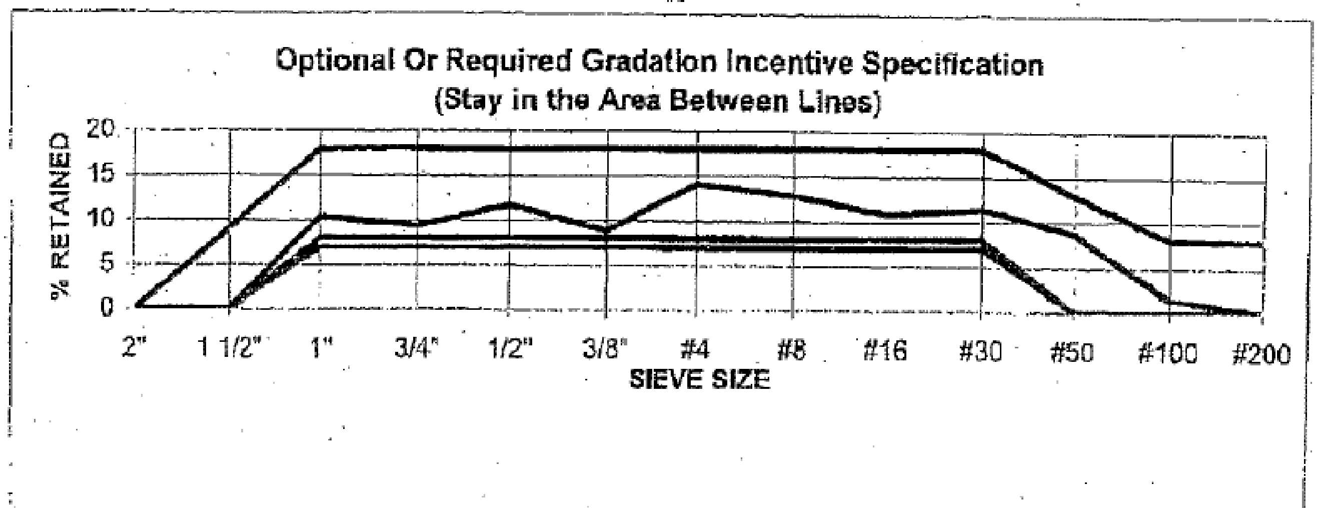

FIGURE D10 Job mix formula and aggregate gradation for mix designs 3A21-13.