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REVISED FIELD TEST REPORT

Use of Fast-Setting Hydraulic Cement Concrete for Interstate Concrete Pavement Rehabilitation

I-10, Pomona, California
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FHWA MCL Project # 9902

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Introduction

The United States Interstate Highway system was constructed during the 1960's, '70's and '80's, and is in urgent need of repair or replacement in many locations. Due to the heavy traffic volumes today, state highway agencies do not often have the luxury of completely rerouting traffic and replacing the worn pavements in their entirety. Most interstate pavements need to be repaired or replaced while under traffic. As a result, new demands are being placed on the performance of concrete materials. These demands often include earlier strength gain in order to place the pavement back in service as fast as possible to minimize user delays and inconvenience. Because the State of California Department of Transportation (Caltrans), probably more than any other state highway agency, is required to complete highway repair as quickly as possible, they are currently testing and evaluating the potential of fast-setting hydraulic cement concrete (FSHCC) to satisfy the early open to traffic 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 such a pavement reconstruction project utilizing FSHCC in the State of California. Caltrans requested that FHWA employ the use of the mobile concrete laboratory (MCL) as part of Demonstration Project 75, "Field Management of Concrete Mixtures" to introduce Caltrans to maturity and the HIPERPAV program to aid in and enhance Quality Assurance/Quality Control testing for concrete pavements.

Background

The I-10 pavement reconstruction project is located in Los Angeles County in Pomona from the route 210/57/10 interchange to the Garey Avenue undercrossing. This portion of I-10 consists of four lanes each way. The project includes complete removal and replacement of concrete pavement sections exhibiting significant damage/cracking, as well as dowel bar retro-fitting other areas. Date of original construction is 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. However, deformed tie bars, 16 mm in diameter and 0.75 m long are spaced at 0.75 m along all longitudinal joints.

The removed concrete pavement sections are being replaced with jointed FSHCC. Removal involved sawing the existing PCC section into sections that could be “peeled back” and removed with a conventional track-hoe. After removal, the exposed CTB was cleaned with brooms, and a bond breaker (plastic) was applied. Joints are spaced at approximately 4.5 m. To allow for load transfer, 0.6 m long, 38 mm diameter epoxy-coated dowel bars are 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 are installed at 0.75 m along all longitudinal joints (see Photos 1 and 2). FSHCC was chosen in order to minimize user delays and inconvenience to the public, as this portion of I-10 has very high daily traffic volumes (2050 vehicles/lane/hour). 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 varies with day of the week and holidays. During the week, the typical construction window available for the contractor is only eight hours. A copy of the FSHCC mixture proportions is shown in Table 1 in Appendix A.

Photo 1: Dowel bars and tie bars are being placed

Photo 2: FSHCC being placed

FSHCC contain proprietary cements with very rapid initial strength gain characteristics. These cements do not meet the prescriptive chemical requirements of ASTM C150 and can not be classified as portland cements (1). Several State Departments of Transportation (DOT) have utilized FSHCC where lane closure time has been critical, but have had mixed success in achieving consistent and predictable early-age performance. Recent experience suggests that FSHCC is particularly sensitive to temperature and delivery time. The Strategic Highway Research Program (SHRP) C-206 studies also raise concerns about the durability of FSHCC, as two full depth test sections in Ohio showed significant cracking after only 5 years in service. The fast-setting hydraulic cement utilized for Caltrans' I-10 Pomona reconstruction project is CTS Rapid Set Cement. A copy of an information sheet provided by the cement manufacturer, as well as a Caltrans report summarizing the characteristics of various rapid set materials are included in Appendix C

Since both the construction industry and Caltrans have limited experience with FSHCC, and since the strength gain is so time-critical, a very extensive quality control and materials testing program is required. As a result of this, and since the costs of such a test program are quite high, 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, and HIPERPAV to minimize cracking potential. Both of these technologies have been used successfully for conventional concrete pavements, but have never before been applied to FSHCC pavements.

The advantage of using maturity testing is the ability to measure the concrete strength in-place. Use of maturity testing also has the potential for reducing the cost of testing, as well as improving concrete curing through temperature management of the slab. The maturity method is applicable for both conventional and high performance concretes. A brief description of the maturity method is included in Appendix B.

The objective of FHWA's involvement with this project included examining how the maturity and HIPERPAV technologies work with FSHCC and to see if these technologies can be implemented as effective QC 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 both be introduced to the technology, as well as to learn more about the behavior of FSHCC. Specifically, the objectives of this project include: 1) Examine how well the maturity concept applies to FSHCC, 2) Establish whether HIPERPAV accurately models the behavior of FSHCC pavements.

Testing Program

Caltrans is currently employing the use of flexural beams as a means of determining whether paving materials are meeting strength requirements. A total of three 152x152x533 mm flexural beams are cast for each test age of three hours, four hours, and 28 days, plus one spare. 150x300mm cylinders are also cast for each test age, but used only for "refereeing" in disputes. FHWA's testing program for the I-10 Pomona project included both field and laboratory work with the concrete mixture delivered to the construction site. The testing plan was built around the two objectives listed in the previous section. Sampling and testing took place on two consecutive nights. The first night, testing was related strictly to developing the maturity calibration curve for the maturity evaluation. On the second night, the test program involved testing and instrumentation for both the maturity evaluation and strength prediction, as well as for the HIPERPAV validation.

Maturity

The methodology for testing the maturity method for FSHCC involved three primary steps. First, a maturity relationship needed to be selected. For this study, the Nurse-Saul approach was selected. Second, a calibration curve relating concrete flexural strength to maturity needed to be developed. Again, flexural beams were used since Caltrans relies on flexural strength for acceptance rather than compressive strength. Finally, the same mixture would need to be monitored for maturity again, but with strength tests along the way, to check if the strengths predicted by the calibration curve held true. Figure 1 in Appendix B schematically illustrates how the maturity method would typically be applied in the field. For convenience, the desired strength values used are the 4 hour flexural strengths required in the specifications.

Photo 3: Beams being cast

During the first night (July 22 - 23, 1999) samples were retrieved from transit mix trucks at the construction site. Slump, concrete temperature, unit weight and air content were measured and recorded, and 12 flexural beams were cast (see Photo 3) . The beams were cast 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 keep the moisture and heat in (see photo 4).

Photo 4: Beams and cylinders being covered during initial curing

Two beams were tested for flexural strength at each age 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 specifies that the flexural strength must reach 2.8MPa in 4.0 hours and 4.0MPa in 28 days. Only two specimens were cast for each test-age because the quick 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 are 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 maturity value of the beams was recorded at each test age, and the calibration curve was generated by plotting the average flexural strength value vs. the maturity at each age. All concrete maturity values were calculated using the Nurse-Saul approach.

During the second night (July 23-24, 1999), samples were again retrieved from concrete delivered to the site. The concrete was of the same mixture design 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 (see Figure 2). Again, one of the 28-day beams was instrumented with a maturity probe to monitor maturity. The flexural 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 “verification curves” were generated by plotting the average strength values vs. the maturities at each age. The verification curves were generated for comparison to the calibration curve to check the validity of the maturity method for this concrete. According to maturity theory, two identical concrete mixtures at equal maturities will have the same strength, regardless of the concrete curing time and temperature histories. This “maturity rule”, as it is known, generally hods true provided there is enough moisture available for continuous hydration (i.e. proper curing), and the early-age temperature histories of the concretes are not vastly different. Therefore, provided that the concrete is properly cured and that the ambient temperature conditions are not significantly different, it should become readily apparent whether the maturity method as applied here to FSHCC is valid, by comparing the calibration and verification curves. It should be noted however, that for typical field applications, it would only be necessary to cast a few “verification” beams at some predetermined frequency to ensure that the strength predictions are within limits.

HIPERPAV

HIPERPAV is a Windows based computer program that evaluates the potential for uncontrolled cracking of pavements. Developed by Transtec Inc. under contract with FHWA, it runs numerous models iteratively to predict the pavement stresses and strengths during the first 72 hours after placement. Inputs to the program include: pavement design parameters, mixture parameters, construction parameters, and environmental conditions. The program output is a plot of the pavement stress and strength vs. time for the first 72 hours after placement. Where stresses exceed the strength, the potential for tensile cracking of the slabs exists. If cracking potential is found to exist, changes in one or more of the input variables may be made in subsequent runs of the program until an acceptable combination is obtained.

The testing required to validate the HIPERPAV program for FSHCC included both field and laboratory testing during pavement construction, as well as off-site laboratory testing. Field testing included measuring slump, concrete temperature, unit weight and air content, and casting 14 150mm x 300mm cylinders and two 100mm x 200mm cylinders. The flexural strength data and maturity data collected as part of the maturity validation were also utilized for the HIPERPAV evaluation. Ten of the 150mm x 300mm cylinders were cast for compression and elastic modulus testing at ages of 3 hours, 4 hours, 12 hours, 48 hours and 28 days. Only two specimens were tested at each test-age, due to space constraints in FHWA’s Mobile Concrete Laboratory. The remaining four 150mm x 300mm specimens were cast for split tensile testing at ages of 4 hours, 12 hours, 48 hours and 28 days. The two 100mm x 200mm cylinders were cast to determine the coefficient of linear expansion of the concrete. These specimens were tested at an age of approximately 42 days. A weather station was also erected near the site to collect environmental information such as temperature and wind speed during the first 72 hours after concrete placement. This information was also needed for input to the HIPERPAV program. Adiabatic tests were performed on the job supplied materials by Federal Highway Administration's Turner-Fairbank Highway Research Center (TFHRC) in order to characterize the heat of hydration of the FSHCC. Details of this testing and the subsequent hydration modeling and temperature predictions is presented in The Transtec Group Technical Memorandum No. 298007-24, presented in Appendix E.

Results

The results of this work are presented in two separate sections. The first section deals with the first objective – does the maturity method adequately describe the strength development of FSHCC? The latter section deals with the second objective - how well does HIPERPAV model the FSHCC temperature and early strength development?

Maturity

All plastic concrete test results and flexural 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 strengths increase in strength very quickly but also level off shortly thereafter. This rapid but smooth strength gain is also evident from the maturity calibration curve presented in Figure 3. 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 1.0 hour after batch time, although actual placement times may have varied significantly). Using traditional curve fitting techniques, it was determined that the relationship between flexural strength and maturity is close to logarithmic. This 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 3, 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 our maturity function or the logarithmic curve fitting function may be more appropriate for use at earlier ages (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.

Plastic concrete test results and strength tests related to the maturity verification/ strength prediction testing are 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 maturity method. Upon closer inspection of the final maturity verification curves however (Figures 4 and 5), 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 4 and 5) are largely logarithmic, however their respective R^2 values are both 0.86 based on 48 hour data. Both plots show a clear hump 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. 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 concrete was not cured properly, 3) The logarithmic curve fit does not appropriately describe the strength-maturity relationship, 4) The flexural strengths are not representative of the concrete strength. For reasons discussed in the following paragraph, and because the on-site 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 6, where the fitted calibration and verification curves are overlaid. From this figure it is apparent that within the region of interest, defined by flexural strengths from approximately 2.8MPa to 4.0MPa, the maximum difference between the two curves is less than 0.3MPa.

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 7). 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 modulis of elasticity, an extremely strong linear correlation is apparent (Figure 8). When plotting flexural strength vs. modulus of elasticity or compressive strength, no such trends are apparent. This raises the question whether the flexural strength test results are in fact representative of the strength of the material.

The test method used for determining the flexural strength of concrete beams (ASTM C 78) mentions the methods 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 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 9. 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 10 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 you cast are in fact maturing or gaining strength in unison with the pavement.

HIPERPAV

Details of the testing and evaluation of HIPERPAV's temperature and cracking potential prediction are presented in Appendix E of this report. Based on the results of this testing, it appears that HIPERPAV can provide an accurate estimate of the temperature development of FSHCC pavements, provided the hydration model in HIPERPAV is modified to account for the two distinct heat of hydration peaks. The presence of two distinct temperature peaks due to the heat generated in the concrete is very characteristic of FSHCC. Unfortunatley, HIPERPAV in its off-the-shelf version does not include the two-peak hydration model, and can therefore not accurately predict the FSHCC temperature development. The cracking potential of the FSHCC could not be evaluated (even with the two-peak hydration model), as data about FSHCC's creep and shrinkage characteristics is not currently available.

Conclusions

Maturity

As a whole the data from our study of maturity's applicability to this FSHCC is very encouraging, but further study is required to validate this limited study before considering statewide implementation of the maturity method for FSHCC. Based on this limited investigation, it appears that the maturity method predicts the early age flexural strength with a relatively high degree of certainty. At these early ages, the maturity method may predict the flexural strengths to within 0.3MPa. The probable reason for the lack of a more consistent and predictable relationship between flexural strength and maturity may have to do with variability and thermal sensitivity of the flexural test itself. To get a repeatable flexural strength-maturity relationship, it is necessary to reduce the variability of the flexural 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 also sheds some light on 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. In summary, although FSHCC reacts quickly, with rapid gains in strength, the reaction is not accompanied by large temperature increases (at least not under these ambient conditions).

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, without having to rely on the assumption that the specimens cast are in fact maturing or gaining strength in unison with the 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 a whole should be mentioned. The maturity method offers state 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 to help with early form removal. 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. If the concrete temperatures are increasing beyond the maximum allowed or if the thermal gradient is getting too large, the curing regime can be adjusted to help correct the situation. 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.

HIPERPAV

HIPERPAV in its current version should not be used to evaluate the cracking potential of FSHCC. The hydration models included in HIPERPAV do not account for the two hydration peaks of FSHCC, and can therefore not accurately model the strength and stress development. However, it was demonstrated that HIPERPAV can provide an accurate estimate of the temperature development of FSHCC pavements, provided the hydration model in HIPERPAV is adjusted to account for the two distinct heat of hydration peaks. Even with the modified hydration models however, more data is needed on the shrinkage and creep characteristics of FSHCC before HIPERPAV can be used to accurately predict the cracking potential of FSHCC pavements.

Recommendations

Based on the conclusions presented in the preceding section, FHWA makes the following recommendations:

- Caltrans should purchase a few maturity system units for trial use to 1) become familiar with the implementation and interpretation of the maturity method, and 2) to develop more data for a more comprehensive study of maturity and FSHCC
- A comprehensive study of maturity and FSHCC is required to validate this limited study prior to considering statewide implementation of maturity for FSHCC
- The use of flexural 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
- Consider the implementation of maturity for concrete bridges as well, including pre-cast and cast in place.

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