

MATURITY METHOD IN PRESTRESSED CONCRETE APPLICATIONS

December 2004

Submitted by

Allyn Luke

Walter Konon

Sun Punurai

**New Jersey Institute of Technology
Civil & Environmental Engineering**



**NJDOT Research Project Manager
Tony Chmiel**

In cooperation with

New Jersey
Department of Transportation
Bureau of Research and Technology
and

U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the New Jersey Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

1. Report No. FHWA-NJ-2004-00		2. Government State of New Jersey		3. Recipient's Catalog No.	
4. Title and Subtitle Maturity Method in Prestressed Concrete Applications				5. Report Date December 2004	
				6. Performing Organization NJIT	
7. Author(s) Allyn Luke, Walter Konon, Sun Punurai				8. Performing Organization Report No. FHWA-NJ-2004-022	
9. Performing Organization Name and Address New Jersey Department of Transportation CN 600 Trenton, NJ 08625				10. Work Unit No. 997943	
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation Washington, D.C.				13. Type of Report and Period Covered 1/2004-1/2005	
				14. Sponsoring Agency Code	
15. Supplementary Notes luke@njit.edu					
16. Abstract <p>The maturity method is used to make excellent predictions of the prestress transfer strength for precast/prestressed box beams. Temperature measurements find the bottom end of the beam, where the prestressing strands leave the forms for the anchorages, to be the critical area for strength measurement. Maturity measurements in this area allow evaluation of the strength in parts of the prestressed section where strength measurements could not be made before. It is also found that companion test cylinders predict the strength in this area very well. Verification procedures, recommended in previous work, are validated. After the strength of companion cylinders were accurately predicted, it was found, by testing cured in place lift-out cylinders cast into the structure, that the structural strength predictions were between 0.5 % and 7.5 % in error. Recommendations for using the maturity method on prestressed concrete are made.</p>					
17. Key Words Maturity Method, Concrete Strength Prediction, Prestressing Release Strength				18. Distribution Statement	
19. Security Classification Unclassified		20. Security Classification. (of this page). Unclassified		21. No of Pages 34	22. Price

Acknowledgements

The authors acknowledge the indispensable assistance of the following people and organizations without whose help this report would have been impossible:

Phil Potter, Steve, Frank, Carlo and the other workers at Precast Systems who educated us on the way prestressed items are made and tested.

Paul Natalazano, Esam, Rich, with Anselmi & Decicco for providing a long-term concrete test bed for the maturity method and, for the all the help with the various iterations of the CIPLOC development.

Nick Alfanao, Donnie, Hernando and the other front-line NJDOT Secaucus field staff for all their help and information. Harry Capers and Jose Lopez at the NJDOT Bridge Group for their extraordinary support over the years.

Herb Degan of Controline who helped us so much with the ACR data loggers.

Caz Bognacki and David Potts of the Port Authority of New York and New Jersey for the use of their Wake wireless system.

Lu XiaoBien, Brent Buttner-Obetech hard working graduate and undergraduate student assistants here at NJIT.

Table of Contents

Table of Contents.....	iii
List of Figures	iii
List of Tables	iii
SUMMARY	1
INTRODUCTION	1
MATURITY METHOD.....	4
EXPERIMENTAL SETUP	5
Cast in-place lift out cylinders (CIPLOC)	5
Testing setup.....	7
Mix requirements.....	8
EXPERIMENTAL RESULTS.....	8
Temperature histories	8
Computation of maturity and prediction of strength.....	10
Strength-maturity verification and structural strength prediction.....	12
Prediction of release strength.....	13
Prediction of 28-day strength	14
Iterative development of strength-maturity relationship	14
Overall results	16
Restricted results.....	16
DISCUSSION OF RESULTS	17
CONCLUSIONS.....	23
RECOMMENDED ADDITIONS TO PROPOSED MANUAL	24
APPENDIX.....	25
REFERENCES	29

List of Figures

Figure 1 Schematic of CIPLOC.....	6
Figure 2 Experimental set-up.....	7
Figure 3 Temperatures measurements for beam 4S	9
Figure 4 TTF and strength predictions for cylinders and critical area.....	11
Figure 5 Iterative development of predictive equation.....	15
Figure 6 Trendline with all cylinder tests.....	16
Figure 7 Strength-maturity relationship for Clayton Class P2 concrete.....	17

List of Tables

Table 1 Predictive verification tests with structural strength prediction	12
Table 2 Predicted release strengths	13
Table 3 Time to 28-day strength	14

SUMMARY

The ability of the maturity method to predict the prestressing release strength for steam cured precast/prestressed concrete box beams is investigated. Recommendations for implementation of this method, made in previous studies, were applied to 7 precast concrete box beams fabricated for a NJDOT supervised project. The method, applied as recommended, produced excellent predictions of the structure's prestressing transfer strength after only several field trials. This prediction was applied to the critical area of the precast structure, an area of interest from both maturity and structural standpoints. It was found that the measured strengths of the standard companion cylinders, cured with the structure, matched closely the predicted release strength in the critical area of the precast box beam as measured by the maturity method. The verification principal for the maturity method was upheld by the testing results. Selection of the datum temperature, location of the critical testing area, and the iterative development of the predictive equation were also addressed. Recommendations for expanding the guide manual for the maturity method to include precast items are made.

INTRODUCTION

The maturity method is a non-destructive method for estimating the strength of newly placed concrete. It is ASTM C 1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method*.⁽¹⁾ It has been used in New Jersey to accurately predict the strength of very early strength concrete highway slabs, bridge decks, foundations, and other highway structures.^(2,3,4,5,6) A guide manual for using the maturity method on highway projects was produced as part of a previous research study, *Implementation of Concrete Maturity Meters*.⁽⁷⁾ That report, however, did not cover steam cured precast concrete members. Since steam curing is a very special way of making structural elements this study was

proposed to examine how the maturity method would be applied to prestressed concrete bridge beams.

Precast/prestressed concrete items are made in large prestressing beds. Many prestressing strands are stretched and anchored between anchorages hundreds of feet apart. After the forms have been assembled and additional reinforcement installed, the concrete is cast, vibrated and finished. After allowing about 3 hours for the concrete to set, steam is applied for 12 hours. It is expected that the prestressing load transfer strength in the concrete would have been reached within that time period. Before the prestressing force can be released into the item the concrete must have reached strength adequate to absorb that force. Without adequate strength the strands will shear out and the whole element, possibly the whole bed's production will be ruined. Companion cylinders (ASTM C 31 test cylinders) subjected to the same curing conditions as the structure, are tested to verify this strength. If the cylinders have reached the required strength the prestressing load is released, the items are removed from the prestressing bed and, the cycle started over again. If the maturity method could be used to predict the transfer strength, the number of test cylinders needed for prestressed applications could be reduced.

This study seeks to verify several recommendations for implementing the maturity method made in previous work.⁽⁷⁾ The first is to utilize the temperature-time factor method with a specified datum temperature. Next, the predictive equation is generated from analysis of the strength and maturity data using an Excel spreadsheet menu item. A process of iterative development is used to refine the strength-maturity relationship to a statistically acceptable level. Finally, the predictive equation is subject to verification before it can be applied to the concrete of the structure. Specification recommendations for overcoming the problems identified with applying the maturity method to steam cured prestressed concrete are made.

The method will be used to predict the prestress release, and the 28-day strengths. Those predictions will then be compared to the cylinder tests results used by the precasting plant to measure the release strength and subsequently reported to NJDOT as specified. Since the concrete in the area of the prestressing strands will have to deliver all of the prestressing load to the rest of the structure, consideration of the strength in this area is of particular interest. The maturity method will be used to make measurements of the concrete strength in this area where, direct strength measurements have not been made before.

The testing program will use a new kind of in-place test cylinder, referred to as a cured in-place lift out cylinder (CIPLOC), to demonstrate the maturity method's ability to make good estimates of the concrete strength in the structure. Box beams, with CIPLOCs embedded, and companion cylinders, will be instrumented for temperature measurements. The temperature-time factor will be computed from those temperature histories and, the strengths predicted from that. The verification principal for the maturity method will be evaluated. The method is required to accurately predict the strength of companion cylinders before it can be applied to the structure. The companion cylinders will be tested and the results then compared to the strength predicted using the maturity method. If the strength of the companion cylinders is accurately predicted then application of the prediction to the structure follows. The prediction of the strength of the concrete in the area of the CIPLOCS can now be accepted. That prediction will be compared to the CIPLOC strength test from that area to see how good the prediction was.

The use of laboratory mixes is eliminated but there are still many laboratory strength tests to be done. The results of several field trials, instead of laboratory trial mixes, will be used to determine the strength-maturity relationship. This procedure not only hastens the implementation of the method to a particular project, but is a consequence of the verification procedures which require that the

strength-maturity relationship prove itself. This procedure is able to quickly generate a highly accurate, highly precise prediction that can find general application at the precast plant once qualified. The iterative development of the strength-maturity relationship will be demonstrated. The strength and maturity values of successful tests are added to the database from which the strength-maturity relationship is derived. The relationship is recomputed, using the simple Excel Trendline function, until a sufficient number of tests are included in the strength-maturity database. A statistical analysis of the error of the prediction ultimately establishes the bounds for acceptable tests.

Conclusions will be drawn and recommendations made for additions to the guide manual for applying the maturity method to highway structures.

MATURITY METHOD

Even though the maturity method was developed out of experiments in heat-accelerating concrete it has had little application in the precast industry. The maturity method grows from experiments in accelerated curing conducted by McIntosh, Nurse and Saul in the late 1940s. McIntosh worked with electrical curing, Nurse and Saul with steam.^(8,9,10) They found that the strength of concrete could be related to a quantity that has come to be known as “maturity.” Essentially, maturity is the product of temperature and time, found by calculating the area under the temperature-time curve. Maturity theory has it that regardless of the combination of temperature and time needed to reach a given value of maturity, the strength of the particular concrete will be the same. The predictive equation for each particular concrete mix, its strength-maturity relationship, is determined by experiments done prior to use of the maturity method. This prediction is later applied to the same concrete mix used for a structure.

In a previous report, *Implementation of Maturity Meters*,⁽⁷⁾ several recommendations were made for using the maturity method on highway projects.

These recommendations are intended to address the limitations of the maturity method and simplify its use as much as possible.

These recommendations were to:

1. Use the Temperature-Time Factor option,
2. Choose the datum temperature from values specified for expected strength gain rates.
3. Utilize a strength-maturity relationship having the form introduced by Plowman ⁽¹¹⁾, provided by Excel's logarithmic Trendline function, $f_c = b \ln(ttf)+a$.
4. Test companion cylinders to verify the strength-maturity relationship,
5. Iteratively refine the strength-maturity relationship,

These recommendations are applied to precast/prestressed box beams produced for an NJDOT project.

EXPERIMENTAL SETUP

Cast in-place lift out cylinders (CIPLOC)

CIPLOC is a new nondestructive technique developed at NJIT to answer the question of what is the in-situ strength of the concrete in a structure. This technique stems from ASTM C 873, *Standard Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds*,⁽¹²⁾ sometimes called cast in place, pop-out cylinders (CIPPOC.) The cured in place lift out cylinder is inserted into the concrete in the area where assessment of the in-place strength is wanted. A CIPLOC consists of two parts, a heat well and the test cylinder. The heat well is a hollow, cylindrical, volume of the structure that is formed to accept a standard test cylinder. The test cylinder is an ASTM C 31

field cylinder that is placed into the heat well after the structure has been cast. Figure 1 is a diagram.

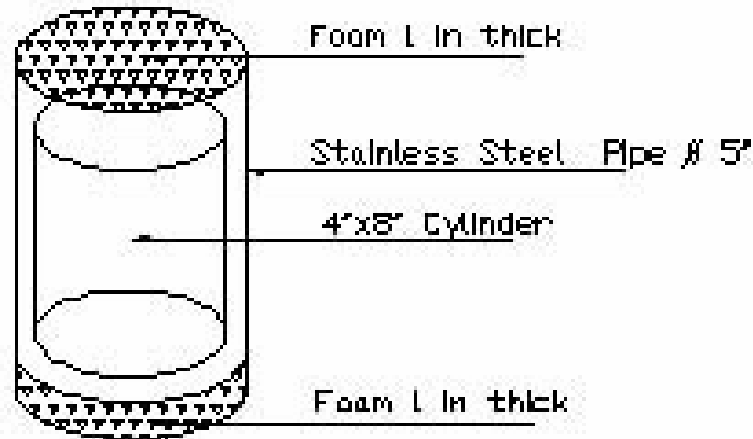


Figure 1 Schematic of CIPLOC

The heat well is a stainless steel or plastic tube which is tied to the reinforcing steel prior to casting. After the structure has been cast, during the finishing stage, the heat well lid is removed and a concrete test cylinder inserted. Alternatively, the test cylinder, already in the heat well, can be vibrated into the fluid concrete while casting the structure.

After the structure has cured for the specified amount of time the cylinder is lifted out of its heat well and tested. The hole is filled in with concrete later. It is asserted that CIPLOCs are a form of match-cured cylinders where the heat is supplied by the hydration of the cement comprising the structure rather than electrical heaters. Match-cured cylinders are standard test cylinders that are cured in special chambers that are controlled to match the temperature experienced by the structure. Since the concrete is the same as that of the structure, and it has undergone the same temperature history as the structure, the CIPLOC's strength is assumed to be the same as that of the structure in the area in which it is placed.

Testing setup

The procedures recommended in *Implementation of Maturity Meters* call for computation of the temperature-time maturity factor. To do so a datum temperature must be assigned. None of the choices given in the guide manual were for the heat accelerated precast case. Since this value is representative of the initial rate of strength gain, and since the expected rate for the steam accelerated is very fast, even faster than the very early strength concrete which uses 45° F. A value of 50° F for the datum temperature is suggested. The use of this datum temperature will ultimately be justified by the accuracy of the predictions.

Nine CIPLOC installations were made into 5 prestressed concrete box beams, produced under NJDOT supervision at Precast Systems of Allentown, NJ, as shown in Figure 2.

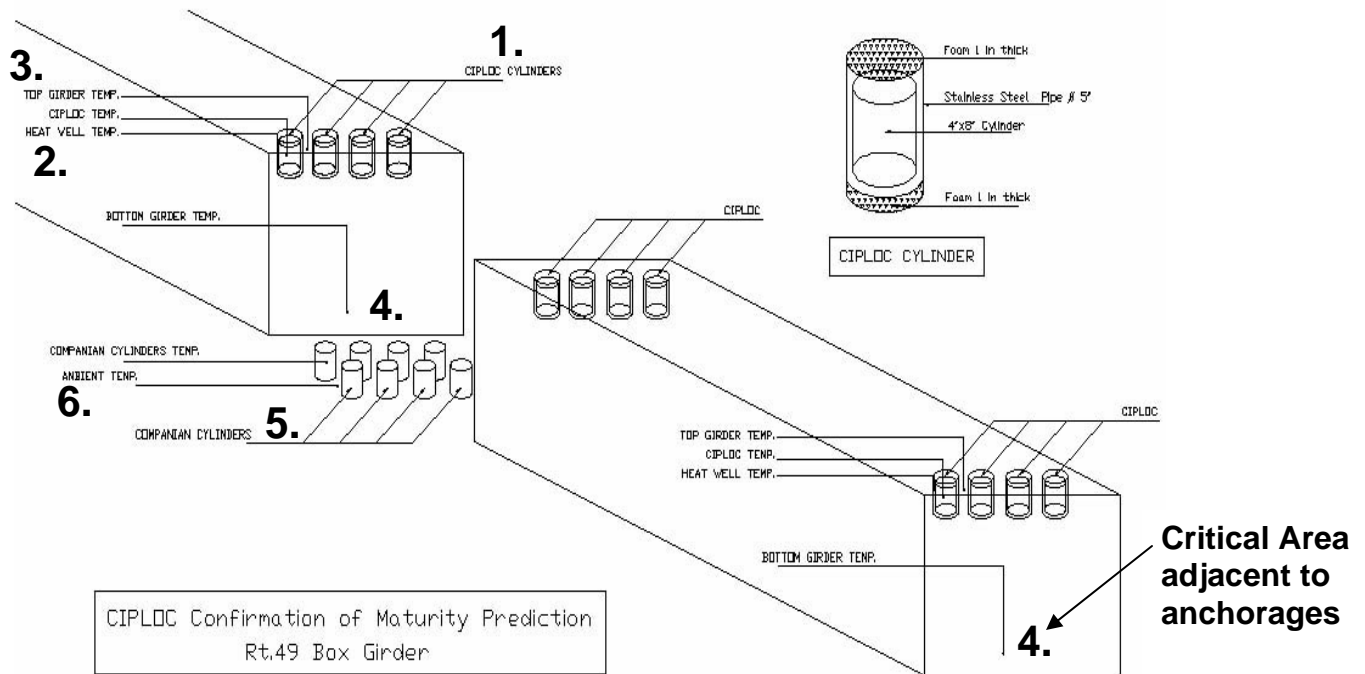


Figure 2 Experimental set-up

Six to eight CIPLOC cylinders were placed into the top of the beams, near the ends, as shown in Figure 2. Six thermocouples were installed around each CIPLOC field at various positions:

1. In a CIPLOC
2. In the heat well
3. At the top of the beam in the neighborhood of the CIPLOCS
4. At the bottom of the beam as the prestressing strands exit for the anchorages
5. In a companion cylinder
6. In the air with the companion cylinders.

Thermocouples were installed not only to predict concrete strengths but also to locate the coolest area of the beam which has the weakest concrete based on maturity predictions.

T-type thermocouples were wired, in sets of six, to ARC SmartReader 6 temperature data loggers. A wireless concrete maturity monitoring system, from Wake Inc., was used to measure the temperatures in other more remote areas of the beam. This system uses sacrificial recording devices embedded in the concrete which can be read wirelessly using a Pocket PC[®]. Data was recorded every 6 minutes in both cases.

Mix requirements

A NJDOT P2 class concrete was specified for the box beams. For this class, form removal is permitted at a required average strength of 2000 psi, transfer of the prestressing load is allowed at 4930 psi, and a 28-day strength of 6500 psi is specified.

EXPERIMENTAL RESULTS

Temperature histories

The maturity method bases its predictions on measured temperature histories. The ACR Trendreader recorded temperatures of the south end of the fourth beam, presented in Figure 3, are typical of those encountered during this study.

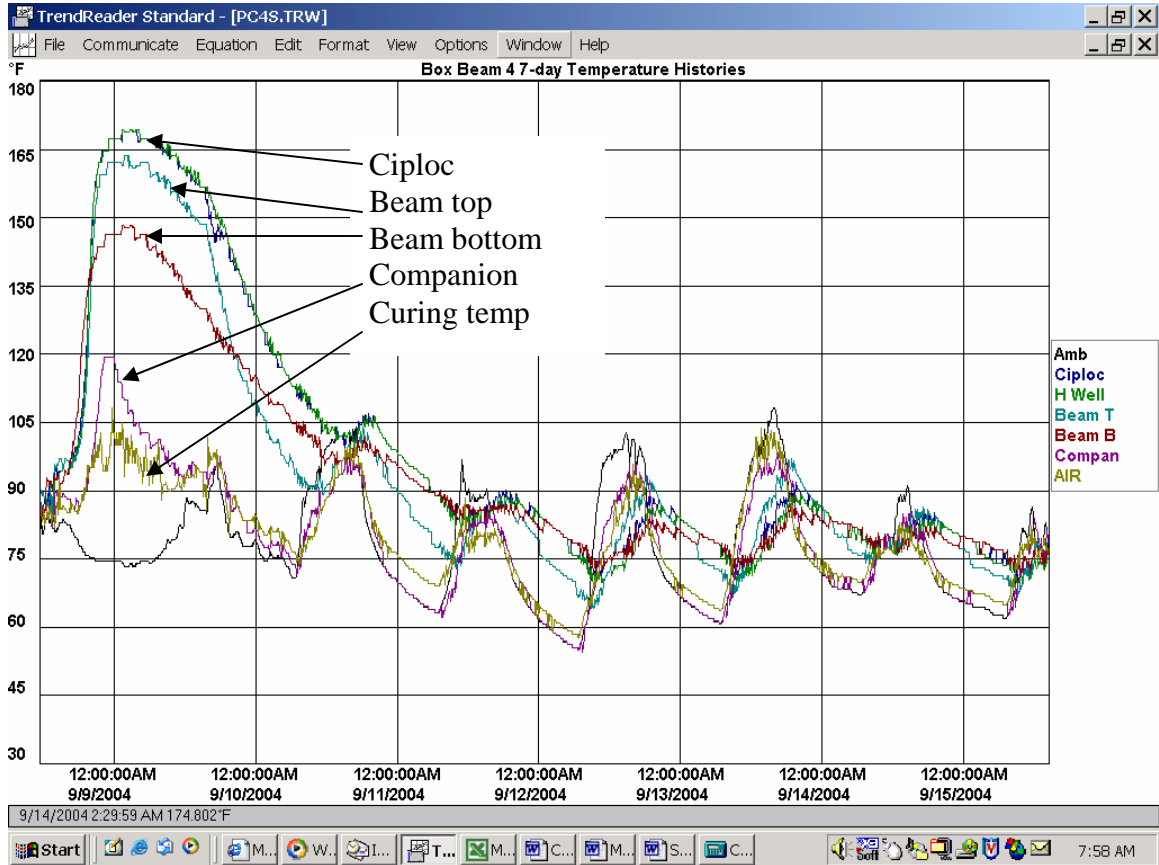


Figure 3 Temperatures measurements for beam 4S

Seven temperature traces from the different locations previously listed are shown. Reading up at midnight 9/9/2004 the first trace is the ambient air temperature. The next up, the jittery trace, is the air temperature with the companion cylinders, followed up by the temperatures of the companion cylinder, the bottom of the beam, the top of the beam, and finally the CIPLOC and heat well temperatures running together. Consideration of the air temperature under the tarps with the companion cylinders, the jittery trace, shows that application of the steam started at 6:00 pm in the evening and was continued until 6:00 am the next morning, as required. A temperature peak of 110° F was recorded where a steady soak at 150° was expected. These observations alone demonstrate the usefulness of simple temperature monitoring. After the steam curing was stopped, it took 4 days before the beam temperatures regularly follow the ambient temperature. Average daily temperatures around 75° F are seen.

Summertime high temperatures are recorded in the ambient temperature record, with daytime temperatures within the logger's protective container reaching over 100° F. An almost 30° F difference is seen between the temperatures of the companion cylinders and the beam bottom. Attention is drawn to the 15° F temperature difference between the top and the bottom of the beam, the coolest part of the structure. As the coolest part of the structure it becomes a critical measurement point. It is also the part of the beam that must immediately absorb the prestressing force. For these reasons, this area is identified as the part of the beam where the assessment of the concrete strength is most critical.

Computation of maturity and prediction of strength

The TrendReader program, used to log the ACR logger temperature data, is easily used to compute the temperature-time factor, and after that the strength can be estimated by adding compound lines to the temperature graphs. The recommended procedures require verification of companion cylinder strengths and interest focuses on the critical area, so these two traces are separated out for analysis. The result of this 1 minute procedure is presented in Figure 4.

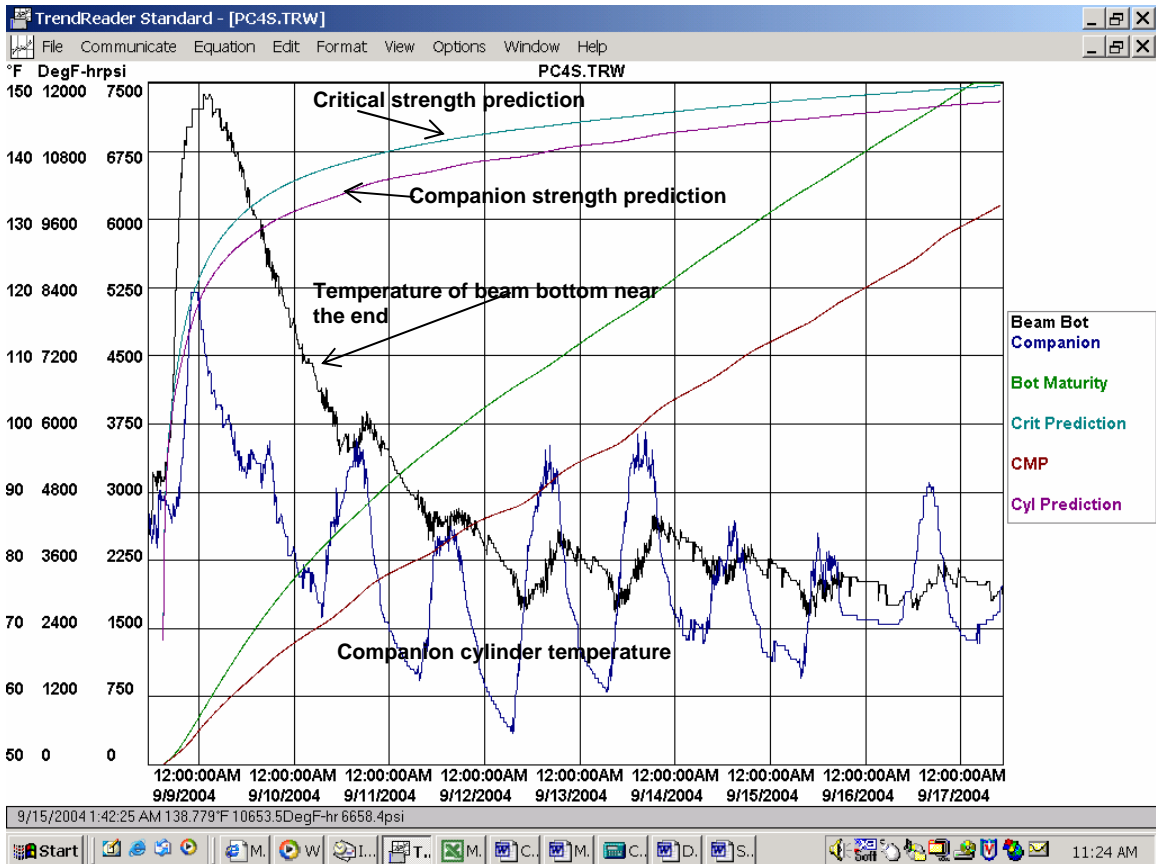


Figure 4 TTF and strength predictions for cylinders and critical area

The temperature traces for the beam-end bottom and the companion cylinder are chosen out of all the traces. Starting in the lower left corner, the maturities increase quickly, the bottom somewhat faster than for the companion cylinders, for the first couple of days, tapering off to increases of 1200 to 1000 °F-hr./day by the end. The strengths increase very rapidly after the final set and the application of heat. The strengths increase at 1 to 2 ksi per hour for these first few hours. After 2 days, the strength only increases 750 psi over the next 5 days. The release strength, just under 5000 psi, is predicted at 10:00 pm on 9/8/2004, only 7 hours after casting and 4 hours after application of the heat. The difference in strength between the critical area and the companion cylinders is predicted to be about 350 psi at 7:30 am on 9/9/2004. High daytime ambient temperatures narrow the strength gap after 3 days.

Strength-maturity verification and structural strength prediction

The verification principal requires that the strength-maturity relationship be able to prove itself by predicting the strength of companion test cylinders. If it is able to do so, the prediction can then be applied to the structure. Table 1 shows predicted companion concrete strengths, using results gathered only over the first few days, compared to the measured values of companion cylinder pairs; and the structural strength predicted from the ultimately validated strength-maturity relationship compared to the structural strength measured by paired CIPLOCs.

	Companion prediction	Companion measured	% error	Structure predicted	Structure Measured	% error
Beam 2	5648	5805	-2.7%	5839	5790	0.9%
	6471	6230	3.9%	6627	6485	2.2%
Beam 3	5824	6088	-4.3%	6052	6068	-0.3%
	5824	6088	-4.3%	6097	6370	-4.3%
	6229	6573	-5.2%	6515	6785	-4.0%
Beam 4	5466	5730	-4.6%	5939	6088	-2.5%
	6211	6421	-3.3%	6576	6657	-1.2%
	6056	6270	-3.4%	6920	6788	1.9%
Beam 5	5540	5475	1.2%	6030	5608	7.5%
	6317	6092	3.7%	6705	6670	0.5%
		average error	-1.9%			0.1%

Table 1 Predictive verification tests with structural strength prediction

The average error for predicting the companion cylinder strengths is below 2%. Since the verification principal has a statistical basis coming from tests of many cylinders, low values within a standard deviation are acceptable, 289 psi in this case. It is seen that no value falls below that range. The equation is therefore validated and can be applied to structures made of this concrete for these steam accelerated conditions. Predictions of the strength at the top of the beam, near the CIPLOCs, are shown to be very accurate. The only outlying point, with an error of 7.5 percent, is for beam 5, which was not steam cured, at 1 day.

Prediction of release strength

For all the trials the release strengths predicted for the critical area, the companion cylinder strengths, and the strengths measured by the plant to assure prestressing release strength at around 7:30 am, following 12 hours of steam curing are shown in Table 2.

CIPLOC site	7:30 am crit prediction	7:30 am cyl prediction	7:30 am cyl measured	Crit pred error	Crit pred error	Cyl pred error	Cyl pred error
	psi	psi	psi	psi	%	psi	%
1N	5860	6050	6090	-230	-3.8%	-40	-0.7%
2N	5740	5810	5650	90	1.6%	160	2.8%
2S	5720	5720	5650	70	1.2%	70	1.2%
3N	6000	5810	5650	350	6.2%	160	2.8%
3S	5850	5550	5650	200	3.5%	-100	-1.8%
4N	5830	5780	6090	-260	-4.3%	-310	-5.1%
4S	5890	5600	6090	-200	-3.3%	-490	-8.0%
5N	5830	5530	*5575	425	7.6%	125	2.2%
5S	6800	6490	**6250	550	8.8%	240	3.8%
Std dev	94	164	235	237			
# Avg.	5841	5760	5839	3	0.2%	-79	-1.2%
Cof of Var	1.6%	2.8%	4.0%				

* tested at NJIT Saturday Sept. 18 @ 3:30 pm

** release strength measured Monday

Sept. 20 @ 7:30 am

beam 5 results excluded from averages

Table 2 Predicted release strengths

Beam 5 was cast on Friday and allowed to cure naturally, with no steam, over the weekend. Samples were collected and tested at NJIT on Saturday. The release strength was tested the following Monday. The strength-maturity prediction tends to overestimate strengths outside a narrowed range of maturities, for reasons that will be explained, and so is excluded from the averages of Table 1. The cylinder predictive error is the difference between the measured cylinder strength and the cylinder strength prediction (cylinder – cylinder prediction.) The critical predictive error is the difference between the measured cylinder strength and the maturity method's prediction of the critical strength (cylinder -critical

prediction.) It is noted that sometimes the companion cylinders overestimate the strength in the critical area while at other times they underestimate it.

Prediction of 28-day strength

The amount of time needed to reach the 28-day strength in the critical area can also be predicted from the strength development curves shown in Figure 4 and the appendix. These are summarized in the following table.

CIPLOC test site	Days to 28-day strength
1N	2
2N	1.5
2S	1.5
3S	1.75
4S	1.75
5N	1.75
5S	1.75
Avg.	1.71

Table 3 Time to 28-day strength

The amount of time to reach the 28-day strength is predicted between 1.5 and 2 days averaging 1.71 days.

Iterative development of strength-maturity relationship

The final strength-maturity relationship, the predictive equation for the maturity method, was developed through a process of iterative refinement. Field monitoring of structures can begin after a strength-maturity relationship for the particular concrete has been developed in the laboratory. A tentative equation was developed from 2 cylinders, one tested at 11 the other at 18 hours, for the first day of testing. Alternatively, as suggested in *Implementation of Maturity*

Meters, a predictive equation might be assumed to start the iterative development process. Wherever the prediction comes from it is subject to the verification principal. However developed, once a strength-maturity relationship is shown able to make predictions within a standard deviation of predictive error, the validated results can be added to the database from which the predictive equation is derived. The strength-maturity relationship is then recomputed. The following diagram illustrates this process.

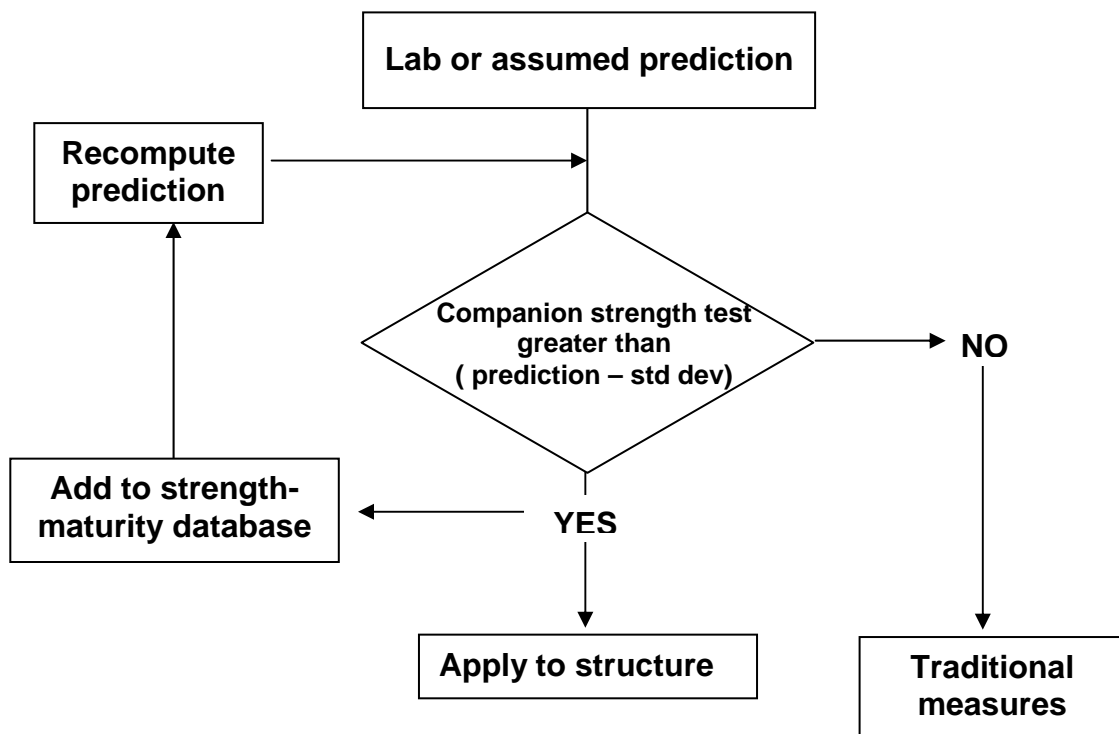


Figure 5 Iterative development of predictive equation

An initial prediction, $f_c = 820 \ln(ttf)$, was based on 2 individual cylinder tests of the concrete mix that compares well with the final one, $f_c = 796 \ln(ttf) + 7.9$, based on 57 individual tests.

Overall results

To demonstrate how well the maturity method was generally able to predict the strengths of the concrete under study, all of the strength test results were plotted with the Excel best-fit Trendline. These results are shown in Figure 6.

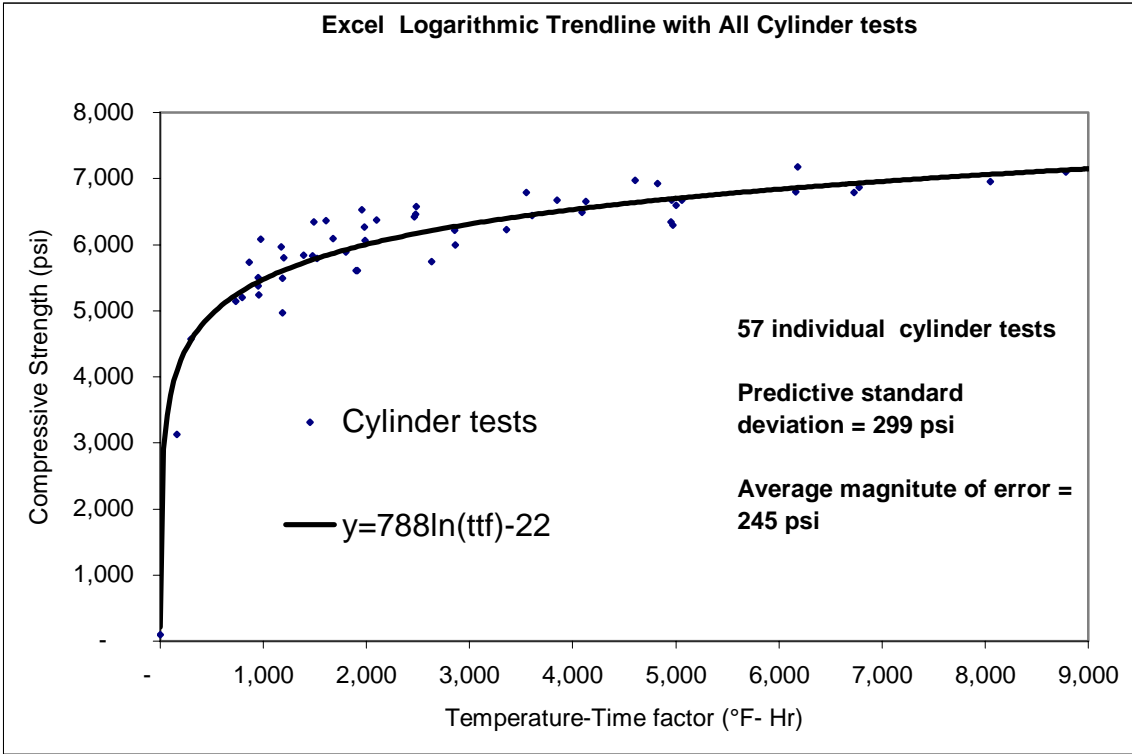


Figure 6 Trendline with all cylinder tests

Analysis of this data shows that the strength-maturity relationship is able to predict the strength of concrete cylinders with good accuracy and precision. The regression coefficient is 0.92. The average error is 1 psi. The average magnitude of the error is found to be 245 psi. The standard deviation of the error is 299 psi.

Restricted results

It is seen that this prediction tends to underestimate the cylinder strengths in the early period, which is of particular interest in this study. The predictive equation

can be further refined by restricting attention to the early part of the data. Figure 7 is restricted to the period up to 6000 °Fhr.

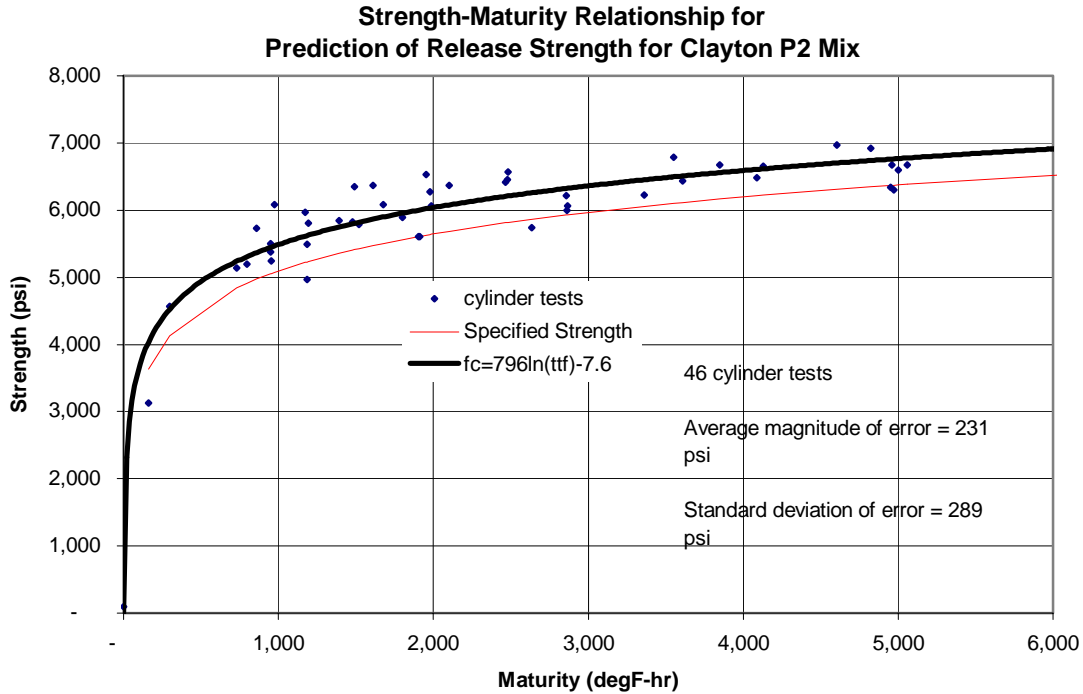


Figure 7 Strength-maturity relationship for Clayton Class P2 concrete

Both the average magnitude and the standard deviation of the error are further reduced, to 231 psi and 289 psi, respectively. This relationship can now be used to predict the release strength for precast/prestressed steam accelerated elements using this concrete.

DISCUSSION OF RESULTS

Averaging the predictive error, the difference between the prediction and the cylinder test, the strength-maturity relationship is off by 2 psi. This is the consequence of the least squares fitting method utilized by Excel for generating its Trendline. “Best-fitting” procedures operate by averaging the errors above the proposed line with the errors below it. The low standard deviation of the

prediction error, 289 psi, is a reflection of the maturity method's ability to make precise estimates of the strength of steam accelerated precast/prestressed concrete elements. It is also a reflection of good quality control on the part of the concrete and prestressing plants, and consistency in the cylinder testing. Comparable testing results from bridge decks display standard deviations around 500 psi. Because it averages the errors from many tests, the strength-maturity representation of strength smoothes out the fluctuations of normal cylinder testing.

The investigations of the maturity method's ability to predict the prestress load transfer strength are summarized in Table 2. Predictions of strengths in the critical area and the strengths of companion cylinders are compared to the release strengths measured by the plant using their NJDOT accepted companion cylinders. The maturity method is able to predict the companion cylinder strengths within 6 percent of the strengths actually measured.

Of particular interest is the ability of the companion cylinders to predict the release strength in the critical area. In studies where the structure's strength has actually been measured; by coring, or match-curing,^(13,14) the structure was found to be about 10 percent stronger than the standard companion cylinders. This is also what the CIPLOC testing showed. However, the part of the structure that can be tested must be accessible. The accessible areas are not necessarily the in the area of critical interest, and were not the areas tested in the previous studies. This is why the other studies have found the structure to be stronger than the companion cylinders. They were sampling in the wrong place! The temperature testing, represented by Figure 3, shows that the temperatures vary considerably within the structure. The temperature at the location of the CIPLOCS, at the top of the beams, was seen to be consistently 20° to 30° F warmer than the critical area, therefore the CIPLOCS were more mature, and stronger. Since the strength-maturity equation was validated using the companion cylinders, and further proved by the CIPLOCS, it can be quite

confidently applied to the critical area. If the naturally cured beam results are excluded, the ability of the companion cylinders to predict the strength of the precast structure in its critical area is almost as good as the maturity method's ability to predict the strength of the companion cylinders. The companion cylinders are a good representation of the precast/prestressed concrete's strength in its critical area.

The time needed for the steam accelerated precast/prestressed elements to reach the required 28-day strength, at which time the item can be transported and placed into service, was found to range between 1.5 and 2 days, averaging 1.71 days in late summer conditions. This amount of time falls within the minimum 3 days specified before transportation and use are permitted.

The verification principal for the maturity method was upheld. The strength-maturity relationship developed was validated. Consideration of Table 1 shows the operation of the verification principal for the maturity method. All three measures of the release strength are close. The coefficient of variation, V , is excellent for all the measures. The maturity predictions have a better V than the cylinder compression tests, are subject to normal variations of cylinder testing. Companion cylinder strengths were predicted within the standard deviation of the predictive error for all tests in 9 cases out of 10. The only one outlier was higher than the prediction, it could have been lower. After the strength-maturity relationship was validated it was then applied to the structure. CIPLOC strengths, representing the structure, were predicted within a standard deviation in 9 of the 10 trials. This outlier was the only observed case where the companion cylinder was properly predicted while the prediction of the structure's strength was higher, by more than one standard deviation, than the actual strength measured by CIPLOCs. This is explainable by noting that this beam was naturally cured where all the other ones were steam cured. The smaller test cylinders were able to benefit from the heat released by the larger mass of the structure whereas the structure got no additional heat at all.

The developed strength-maturity relationship is only valid when steam is applied. It can not be applied to the natural cure case.

CIPLOC testing is shown to be a good method for assessing the strength of a structure. Not only do CIPLOCs validate the maturity method, they themselves are validated by the strength-maturity prediction. It is emphasized that their use is not intended as a normal part of using the maturity method. They have served, in this study, to demonstrate the accuracy of the maturity method's prediction of the structure's strength.

The method of iterative refinement for the development of the strength-maturity relationship is shown able to produce an accurate and precise predictive equation within a few trials. Although there were only slight changes in the constants of the equation as the experiment proceeded, the statistical confidence in the equation increases with the number of tests. Iteration should continue until at least 30 tests are included. It is anticipated that there may be some seasonally induced drift in the strength-maturity relationship which could cause a failure to validate the predictive equation. In such a case, recomputation of the strength-maturity relationship based on the last 30 tests should be considered. With experience a precasting plant might have several equations, based on their experience. Analysis of equations of this sort might allow for adjustment of the strength-maturity relationship based on something as simple as the average temperature during the first day of curing.

The last adjustment made to improve the predictive ability of the strength-maturity relationship, restricting the range of this strength-maturity relationship, comes at the cost of overestimating the strength at later ages. In heat accelerated type III cement concrete the required strengths are reached quickly, but exhibit little strength gain after that. Exponential equations increase forever. Use of this strength-maturity relationship is therefore restricted to the 6000° F-hr.

range of the chart which is sufficient for the prediction of the prestressing transfer strength. Further inclusion of additional early strengths in the iterative improvement scheme could remove this restriction in the future.

The results shown in Table 1 generally agree that the release strength was 5840 psi, 18 percent higher than the required release strength after 12 hours of steam curing. Consideration of Figure 4 indicates that the release strength of 4932 psi was reached 7 hours after casting and 4 hours after the start of the steam curing. Consideration of all the strength development curves, like Figure 4, in the appendix, for all 9 observations shows 5000 psi being reached within 6 to 8 hours after casting. A cylinder tested at NJIT automatically at 2 am, 11 hours after casting produced a compressive strength of 5750 psi, right in line with the prediction. So, it seems possible that the release strength had actually been reached after about 7 hours. It is very tempting to save 6 to 8 hours of steaming, significantly reducing energy, and hopefully overall, costs. Such a radical departure from the current practice of 12 hours of steam curing would need much additional testing. Early-age testing with CIPLOCs throughout the steam application period might be used to determine whether or not the maturity method could be used to regulate the steam. If so, substantial energy costs could be saved.

Included on Figure 7 is a plot of the minimum required average strength prediction. This plot shows the early-age development of ACI 318's f'_{cr} . The minimum required average strength expresses the strength in such a way that 90 percent of tests will exceed it. The plot is derived through a statistical procedure recommended in ACI 228-1R, the one-sided tolerance factor method. The predicted strength is adjusted in such a way as to assure that 90 percent of the strength tests will be higher. Also implied is a statistical acceptance that 10 percent of tests might be lower, which is demonstrated on Figure 7. Of the original 57 points, only the 5 shown fell below the specified strength prediction, exactly as might be expected. Since NJDOT's specified release strength already

assures the minimum required average strength it is not necessary to apply this procedure again for purposes of determining the prestressing release strength.

The steam curing method used to produce precast/prestressed items is a more controlled environment than that of normal cast in place methods. The inability of the maturity method to adjust for variations of the initial temperature history and, for anticipated variability of the concrete mix are limitations of the maturity method. However, those particular variables are well controlled at precasting plants. The consistency of temperature histories and a greater level of supervision and care for the concrete quality make precasting an ideal situation for application of the maturity method. Under these circumstances the maturity method can make highly accurate, highly precise estimates of the concrete strength in precast/prestressed elements.

Frequent verification testing is the key to achieving and maintaining confidence in the predictive equation. For precast/prestressed applications a recommendation is made that the strength-maturity equation be tested at least once a week with tests at 1 day, 2 days and 3 days in addition to testing at the prestressing release time. This recommendation is considered a minimum. More verification testing is encouraged. With enough tests, strength testing using the maturity method can be as good as standard cylinder testing. The verification testing applies to all the concrete using the particular concrete mix

Several additions to the proposed manual for implementing the maturity method on highway structures are recommended to cover steam-accelerated curing.

CONCLUSIONS

1. The maturity method can make accurate, precise measurements of the strength of precast/prestressed heat accelerated concrete elements.
2. The maturity method can be used for determining adequate concrete strength in an element to allow release of the prestressing force.
3. A datum temperature of 50° F produced accurate predictions of the heat accelerated concrete. This value recommended as the default value for steam accelerated concrete items in cases where actual laboratory or previous field tests are not available.
4. The verification principal for the maturity method is validated by the experiments.
5. Companion cylinders are shown to be an unexpectedly good representation of the structure's strength in the critical area for the precast/prestressed steam accelerated items tested.
6. A good strength-maturity relationship can be derived for precast heat-accelerated concrete mixes from a few good field trials.
7. The iterative refinement process, based on Excel's logarithmic Trendline function for the curve fitting, is able to produce a very accurate and precise predictive equation.
8. The required 28-day strength for the steam cured elements was reached within 2 days for all observations.
9. The cured in-place lift out cylinders were shown to be a practical alternative for measuring in-place concrete strength.
10. The ability of maturity method in conjunction with the one-sided tolerance factor analysis to express the required average strength is demonstrated.
11. Some consideration should be given to temperature conditions other than the late summer ones of this study. In these conditions the specimens were able to reach their 28-day strengths within the minimum acceptance time of 3 days. This might not be the case in winter conditions.

RECOMMENDED ADDITIONS TO PROPOSED MANUAL

1. A datum temperature of 50° F is assigned for use in steam accelerated applications.
2. The bottom ends, where the prestressing strands leave the forms, are the critical areas for assessing the concrete strength. Not only is this the coolest area of the structure it is also the region into which the prestressing force is directly released.
3. Maturity measurements are to be made in the critical areas of the beams adjacent to the anchorages at both ends of the prestressing bed. The maturity measurements in the section cast last are expected to be lower and will probably control the release strength. However, the lowest strength prediction will always control.
4. The strength-maturity relation must be validated by predicting accurately the strength of companion cylinders cured with the structure. After the required curing time the maturity method is used to predict adequate strength for the prestressing release. A strength test of companion cylinders is simultaneously conducted to check that the strength-maturity relationship is able to predict this concrete's strength. If the strength of the companion cylinder is predicted within the standard deviation, from at least 30 previous tests, then the prediction can be applied to the structure.
5. If the strength maturity relationship is not validated it will be necessary to determine the release strength by conventional means. This would constitute a reversion to the acceptance of the release strength in companion cylinders as indicative of that strength in the structure. If the validation has failed the causes must be investigated. It might be necessary to recompute the strength-maturity relationship.
6. The iterative refinement process shall continue until at least 30 tests are included in the strength-maturity data base for that concrete. Tests at 1 day, 2 days and 3 days should also be included when developing the strength-maturity relationship and be counted towards the 30 tests. Most

of the tests should concentrate around the release strength if measurement of that is to be the primary use.

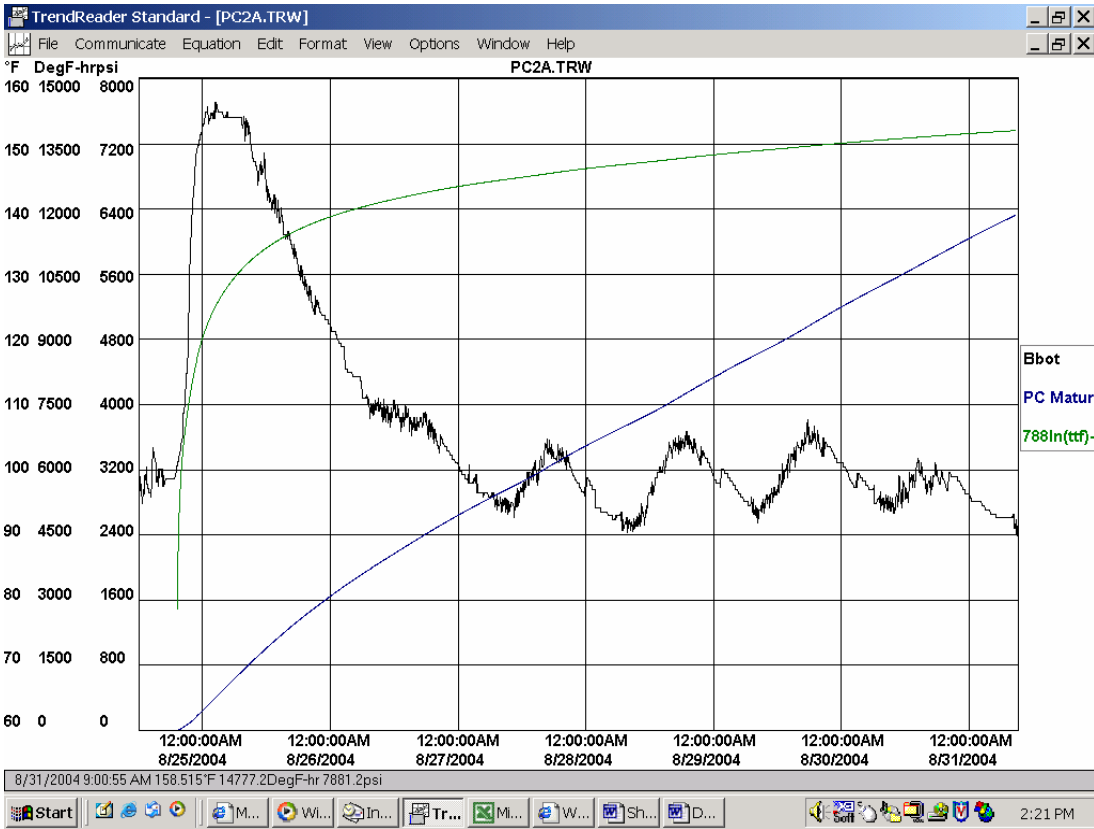
7. A verification test shall be conducted for each particular mix at least once each week of production. The verified strength-maturity relationship may be used for all production using this concrete at this plant.

APPENDIX

TrendReader temperature, maturity and strength predictions in the critical area for all the box beams tested.



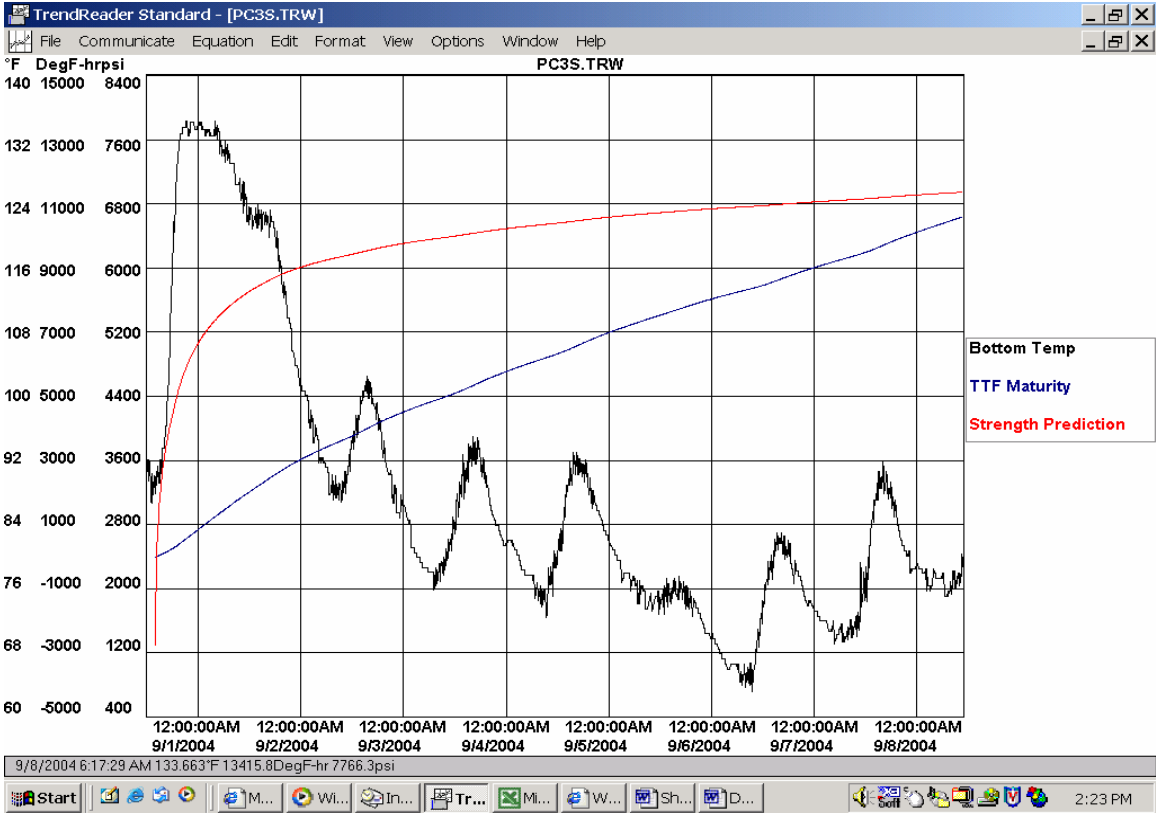
Beam 1 north critical strength prediction



Beam 2 north critical strength prediction



Beam 2 south critical strength prediction



Beam 3 south critical strength prediction



Beam 4 south critical strength prediction



Beam 5 north critical strength prediction



Beam 5 south strength predictions

REFERENCES

1. Standard Practice for Estimating Concrete Strength by the Maturity Method, ASTM C 1074-93 Annual Book of ASTM Standards, Vol 4.02 Concrete and Aggregates.
2. Ansari, F. and Luke, A. "High Early Strength Concrete for Fast-track Construction and Repair," Report to NJDOT, March 29, 1996.
3. Ansari, Luke, Vitillo, Blank, Turhan, "Developing Fast Track Concrete for Pavement Repair," Concrete International Vol 19 (5), pages 24-29, May 1997.
4. Ansari, F. , Luke, A. and Dong, "Development of Maturity Protocol for Construction of NJDOT Concrete Structure," Report to NJDOT, July 27, 1999.
5. Dong, Luke, A., Vitillo, N. and Ansari, F, "Use of the Maturity Method During Highway Construction," Concrete International Vol 24 (2), Feb. 2002
6. Hsu, T.C.T., Luke, A., Balaguru, P., Vongvorakarn, V., Punurai, S., "Optimization of VES Concrete, FHWA-NJ-2002-004," Report to NJDOT, January 2002.
7. Luke, A., Hsu, T.C.T., Punurai, S., "Implementation of Concrete Maturity Meters, FHWA-NJ-2002-003," Report to NJDOT, December 2002.
8. McIntosh, J.D. , "Electrical Curing of Concrete", Magazine of Concrete Research, Vol. 1(1), page 21 , 1949
9. Nurse, R.W., "Steam Curing of Concrete", Magazine of Concrete Research, Vol. 1(2), page 79-88, 1949
10. Saul, A.G.A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure", Magazine of Concrete Research, Vol. 2(6), page 127-140, 1951
11. Plowman, J.M., "Maturity and the Strength of Concrete", Magazine of Concrete Research, Vol. 8(22), page 13-22, 1956
12. Standard Test Method for Compressive Strength of Concrete Cylinders Cast in place in Cylindrical Molds, ASTM C 873.
13. Roller, John J., Russell, Henry G., Bruce, Robert N. & Hassett, Bryan, "Effect of Curing Temperature on High Strength Bridge Girders", PCI Journal March-April 2003, pp. 72-79.
14. CTA Technical Bulletin 73-B9, September, 1973
15. ACI 318.5.3 ACI Manual of Concrete Practice 2004