USING MATURITY CONCEPTS TO DETERMINE STRENGTH OF RAPID SETTING HYDRAULIC CEMENT CONCRETE

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ABSTRACT

One of the perplexing problems faced by highway agencies today is how to rehabilitate or reconstruct aging pavements with a minimal inconvenience to the motoring public. The crowded urban freeway system in California offers an extraordinary challenge. In an effort to minimize user delays, Catrans is using Fast-Setting Hydraulic Cement Concrete (FSHCC) to replace deteriorated portland cement concrete pavement.

This paper details the work of the Federal Highway Administration's Mobile Concrete Laboratory (MCL) during pavement replacement on Interstate 10 near Pomona, California. The objective of the activity was to determine if maturity concepts could be used to predict early strength of FSHCC. Based on this limited investigation, it appears that the maturity method predicts the early age flexural beam strength with a relatively high degree of certainty. Predictions of later age flexural beam strength are less certain. Compressive strength and maturity values correlated well for both early and later ages.

INTRODUCTION

Most of the Interstate Highway System in the United States was constructed between 1960 and 1990. Today, in many locations, the system is in urgent need of repair or replacement. Due to the heavy traffic volumes, highway agencies often do not have the luxury of completely rerouting traffic to replace pavement in its entirety, especially in urban areas. Most interstate pavements need to be repaired or replaced while open to traffic. As a result, new demands are being placed on the performance of concrete materials used in these projects. These demands often include earlier strength gain to place the pavement back in service as fast as possible, in order to minimize user delays and inconvenience. California has more urban freeways than any other state. Caltrans, probably more than any other state highway agency, is required to complete repairs as quickly as possible. The agency is evaluating the use of fast-setting hydraulic cement concrete (FSHCC) to satisfy the early opening requirements. As part of a continued effort to transfer new technologies to highway agencies and promote the effective use of high-performance materials, the Federal Highway Administration (FHWA) became involved in a pavement reconstruction project utilizing FSHCC in California.

The objective of FHWA's involvement with this project included examining how the maturity technology works with FSHCC and to determine if maturity methods can be implemented as effective quality control tools for this material. Caltrans expressed an interest in using the maturity concept for concrete strength prediction, and felt that this would be an excellent opportunity to be introduced to the technology, and learn more about the behavior of FSHCC.

Project Background

The I-10 Pavement Reconstruction Project was located in Los Angeles County in the city of Pomona. It extended from the Route 210/57/10 interchange to the Garey Avenue underpass. This portion of I-10 consists of four lanes in each direction. The project included complete removal and replacement of concrete pavement sections exhibiting significant deterioration, and dowel bar retrofitting to restore load transfer between slabs in other areas. The pavement was originally construction in 1955. The inner and outer lanes were added in 1960 and 1970, respectively. The original pavement section consists of 205 – 230 mm portland cement concrete (PCC), 100 – 150 mm cement treated base (CTB), 105 – 150 mm Class 3 aggregate base, and 120 mm Class 4 aggregate base. The existing pavement is not doweled at transverse joints. Caltrans selected this project as a pilot for the use of FSHCC in full-scale lane replacement. The method was chosen in order to minimize user delay in a heavily trafficked area. This portion of I-10 has very high daily traffic volumes (240,000 ADT).

Concrete pavement sections were replaced with jointed FSHCC. Removal was done by sawing the existing PCC into sections that could be "peeled back" and removed with a conventional backhoe. After removal, the exposed CTB was cleaned with brooms, and a plastic sheet bond breaker was placed on the CTB. Joints in the new pavement were spaced at 4.5 m intervals. To improve load transfer, 0.6 m long, 38 mm diameter epoxy-coated dowel bars were installed at a spacing of 0.3 m along the joints. Epoxy coated deformed tie bars; 16 mm in diameter and 0.75 m long were installed at 0.75 m along all longitudinal joints.

Caltrans specified that the FSHCC flexural strengths reach 2.8MPa in 4.0 hours or less. Specifications require that pavement reconstruction work is performed only during night hours, and all lanes need to be opened for traffic every morning. Specific hours of lane closure vary with day of the week and holidays. During the week, the typical construction window available for the contractor is eight hours. On weekends the contractor was given a 55 hour construction window. FSHCC mixture proportions are shown in Table 1.

Table 1: FSHCC Mixture Proportions

Material	Quantity per m^3
Cement	
CTS Rapid Set	390 Kg
Fine Aggregate	
Vulcan - Upland	676 Kg
Coarse Aggregate	
3/8" Vulcan - Upland	215 Kg
1" Vulcan - Upland	900 Kg
Air	1.5 %
Water	181 Liters

Varying amounts of Daracem ML 300 and Recover were added depending on ambient temperatures

Fast-setting Hydraulic Cement

Concrete mixtures can be designed to provide high initial rates of strength gain. Typically, high portland cement contents, low water to cementitious materials ratios and accelerating admixtures are used.

Fast-setting hydraulic cements can also be used to make concretes with very rapid initial strength gain characteristics. These cements do not meet the prescriptive chemical requirements of ASTM C150 and cannot be classified as portland cements. (1)

Portland-based cement systems with functional additions of calcium fluoroaluminate have been used for rapid early strength development. These regulated-set products are no longer available in the United States. Calcium aluminate cement is used in special applications for early strength gain. These cements are prone to strength loss with age, thus their use is limited to nonstructural applications.

Rapid-hardening calcium sulfoaluminate cements are commercially available in the United States, and are being promoted for pavement repair and reconstruction. Sulfoaluminate cements are similar to Type K cements, in that they rely on the development of a sulfate compound known as ettringite to form the hardened cement paste. Rapid hardening calcium sulfoaluminate cement was used on the I-10 pilot project to evaluate the use of FSHCC. These cements are capable of attaining a Modulus of Rupture (MOR) in excess of 2.1Mpa (300 psi) within 5 hours.

The advantage to the use of rapid hardening cements is early restoration of traffic in the construction area. Sulfoaluminate cements generate less heat of hydration than portland cements. Concrete manufactured with these cements is often difficult to produce and control, may exhibit early cracking, and is more expensive than ordinary portland cement concrete.

Maturity

The maturity method is a technique for estimating the strength gain of concrete based upon the temperature-time history recorded by a maturity meter. The method is based on the assumption that samples of a given concrete mixture attain equal strengths if they reach equal values of the maturity index. This relationship generally holds true provided that moisture is always available for cement hydration. Using the temperature-time data collected by the maturity meter, a mathematical expression known as a maturity function converts the actual temperature-time history of the concrete to a maturity index that is indicative of strength development. Both AASHTO and ASTM have applicable standards for the test method.

Two maturity functions are commonly used for computing the maturity index. One maturity function, the Nurse-Saul equation, is used to calculate the temperature-time maturity index. The Nurse-Saul approach was first suggested in the 1950's and is based entirely on empirical evidence and observations. The other maturity function, the Arrhenius equation, was developed later and is based upon principles of physical chemistry. The Arrhenius equation is typically used to calculate the equivalent age maturity index. Both of these approaches have been validated in various scenarios, and are used commonly in the concrete industry to monitor concrete strength gain and make decisions regarding form stripping and loading of the structure. The technique has been used primarily with portland-based cement.

TESTING PROGRAM

Caltrans currently uses flexural beams as a means of determining whether paving concrete meets strength requirements. Three 152x152x533 mm flexural beams are cast for each test age; three hours, four hours. Cylinders (150x300mm) are also cast for each test age, but used only for resolving discrepancies.

Since both the construction industry and Caltrans have limited experience with FSHCC, and the strength gain is so time-critical, a very extensive quality control and materials testing program is required when FSHCC is used. FHWA and Caltrans decided to explore the feasibility of using in-place, non-destructive means of predicting strength and performance as a supplement to traditional testing to gain better control and understanding of the material. These means include the use of the maturity concept for strength prediction. The technology has been used successfully for conventional concrete pavements, but has never before been applied to FSHCC pavements.

The advantage of using maturity testing is the ability to measure the concrete strength in-place. Practically, this means that the majority of testing can be performed in the laboratory and making and handling beam specimens in the field is eliminated. Maturity can also improve concrete curing through temperature management of the slab.

FHWA's testing program for this project included both field and laboratory work with the concrete mixture delivered to the construction site. The testing plan was built around the

objective discussed in the Introduction section of this paper. Sampling and testing took place for concrete placed on two consecutive nights. The first night, sampling and testing were related strictly to developing the maturity calibration curve for the maturity evaluation. The second night, the test program involved sampling and field-testing for the maturity strength predictions.

The methodology for determining the maturity of FSHCC involved three primary steps. First, a maturity relationship must be selected. For this study, the Nurse-Saul approach was selected for use, primarily because the activation energy of FSHCC, an input required to use the more rigorous Arrhenius computation, had not been determined. FHWA's Turner Fairbank Highway Research Center is currently conducting tests to determine the activation energy of the cement.

Next, a calibration curve relating concrete flexural strength to maturity was developed. Again, flexural beams were used because Caltrans relies on flexural beam strength for acceptance rather than compressive strength. Finally, the same mixture was monitored for maturity again, but with strength tests performed concurrently, to determine if the strengths predicted by the calibration curve held true. For convenience, the desired strength values used are the 4-hour flexural beam strengths required in the specifications.

During the first night (July 22 - 23, 1999) concrete samples were taken from transit-mix trucks at the construction site. Slump, concrete temperature, unit weight and air content were measured and recorded, and 12 beams were cast. The beams were used to build the calibration curve for the maturity approach. The procedure used was essentially the same as prescribed in ASTM C 1074 [(2)], with some modifications to account for the fast setting nature of the concrete. The beams were cast on site and cured in a manner as close as possible to that of the pavement. The beams were placed adjacent to the pavement and were initially covered with burlap and tarps to retain moisture and heat.

Two beams were tested for flexural strength at ages of 2, 3, 4, 12, and 48 hours. The two remaining beams were saved for 28-day breaks. These test ages were selected in order to adequately describe the strength gain curve during the early ages. Caltrans specified that the flexural beam strength must reach 2.8MPa in 4 hours and 4.0MPa in 28 days. Only two specimens were cast for each test age because the rapid set-time of the FSHCC made casting greater numbers of beams impractical. The specimens were demolded and cured under standard conditions after the 3-hour breaks were completed. One of the 28-day beams was instrumented with a maturity probe (thermocouple) connected to a maturity meter. The maturity probe was placed in the center of the mass of the beam. As all the beams were of identical dimensions and cured in the same manner, it is assumed that the maturity of this beam is representative of the maturity of all the beams. The beam maturity value was recorded at each test age, and plotting the average flexural strength values vs. the maturity at each age generated the calibration curve. All concrete maturity values were calculated using the Nurse-Saul approach.

On the second night (July 23-24, 1999), samples were again taken from concrete delivered to the site. The concrete was the same mixture as the night before. Slump, concrete temperature, unit weight and air content were measured and recorded, and a total of 12 flexural beams were cast. The pavement was instrumented with maturity probes at three depths (25mm from the top, middle and 25mm from the bottom), and a fourth thermocouple was placed near the pavement to

measure the ambient air temperatures. Again, one of the 28-day beams was instrumented with a maturity probe to monitor maturity. The beams were cast and tested in the same manner as for the maturity calibration. The temperature and maturity values of both the pavement and the beam (including ambient air temperature) were recorded at each test age, and plotting the average strength values vs. the maturities at each age generated "verification curves". The verification curves were used for comparison with the calibration curve to validate the maturity method for this concrete. It should be noted that for typical field applications, it would only be necessary to cast a few verification specimens at some predetermined frequency to ensure that the strength predictions are within limits.

RESULTS

Table 2: Maturity Calibration Test Data

	Age (hours)					
	2	3	4.5	12.5	48	840
Flexural Strength (MPa)	2.0	2.8	3.0	3.7	4.2	4.3

Note: Values are average of two tests

Sampling Time: 7/22/99, 11:01pm
Air Temperature: 23 C
Concrete temperature: 31 C

Slump: 222mm
Unit Weight: 2396kg/m3
Air Content: 1.2%

All plastic concrete test results and flexural beam strengths related to the maturity calibration are given in Table 2. The plastic concrete tests were all within ranges expected for this mixture. As the table indicates, the flexural beam strengths initially increase very quickly but slow after about 12.5 hours. This rapid strength gain is also evident from the maturity calibration curve presented in Figure 1. This curve shows how the average flexural strength of the FSHCC and its maturity is related during the first 48 hours after placement. For the purpose of consistency, placement time was defined as 1 hour after batch time, although actual placement times may have varied somewhat. Using traditional curve fitting techniques, it was determined that the relationship between flexural strength and maturity is close to logarithmic. This result is consistent with past experience with maturity testing. When curve-fitting a logarithmic function to the data, the resulting R^2 value is approximately 0.95, a statistical indication that the data fits the function well. As shown in Figure 1, the calibration curve indicates that the concrete reaches a flexural strength of 2.8MPa at a maturity of about 150°C-hours. When plotting the same curve with 28-day data included, however, the curve fit is not as good. The R^2 value decreased to about .85, which is an indication of a marginal curve fit. There was minimal strength gain from 48 hours to 28 days, which is abnormal for conventional concretes. This suggests that either the maturity function or the logarithmic curve fitting function may be more appropriate for use at ages less than 48 hours. The maximum temperature attained in the instrumented beam was 37°C at approximately 2.5 hours after placement. This temperature was unexpectedly low considering the fast reacting nature of FSHCC, even when taking into consideration the relatively low ambient temperatures (12°C) at the time of maximum heat of hydration. Conventional portland

cements give off a great deal of heat, and the faster the reaction rate, the more heat given off. This is particularly true for high-early strength cements that contain higher levels of tricalcium silicate.

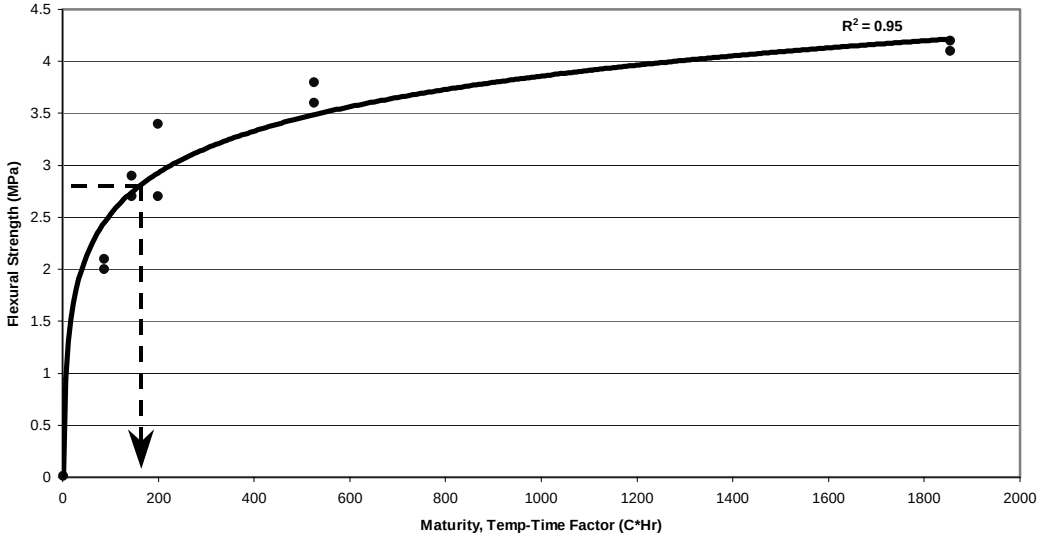

Figure 1: Maturity Calibration Curve

Plastic concrete test results and strength tests related to the maturity prediction testing for the second night's work is given in Table 3. Again, the plastic concrete test results are all within expected ranges. During the second night, the maturity of the pavement was monitored closely for the first few hours after placement. When the maturity reached approximately 150 °C-Hours (the maturity at which the calibration curve indicated the flexural strength had reached 2.8MPa) two flexural beams, cast when the pavement was placed, were tested. This corresponds to an elapsed time of about 3.0 hours since placement. The resulting average flexural strength was 3.0MPa. This corresponds well with the calibration data (2.8Mpa), and is considered to be well within the expected accuracy of the test procedures being used.

Table 3: Maturity Verification Test Data

	Age (hours)					
	2	3	4.5	12.5	48	840*
Flexural Strength (MPa)	2.6	3	4	3.9	3.9	4.3
Split Tensile (MPa)	n/a	n/a	2.4	2.1	2.8	3.4
Compressive (MPa)	n/a	22.7	24.2	26.9	31.3	43.3
Elastic Modulus (GPa)	n/a	n/a	18.1	18.8	20.3	24.3
CTE (in/in/^{o}C)	n/a	n/a	n/a	n/a	n/a	12.1

* Tested at 840 hours (35 days) due to conflict with travel at 28 days

Note: Values are average of two tests

Sampling Time: 7/24/99, 4:50am
Air Temperature: 18 C
Concrete temperature: 30 C

Slump: 210mm
Unit Weight: 2371kg/m3
Air Content: 1.0%

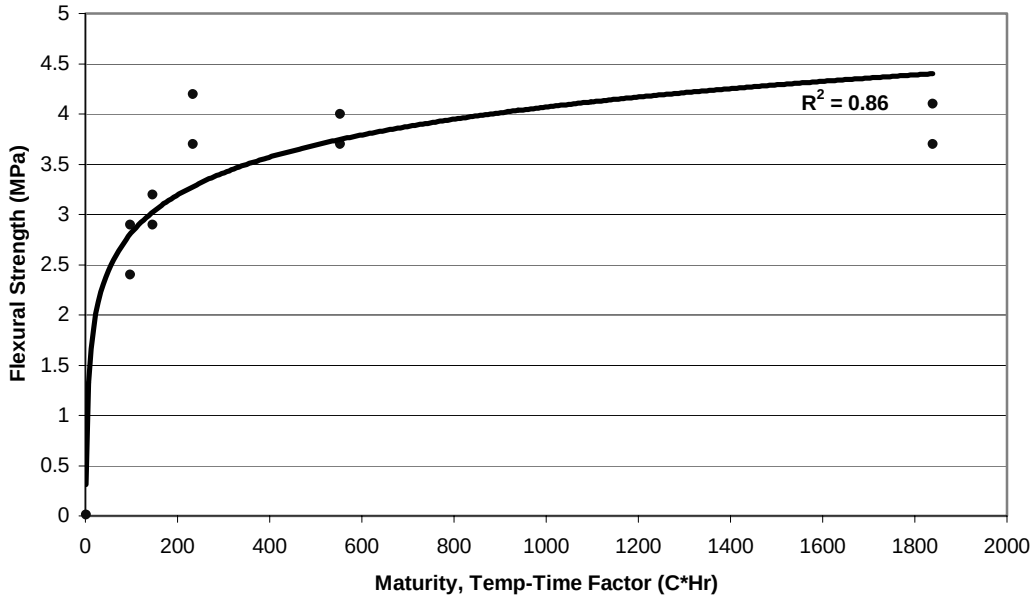

Figure 2: Maturity Verification Curve (beams)

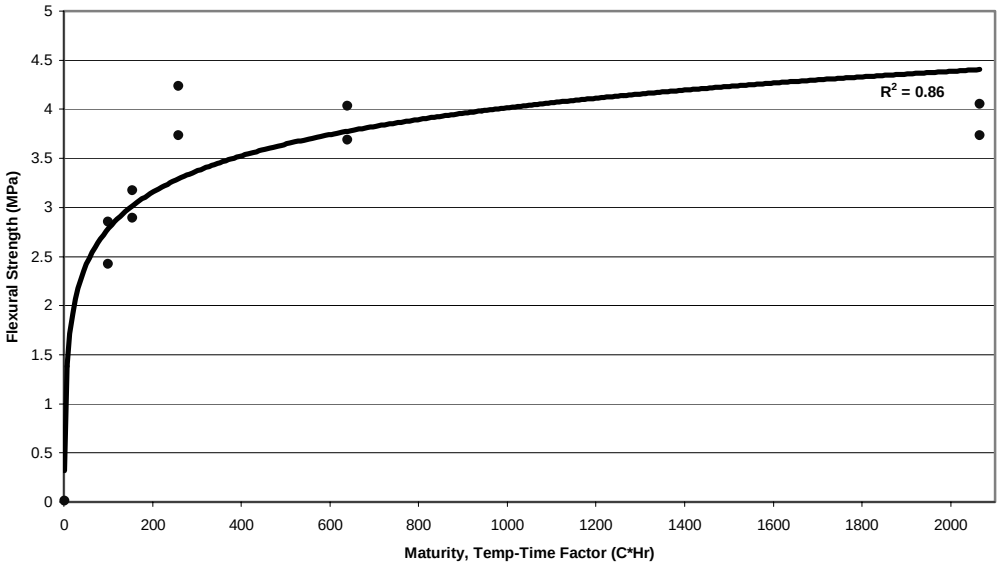

Figure 3: Maturity Verification Curve (pavement)

Upon closer inspection of the final maturity verification curves however (Figures 2 and 3), it is clear that the data does not agree quite as well as initially suspected. The maturity verification curves of both the pavement and beams cast on the second night (Figures 2 and 3) are logarithmic. The respective R^2 values are both 0.86 based on 48-hour data. Both plots show a peak in the flexural strength data at a maturity of about 233°C-hours. This corresponds to an elapsed time of about 5 hours. The decrease in flexural strength after 5 hours is both unexpected and difficult to explain. In normal portland cement concrete, strength continues to increase with time as long as moisture is available to support the hydration process. In this case the strength peaked at 5 hours and then decreased. The source of this behavior could be related to a variety of factors, including one or a combination of the following: 1) The Nurse-Saul relationship describes the time-temperature interaction inadequately for this material, 2) The specimens were not cured properly, 3) The logarithmic curve fit does not appropriately describe the strength-maturity relationship for FSHCC, 4) The flexural strengths are not representative of the concrete strength. For reasons discussed in the following paragraph, and because the on-contractor's quality control laboratory expressed similar variations in flexural strength results on frequent occasions throughout the project duration, the most likely source is related to the flexural strengths. Even with these strength variations, however, the curves do correspond reasonably well with the calibration curve generated the night before. This is illustrated well in Figure 4, where the fitted calibration and verification curves are overlaid. From this figure it is apparent that the maximum difference between the two curves is less than 0.3MPa.

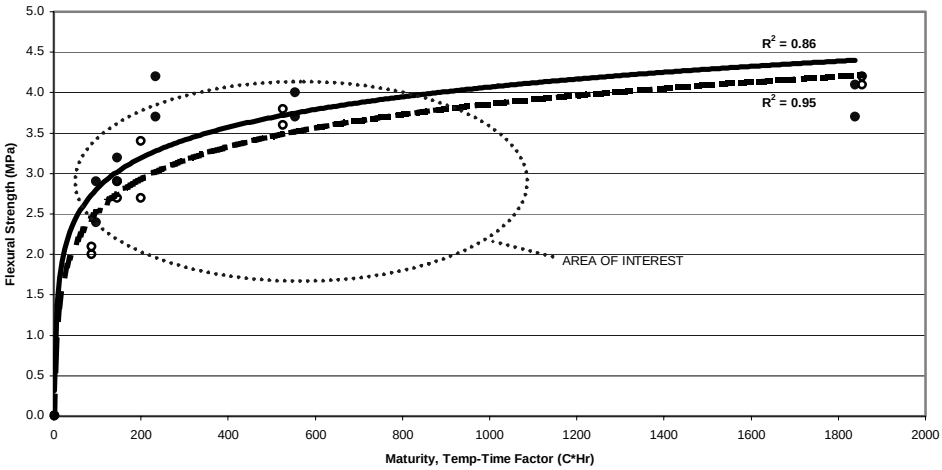

Figure 4: Maturity Calibration/Verification Comparison

After reviewing the results from compression and modulus of elasticity tests, the question about the validity of the flexural strengths surfaced. When plotting the compressive strengths vs. maturity of the pavement, a very good logarithmic curve fit is apparent (Figure 5). The spread in the data at each test-age is small, and the average strength gain is smooth for both early and later ages. The points all fall very close to the best-fit curve, and the R^2 value is greater than 0.99 for both the 48 hour data as well as the 28 day data. In addition, when comparing compressive strengths to modulus of elasticity, an extremely strong linear correlation is apparent. When plotting flexural beam strength vs. modulus of elasticity or compressive strength (Figure 6), no clear trends are apparent. This raises the question whether the flexural strength test results are in fact representative of the strength of the material.

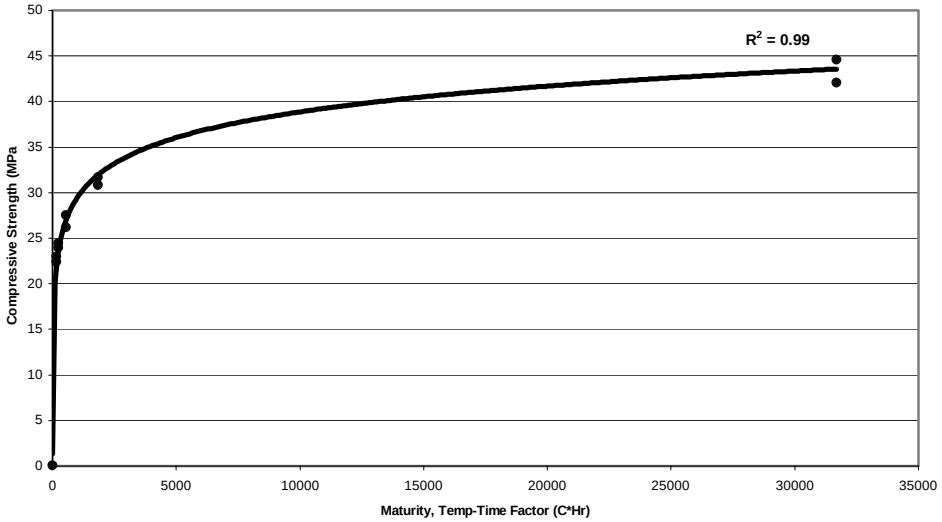

Figure 5: Maturity vs. Compressive Strength

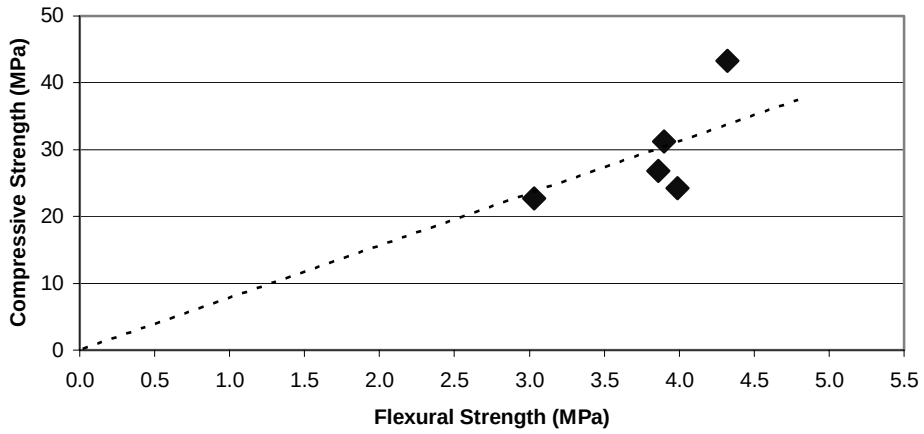

Figure 6: Compresseive Strength vs. Flexural Strengt

The test method used for determining the flexural strength of concrete beams (ASTM C 78) mentions the method's sensitivity to tensile stresses induced by drying during testing. This is exactly why the test method specifies that the specimen must remain moist throughout testing. It is reasonable to assume that the test method is equally sensitive to tensile stresses induced by thermal gradients during testing. Since the specimens for FSHCC typically need to be tested at ages less than 5 hours, when the heat of hydration is at its peak, the specimens are susceptible to thermal tensile stresses. The maturity data from the beams show that the internal temperature of the beam is still near 40°C at an age of 3 hours (Table 4). The external temperature of the beams that were subsequently

Table 4: Maturity Data from Verification Beam

Hour	Temp. (C)	Maturity-TTF (C*Hr)
0.0	30	0
0.5	35	21
1.0	40	45
1.5	44	71
2.0	40	97
2.5	40	122
3.0	39	146
3.5	35	170
4.0	32	192
4.5	31	212
5.0	30	233
5.5	30	253
6.0	30	273
6.5	30	293
7.0	30	313
7.5	30	333
8.0	30	353

submerged in curing tanks at this same time, although not actually measured, can be assumed to be close to the curing tank temperature (approximately 23°C). This translates to a potential temperature gradient from the edges to the center of the beam of almost 20°C. The associated tensile stresses may very well be significant, and could cause damage to the specimens, [3] thus reducing the strengths measured at later ages. The actual thermally induced stresses are difficult to determine without knowing the coefficient of thermal expansion of the young concrete. Compressive specimens are much less sensitive to tensile stresses caused by either drying or thermal gradients.

The time-temperature history of the pavement during the first five days after placement is shown in Figure 7. The maximum temperature of 46°C was attained in the middle of the pavement at approximately two to three hours after placement. The plot shows how the pavement temperatures follow the daily ambient temperature cycles. The maximum measured temperature differential was 9°C between the top and the bottom of the pavement. This is well within the guidelines for the maximum recommended thermal gradient across the depth of a conventional concrete pavement [4].

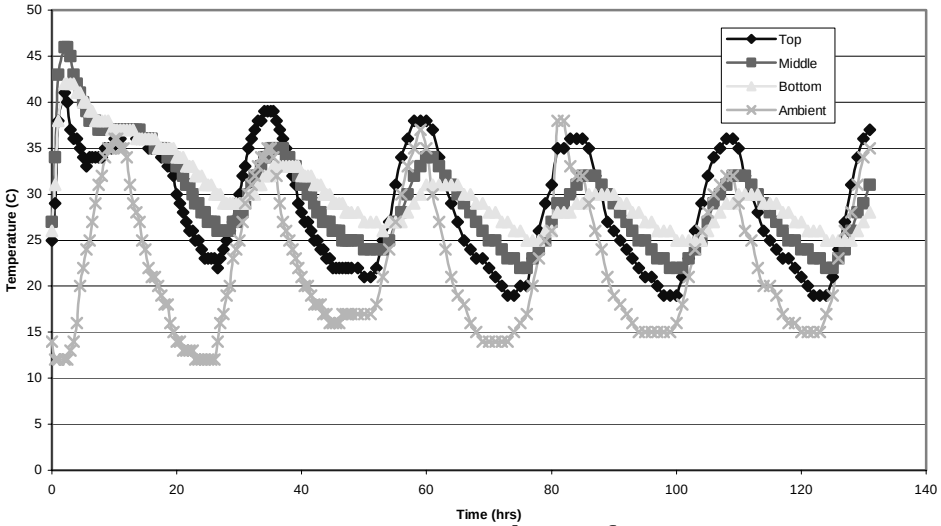

Figure 7: Temperature vs. Time of Pavement

Figure 8 illustrates how the maturity of the pavement increases slightly faster than that of the companion beams. This follows from the fact that the mass concrete in the pavement matures more quickly than the smaller beams, due to the greater thermal mass. Although the difference in this particular case is not significant, it illustrates how in-situ testing such as maturity allows you to determine the strength of the placed concrete, without having to rely on the assumption that the specimens cast are, in fact, maturing or gaining strength in unison with the pavement.

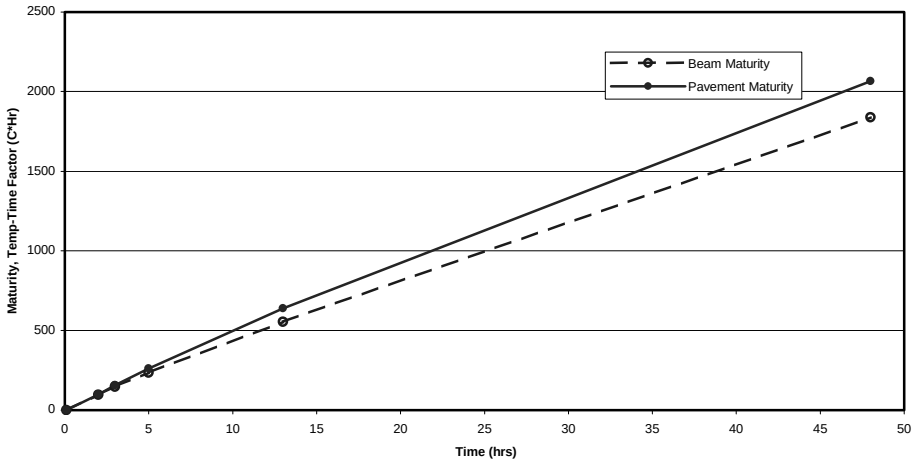

Figure 8: Comparison of Pavement vs. Beam Maturities

CONCLUSIONS

As a whole, the data from this study of maturity's applicability to this FSHCC is very encouraging, but further study is required to validate this limited study before considering wide implementation of the maturity method for FSHCC. Based on this investigation, it appears that the maturity method predicts the early age flexural beam strength with a reasonably high degree of certainty. At these early ages, the maturity method may predict the flexural beam strengths to within 0.3MPa. The probable reason for the lack of a more consistent and predictable relationship between flexural beam strength and maturity may have to do with variability and thermal sensitivity of the beam test. To get a repeatable flexural beam strength-maturity relationship, it is necessary to reduce the variability of the beam test itself. A possible means of doing this may be to minimize the potential for thermally induced tensile stresses before and during testing (for example by not placing the beams in the curing tanks until the temperature of the beams is at or near that of the curing water), or adopt another strength measure for maturity correlation. Compressive strengths show great promise for such a strength measure with FSHCC. The compressive strength results and maturity values followed a logarithmic relationship extremely closely for both early and later ages. In addition, compressive strengths correlated very well with modulus of elasticity values, lending further credibility to the compressive strength results.

The time-temperature/maturity data also suggest that construction control related to delivery time is important. Due to the nature of FSHCC with its rapid rate of set and strength gain, attention must be focused on a consistent time of delivery. The maturity method is extremely sensitive to these factors since the temperature increases and strength gains for this material occur so quickly – usually within 1.0 hour. If the placement time from batch to batch is not kept relatively constant, a common reference point for the maturity method is not available.

The time-temperature/maturity data illustrates the temperature behavior of FSHCC. The pavement reached its maximum temperature at approximately two-and-a-half hours after

placement. The maximum temperature in the middle of the pavement section was only 46°C, which was lower than expected. In addition, the maximum thermal gradient from top to bottom of the slab was less than 10°C – again less than what is considered potentially problematic. Although FSHCC reacts quickly, with rapid gains in strength, the reaction does not appear to be accompanied by large temperature increases.

When comparing the maturity vs. time curves for the pavement and the companion beams, it is apparent how the maturity of the pavement increases slightly faster than that of the companion beams. This is consistent with the theory that mass concrete will gain strength (mature) more quickly than small specimens, due to the greater thermal mass and resulting reduced heat loss. The maturity method allows for the determination of actual concrete strength in pavement.

In light of these observations about the maturity method as applied specifically to FSHCC, a few of the general benefits of the maturity method as should be mentioned. The maturity method offers highway agencies a useful and easily implemented means of estimating in-place concrete strength for a wide variety of concrete structures, including bridge decks, mass foundations and bridge girders. The method has also been used successfully to help contractors decide when joint sawing should commence, or when form removal can be done safely. The effectiveness of retarders can also be measured with the help of maturity, by non-destructively pinpointing the time at which cement hydration starts. Finally, monitoring the concrete maturity allows for temperature management of the concrete in place to minimize potential cracking. In short, the maturity method can offer a viable means of reducing costs through testing and scheduling in a time when both public agencies and contractors are concerned with escalating traffic control costs and shrinking budgets.

Recommendations

Based on the conclusions presented in the preceding section, the following recommendations are offered:

- The use of flexural beam strength test as a measure of FSHCC pavement strengths should be re-evaluated.
- Maturity should be implemented for major conventional paving projects where the cost savings associated with reduced testing are significant, and rapid testing. information is needed to facilitate opening to traffic.
- An additional benefit to using maturity is to get rapid feedback into the contractor's quality control system.
- A comprehensive study of maturity and FSHCC is required to validate this limited study prior to considering wider implementation of maturity for FSHCC.

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