MATURITY METHOD DEMONSTRATION

Final Report

SPR 304-181

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16. Abstract

The concrete maturity method is a quality control/quality assurance tool that can be used to assist contractors and transportation officials in producing cost-efficient, durable concrete structures. This report documents the findings of an investigation performed for the Oregon Department of Transportation to demonstrate the use and benefits of the maturity method. The maturity method was shown to be an easily implemented QC/QA tool that can be used to estimate strength development, speed construction operations, and document contractor mistakes.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		PRESSURE					**PRESSURE**		
psi	pounds per square inch	.0068948	megapascals	MPa	MPa	megapascals	145.038	pounds per square inch	psi
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

DISCLAIMER

MATURITY METHOD DEMONSTRATION

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TERMINOLOGY
(ASTM C 1074, 1998)

Datum temperature: The temperature that is subtracted from the measured concrete temperature for calculating the temperature-time factor.

Equivalent age: The number of days or hours at a specified temperature required to produce a maturity equivalent to the maturity achieved by a curing period at a temperature different from the specified temperature.

Maturity: The extent of the development of a property of a cementitious mixture.

Maturity function: A mathematical expression that uses the measured temperature history of a cementitious mixture during the curing period to calculate an index that is indicative of the maturity at the end of that period.

Maturity index: An indicator of maturity that is calculated from the temperature history of the cementitious mixture by using a maturity function.

Maturity method: A technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strength if they attain equal values of the maturity index.

Temperature-time factor: The maturity index based on the temperature-time maturity function.

1.0 INTRODUCTION

Construction projects with portland cement concrete elements are monitored for strength development after placement. This information is used to determine the following:

- when to proceed with subsequent construction work,
- when to allow traffic onto the project,
- whether the concrete is hydrating at an acceptable rate, and
- when contractual obligations are fulfilled.

Representative cylinders or beams cast from the same batch of concrete as that used in the construction project are typically monitored for strength. Sets of specimens are loaded to failure at prescribed intervals over 28 days for multiple purposes. A primary purpose of such testing is to estimate the increase in compressive strength of the structure by curing the specimens under similar conditions to the in-situ concrete element for quality control purposes.

Concrete strength development is controlled by the extent of hydration. The hydration rate increases with the increase of temperature. The hydration reaction is exothermic in nature and therefore increases the rate of strength gain. Consequently, strength development at a specific location in a structure is strongly influenced by the temperature history at that location. In addition, the strength development through a cross-section is not uniform due to thermal gradients. Because of the dependence of strength development on actual thermal history, specimens cast and aged at the project site do not necessarily reflect the actual concrete strength within a structure. In addition, there may be differences in the hygral (moisture) history between the fabricated specimens and the in-situ product.

The *maturity method* is used to estimate the concrete strength in real-time at critical locations within the structure based on the thermal history at that location. Construction decisions can be made based on the current strength of the structure. In many cases, using concrete maturity in conjunction with, or instead of, testing separately cast specimens to determine when to proceed with subsequent construction operations can expedite a construction project. Quality control is improved because the strength estimates are based on data from the structure instead of separate specimens. In addition, extreme temperatures or thermal gradients that may affect quality can be remedied or at least noted.

1.1 MATURITY METHOD PROCEDURE

There are three general steps required to use the maturity method:

- develop a correlation curve that relates the temperature history to strength for the specific concrete mixture that will be used for a project,

- record the in-situ temperature history at the locations of interest on the project while the concrete ages, and
- verify the validity of the correlation curve for the specific concrete delivered to the project.

The correlation curve consists of a *maturity index* plotted against strength. The maturity index is a value that increases with age according to a *maturity function*. Two maturity functions are recommended by ASTM C 1074 (*1998*): the *temperature-time factor* and the *equivalent age* at a specified temperature.

The temperature-time function assumes that the rate of strength development increases linearly with temperature. A *datum temperature*, or the temperature below which strength gain will cease, is incorporated into the function. Mathematically, the function is as follows (*Saul 1951*):

$$M(t) = \sum (T_a - T_o)\Delta t \qquad \textbf{(1-1)}$$

where:

$M(t)$ = the temperature-time factor at time (t) (units are °C-days or °C-hours),
T_a = average concrete temperature during Δt in °C,
T_o = datum temperature measured in °C, and
Δt = a time interval in days or hours.

The equivalent age maturity function assumes the rate of strength development increases exponentially with time. The function includes an activation energy term, similar to equations that describe chemical reactions. The equation is as follows (*Freisleben Hansen and Pedersen 1977*):

$$t_e = \sum \left[e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \right] \Delta t \qquad \textbf{(1-2)}$$

where:

t_e = equivalent age at a specified temperature T_s (units are days or hours),
Q = apparent activation energy constant in K,
T_a = average temperature of the concrete during time interval Δt in K,
T_s = specified temperature in K,
Δt = time interval in days or hours.

Research has shown that the equivalent age function accounts for temperature more accurately over a wider temperature range than the temperature-time factor. Tikalsky et. al. (*2001*) summarizes the scientific basis for both functions.

Approximate values for datum temperature and apparent activation energy constant are provided in ASTM C 1074. However, the datum temperature and activation energy are affected by parameters such as cement fineness, particle size distribution, water-to-cement ratio, cement composition, added constituents, and initial temperature. Consequently, the accuracy of the strength estimation can be improved by measuring the datum temperature or activation energy for the concrete mixture that is used on the construction project. All materials for these measurements should be the same as those used in the concrete for the construction project. The measurement procedure, described in ASTM C 1074 (*1998*), has the following basic steps:

- Cast three sets of representative mortar cubes and cure in water baths controlled at the maximum, minimum, and average temperatures expected in the in-situ field concrete.
- Measure the concrete strength gain at each temperature at specified periods.
- Plot strength gain versus time and fit the data with the following function:

$$S = S_u \frac{K(t - t_o)}{1 + K(t - t_o)} \qquad \textbf{(1-3)}$$

where:

S = average cube compressive strength at age t (a variable),
t = test age (a variable),
S_u = limiting strength (a regression coefficient),
t_o = age when strength development begins (a regression coefficient), and
K = the rate constant (a regression coefficient).

- Plot the rate constant, K versus the curing temperature for the three test temperatures and fit either an Arrhenius exponential curve through the data to determine Q, or a linear curve through the data to determine T_o.

Creating the correlation curve requires an instrument to record the temperature at least every 1/2 hour to an accuracy of at least ±1°C. The recorded temperature data is used to calculate the maturity index for a strength-maturity index correlation curve. Commercial maturity meters are available to monitor the temperature and calculate the maturity index, thereby reducing the extent of hand calculations. The following general steps, based on cylindrical compression specimens, are necessary for creation of the correlation curve:

- Cast at least 15 cylindrical specimens according to the procedure outlined in ASTM C 192 or equivalent. The concrete must be the same mixture and from the same supplier as the concrete for the construction project.
- Embed one temperature sensor (generally a thermocouple) into the center of each of at least two cylinders. Begin recording temperature data.
- Cure the specimens for the first 24 hours under conditions similar to those expected of the in-situ concrete for which the correlation curve is being prepared. The correlation specimens should be exposed to similar early-age temperatures as the project concrete because these early-age temperatures affect the strength-maturity relationship. A single correlation curve for each concrete mixture developed at a nominal temperature of approximately 23°C will cover most if not all concrete placements. In some cases, however, a summer and a winter correlation curve may be necessary to provide wide enough temperature coverage.
- Perform compression tests on two cylinders at ages of 1, 3, 7, 14, and 28 days in accordance with the procedure described in ASTM C 39. Record the average compressive strength at each test age. The procedure for duplicate testing resulting from inadequate specimens is described in ASTM C 1074. Record the average maturity index at the time of each break based on the temperature measurements from the

thermocouples. In the event that in-situ strength is to be estimated for an extended period beyond 28 days at standard temperature, additional samples should be prepared. Sufficient strength-maturity data should be generated to encompass the largest expected field maturity value for which a strength estimate is desired.

- Plot compressive strength versus maturity index.
- Generate an equation that accurately fits the plotted data.

The correlation curve equation can be based on any function that accurately describes the data. Two of the more common relationships are the logarithmic and hyperbolic functions. The form of the logarithmic function is as follows (*Plowman 1956*):

$$S = A + B \cdot \log(M) \quad \textbf{(1-4)}$$

where:

S = estimated strength of the concrete at a given maturity (a variable),
A, B = regression constants,
M = maturity index (a variable).

The form of the hyperbolic function is as follows (*Carino 1981*):

$$S = S_u \frac{K(M - M_o)}{1 + K(M - M_o)} \quad \textbf{(1-5)}$$

where:

S = estimated strength of the concrete at a given maturity (a variable),
S_u = regression constant analogous to the ultimate strength that the concrete will attain,
M = maturity index (a variable),
M_o = regression constant analogous to the maturity when strength gain begins,
K = regression constant analogous to a rate constant.

A software application that can generate logarithmic and hyperbolic equations for inputted data can be used to determine the regression constants and the correlation equations.

To estimate the concrete strength of the construction project, the following general steps are used:

- Prior to concrete placement, install the temperature sensors. The sensors should be placed at locations deemed critical due to the strength requirements or the rate of hydration.
- Begin recording temperature data as soon as possible after concrete placement.
- Use the temperature data to calculate the maturity during aging. A maturity meter can be used to calculate the maturity and then output the values.
- From the correlation equation, estimate the concrete strength from the calculated maturity. Alternatively, use the correlation equation to determine the maturity of the concrete at a desired strength level and monitor the maturity until that level is achieved.

A specified number of cylindrical specimens are cast when the project concrete is placed to verify the strength-maturity relationship. Two of the cylinders are instrumented with temperature sensors that are monitored with a maturity meter. All of the cylinders are exposed to the same temperature conditions as the project concrete for the first 24 hours. At a specified time, or at specified times, the maturity of the cylinders is calculated and the compressive strength is measured to generate one or more strength-maturity data points, which are then in turn compared with the original correlation curve. If the verification points are within 5% of the correlation curve, then the correlation curve is considered valid.

2.0 OBJECTIVES

Though the underlying concept of the maturity method has been known for decades, it is not used routinely in most states. The objectives of this study were the following:

- Demonstrate the utility of the maturity method on an Oregon bridge.
- Establish a protocol for future applications of the maturity method in Oregon

3.0 APPROACH

The Technical Advisory Committee and Penn State University selected the bridge deck of the new Wells Creek Bridge for the maturity method demonstration. The plan for the bridge deck is shown in Appendix A.

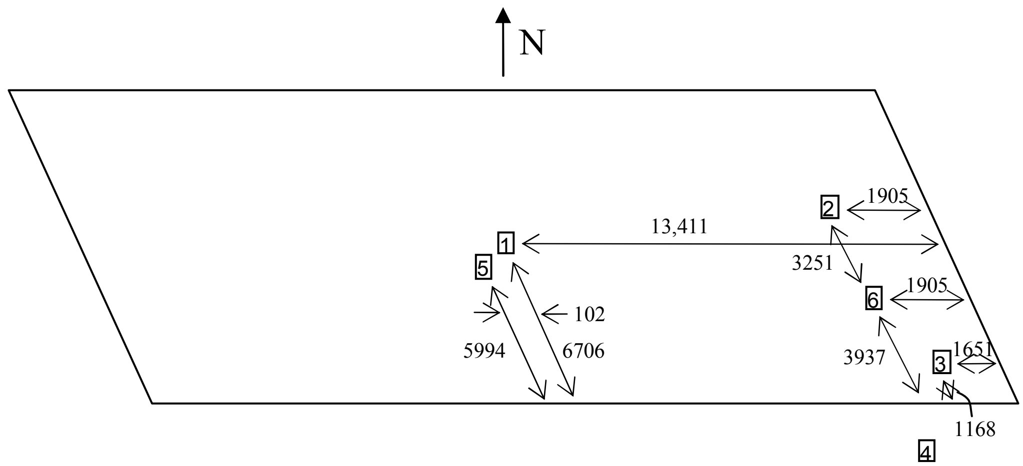
Penn State University measured the datum temperature and activation energy for the concrete mixture using the procedure described in ASTM C 1074 (*1998*). Cement and sand were sent to the University for analysis. Admixtures were provided by the University. The datum temperature and activation energy were used in the subsequent correlation, strength estimation, and verification maturity curves.

The correlation curves were developed from specimens made during the placement of concrete abutments that were cast with the same concrete mixture as the deck. The concrete mixture design is presented in Appendix B. Twenty-two, 152 x 305 mm (6 x 12 inch) cylinders were cast: twelve from each end of the bridge. Appendix C shows the batcher slip information, air content, and slump values for the delivered concrete. A Humboldt 4101, 4-channel maturity meter was used to record the temperature of the cylinders. Four thermocouples were placed in four separate cylinders cast from the west end of the bridge. No cylinders from the east end were monitored. The filled molds were capped and left undisturbed at the construction site for 24 hours. After 24 hours, the cylinders were transported to the concrete supplier where the molds were removed and the cylinders placed in a controlled temperature and humidity environment for the remainder of the curing period. Compressive strength tests were conducted by the concrete supplier at 1, 5, 7, 14, and 28 days.

Penn State University developed the correlation curves based on the compressive strength test results from the contractor and the maturity data from the maturity meter. The Humboldt 4101 maturity meter was used to calculate the temperature-time factor and equivalent age as shown in Equations 1-1 and 1-2. A specified temperature of 296.15 K (23°C) was used for the equivalent age method.

Fifteen verification cylinders were cast using the project concrete on the day the deck was placed. The intent was to demonstrate that the strength-maturity relationship of the cylinders would match the correlation curve because the mixture design used for the two sets of cylinders was the same.

Maturity development in the deck was monitored using a Humboldt 4101 maturity meter. Thermocouples were attached to the deck reinforcing steel at the positions shown in Figure 3.1. The thermocouples were positioned under the rebar and fastened with wire ties as shown in Figure 3.2 to protect the wire from the falling concrete. The maturity meter was placed in a plastic toolbox as shown in Figure 3.3 and situated under the bridge. After the concrete was placed, the maturity meter was activated and collected temperature data for 35 days.



All dimensions in millimeters

#4 monitored ambient temperature
#5 and #6 were alternates

Figure 3.1: Location of thermocouples on the bridge deck

Figure 3.2: Attachment of thermocouples to the rebar

Figure 3.3: Protection of the maturity meter

4.0 RESULTS AND DISCUSSION

4.1 MATURITY CONSTANTS *Q* AND T_O

Table 4.1 lists the data that Penn State University generated for determining the apparent activation energy, *Q*, and the datum temperature, T_o, of the concrete using the method specified in ASTM C 1074. Equation 1-3 was fitted to the data for each temperature as shown in Figure 4.1. The corresponding regression coefficients are given in Table 4.2. The results were typical for concrete: a higher bath temperature produced a more rapid strength gain but a lower ultimate strength. The rate constant, *K*, was plotted for the three test temperatures as shown in Figure 4.2, and the exponential and linear equations shown in the figure were fitted to the data points. The equations were used to determine *Q* and T_o.

Table 4.1: Data for determining activation energy using ASTM C 1074

Bath Temperature (^oC)	Age (Days)	Strength (MPa)			
		Cube 1	Cube 2	Cube 3	Average
8	0.73	3.01	3.10	3.23	3.1
	1.64	16.20	15.69	15.98	16.0
	3.11	22.93	25.70	18.98	22.5
	6.85	31.65	32.54	33.47	32.6
	13.50	42.4	52.00	46.45	47.0
	32.98	49.94	50.50	51.59	50.7
23	0.37	6.18	6.38	5.72	6.1
	0.82	22.32	20.79	21.05	21.4
	1.69	25.42	29.25	34.46	29.7
	3.09	37.06	33.56	40.30	37.0
	6.08	35.06	35.03	41.04	37.0
	13.02	45.85	35.96	49.88	43.9
42	0.18	4.33	4.74	4.69	4.6
	0.40	17.82	17.84	17.89	17.9
	0.79	29.06	29.70	29.03	29.3
	1.70	35.56	32.58	29.53	32.6
	3.10	35.01	34.75	32.85	34.2
	6.06	-	34.59	29.92	32.3
	13.03	32.72	31.51	36.99	33.7

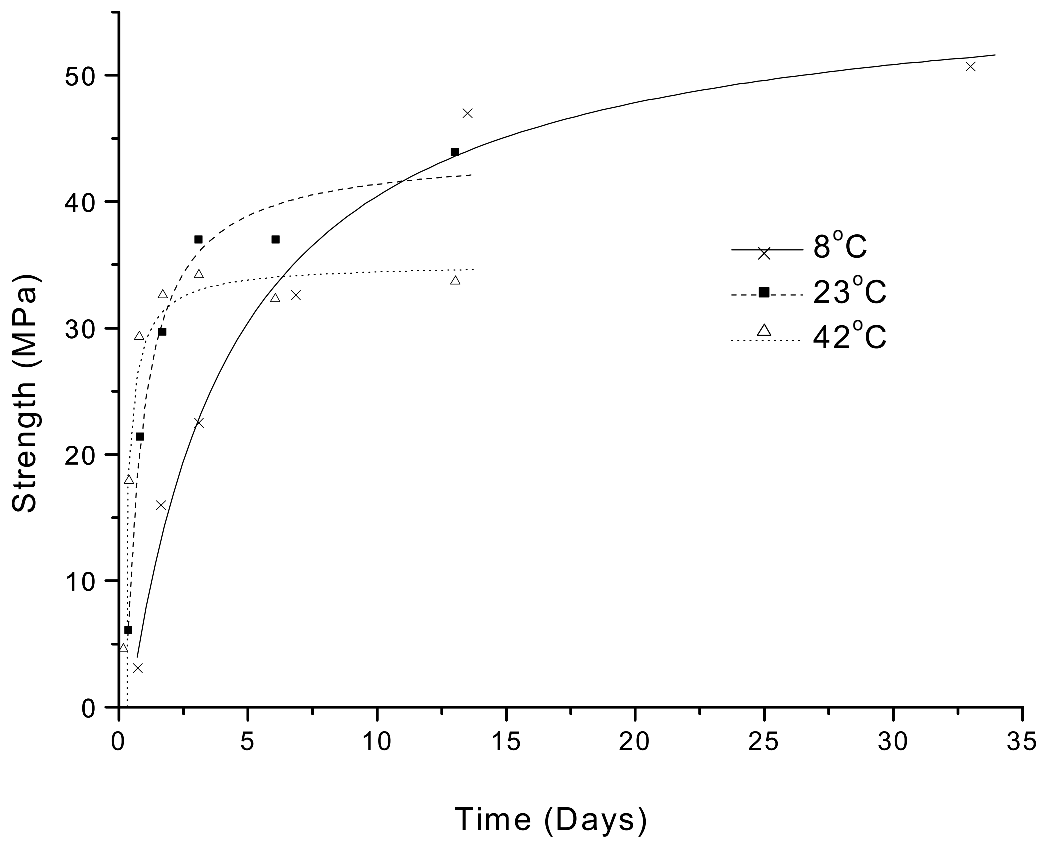


Figure 4.1: Compressive strength development of mortar cubes

Table 4.2: Calculated regression coefficients for Equation 1-3

Bath Temperature (°C)	S_u (MPa)	K (Days^{-1})	t_o (Days)
8	58.0	0.24	0.40
23	44.1	1.57	0.26
42	32.1	5.34	0.15

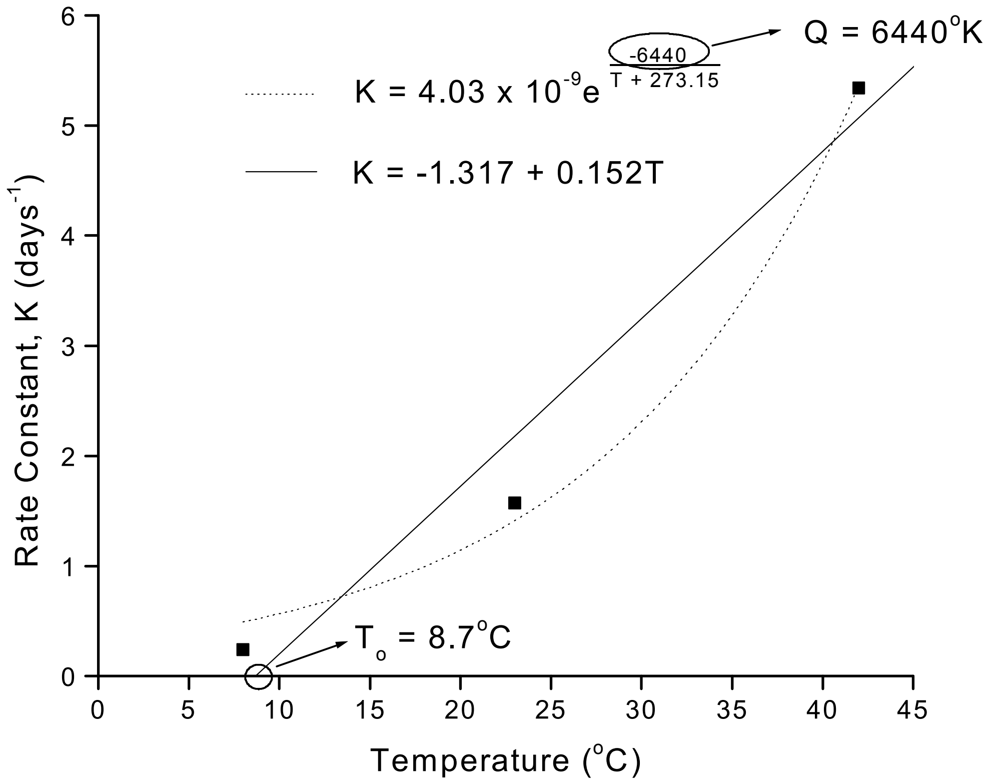


Figure 4.2: Determination of the maturity constants Q and T_o

4.2 CORRELATION CURVE

Table 4.3 shows the maturity and compressive strength data used for the correlation curve. The temperature-time factor and the equivalent age were recorded for each of the four channels of the maturity meter at the time of the cylinder tests. Only two cylinder tests were required at each specified time. The average values for the maturity indices and the compressive strength were calculated and plotted in Figures 4.3 and 4.4. Correlation curves were generated based on Equations 1-4 and 1-5. In both graphs, the logarithmic and hyperbolic curves adequately fit the data as shown by the R^2 values.

Table 4.3: Maturity and compressive strength data for the correlation curve

Elapsed Time at Cylinder Break, hours	Maturity Index		Compressive Strength, MPa (psi)
	Temperature-Time Factor, ^oC-hours	Equivalent Age, hours	
25	399	33.3	
	333	26.3	
	342	27.1	17.8 (2580)
	326	25.4	17.7 (2560)
	Avg.=350	Avg.=28.0	Avg.=17.8 (2570)
121	1660	123	
	1570	115	
	1500	110	36.6 (5300)
	1480	109	38.3 (5560)
	Avg.=1550	Avg.=114	Avg.=37.4 (5430)
167	2260	167	
	2140	156	
	2040	150	40.4 (5860)
	2030	148	43.1 (6260)
	Avg.=2120	Avg.=155	Avg.=41.8 (6060)
333	4420	321	
	4140	300	
	3950	287	45.4 (6580)
	4010	290	44.9 (6510)
	Avg.=4130	Avg.=300	Avg.=45.1 (6540)
680	8850	638	
	8360	603	
	7930	576	52.3 (7580)
	8040	582	50.0 (7260)
	Avg.=8290	Avg.=600	Avg.=51.2 (7420)

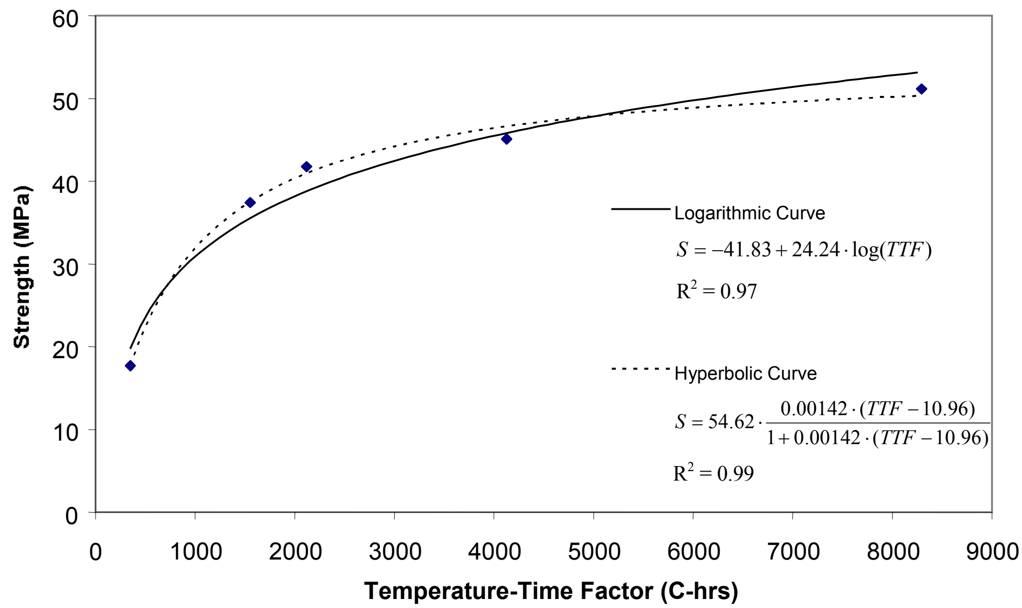


Figure 4.3: Correlation curves based on the temperature-time maturity index

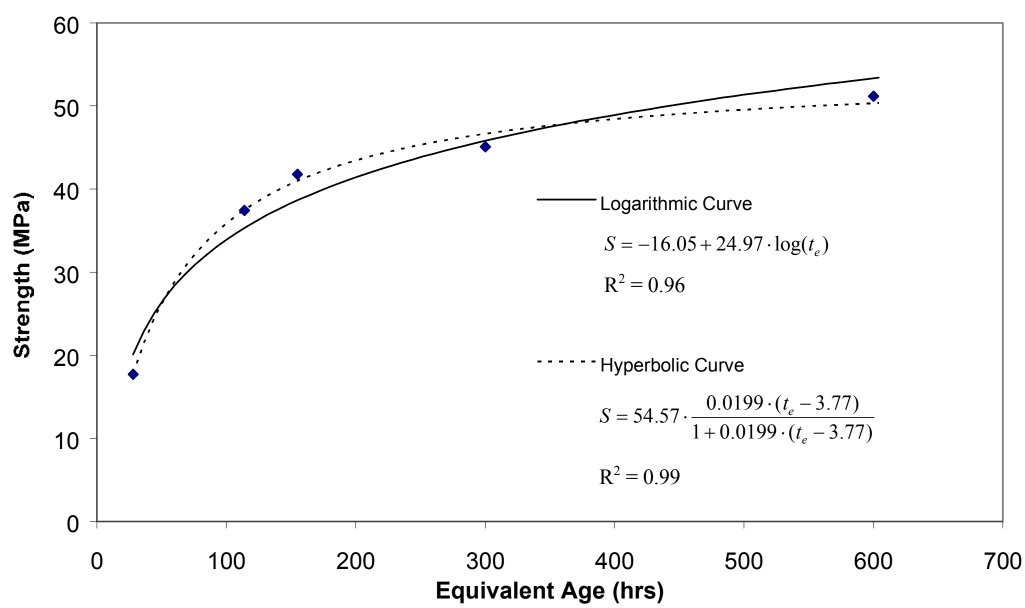


Figure 4.4: Correlation curves based on the equivalent age maturity index

4.3 DECK MATURITY

Table 4.4 shows the maturity and strength data from the verification cylinders. The data is plotted in Figure 4.5 and compared with the correlation curve. Based on batch slips and field tests, the mixtures that were sampled to create the two sets of cylinders were nominally the same; however, Figure 4.5 shows that the strength development of the verification cylinders was substantially less than that of the correlation cylinders.

The principles and application of the maturity method are well established: two batches of concrete based on the same mixture design and input materials will exhibit similar strength development when the strength is plotted against maturity. However, an observer during the deck placement saw the technician who was casting the verification cylinders temper the wheelbarrow of concrete with water while making the cylinders. It is believed that the additional water caused the discrepancy in the strength versus maturity results. Consequently, the data from the verification cylinders could not be used for a fair comparison between the maturity of the deck cylinders and the maturity of the calibration cylinders.

Table 4.4: Maturity and compressive strength data for the verification cylinders

Elapsed Time at Cylinder Break, hours	Maturity Index		Compressive Strength, MPa (psi)
	Temperature-Time Factor, °C-hours	Equivalent Age, hours	
46	405	32	18.4 (2670)
	328	28	18.6 (2690)
	Avg.=366	Avg.=30	Avg.=18.5 (2680)
77	838	63	23.5 (3410)
	702	54	24.1 (3490)
	Avg.=770	Avg.=58	Avg.=23.8 (3450)
165	2080	151	29.2 (4230)
	1780	132	27.7 (4020)
	Avg.=1930	Avg.=142	Avg.=28.4 (4120)
358	4720	340	36.0 (5220)
	4000	293	37.6 (5450)
	Avg.=4360	Avg.=316	Avg.=36.8 (5340)
674	8910	640	39.4 (5710)
	7520	548	39.8 (5770)
	Avg.=8210	Avg.=594	Avg.=39.6 (5740)

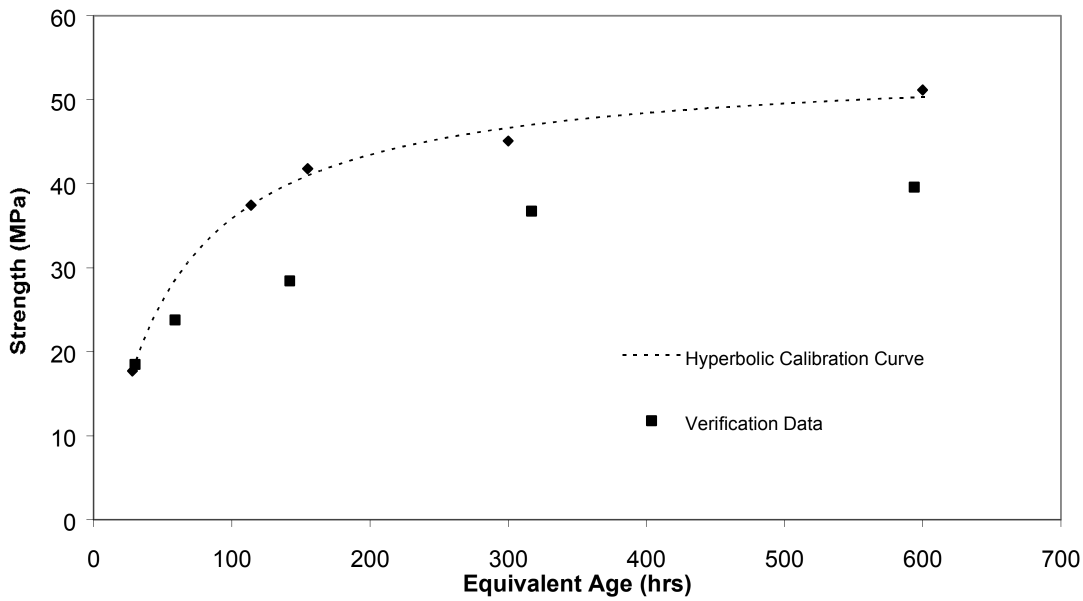


Figure 4.5: Comparison between the maturity correlation curve and the verification data

The strength development of the three monitored deck locations, as estimated by the maturity method, tracked closely during the test period as shown in Figure 4.6. Using this figure as an example for strength estimation, the deck strength reached 27.6 MPa (4000 psi) after 43 hours. If 27.6 MPa had been a target strength level to continue construction operations, the contractor would have had to guess at a schedule for cylinder breaks to document the strength based on conventional monitoring methods. Using the maturity method, the contractor would know to conduct the cylinder tests after 43 hours to verify the concrete strength.

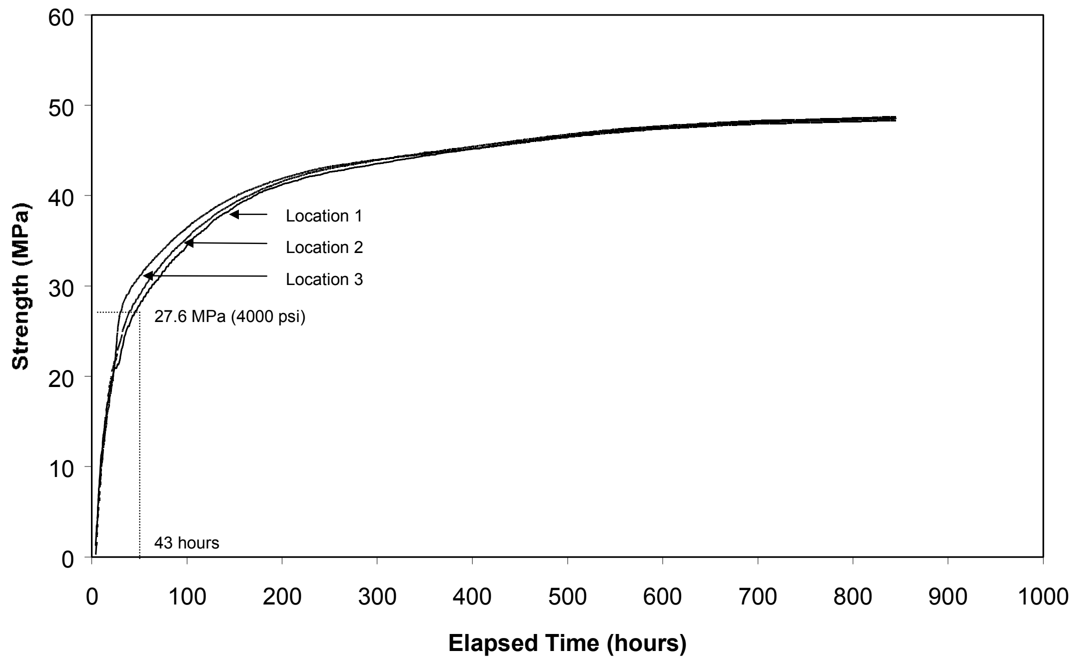


Figure 4.6: Estimation of strength development for each of the instrumented positions in the deck

Application of the temperature-time method consistently predicted lower strengths than the equivalent age method as shown in Figure 4.7. As discussed in Section 1.1, the equivalent age method accounts for temperature more accurately over a wider temperature range. During the monitoring period, the in-situ temperature of the deck dropped below 9°C, the datum temperature for the concrete mixture. The temperature-time method assumes that strength gain stops when the concrete temperature is less than the datum temperature.

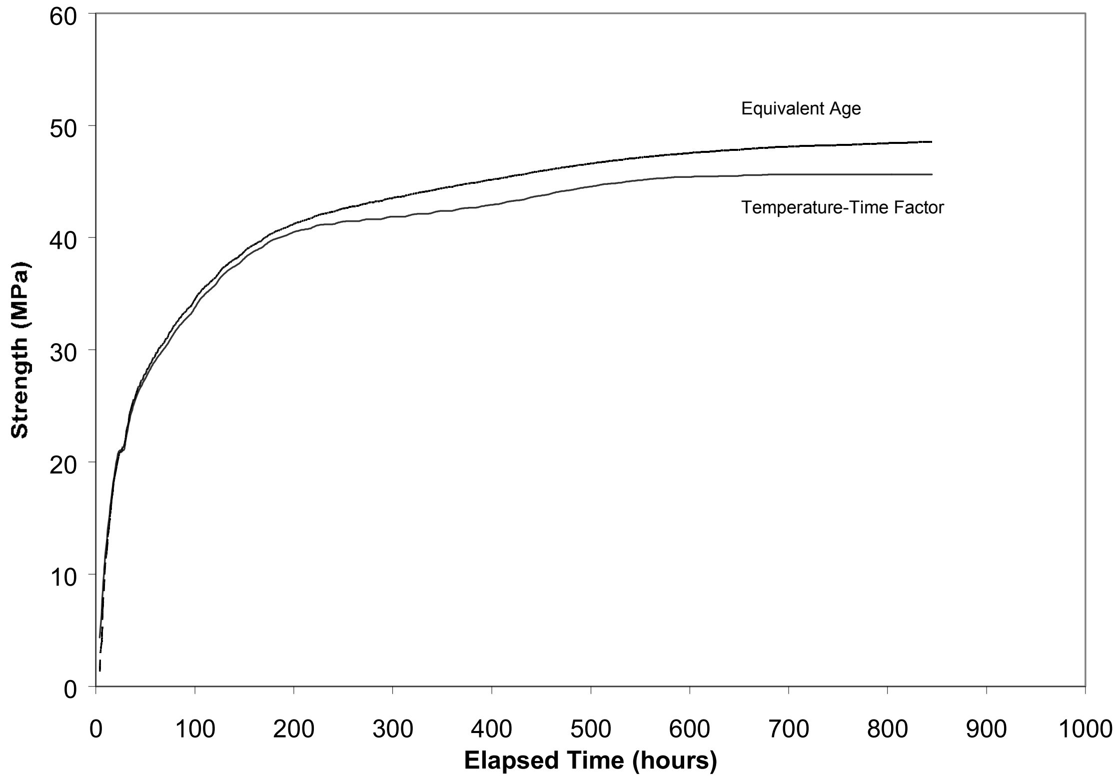


Figure 4.7: Comparison between the temperature-time and equivalent age methods applied to data from location #1

Comparisons between strength predictions made using the logarithmic and hyperbolic functions resulted in a difference within 2.5 MPa (362 psi). Figure 4.8 displays an example of such a comparison. Mathematically, as the maturity index increases with time, the strength prediction from the logarithmic function (Equation 1-4) has no upper bound. On the other hand, the hyperbolic function (Equation 1-5) asymptotically approaches an upper strength level, which is more indicative of actual concrete mixtures. Consequently, the hyperbolic equation is considered more robust than the logarithmic equation.

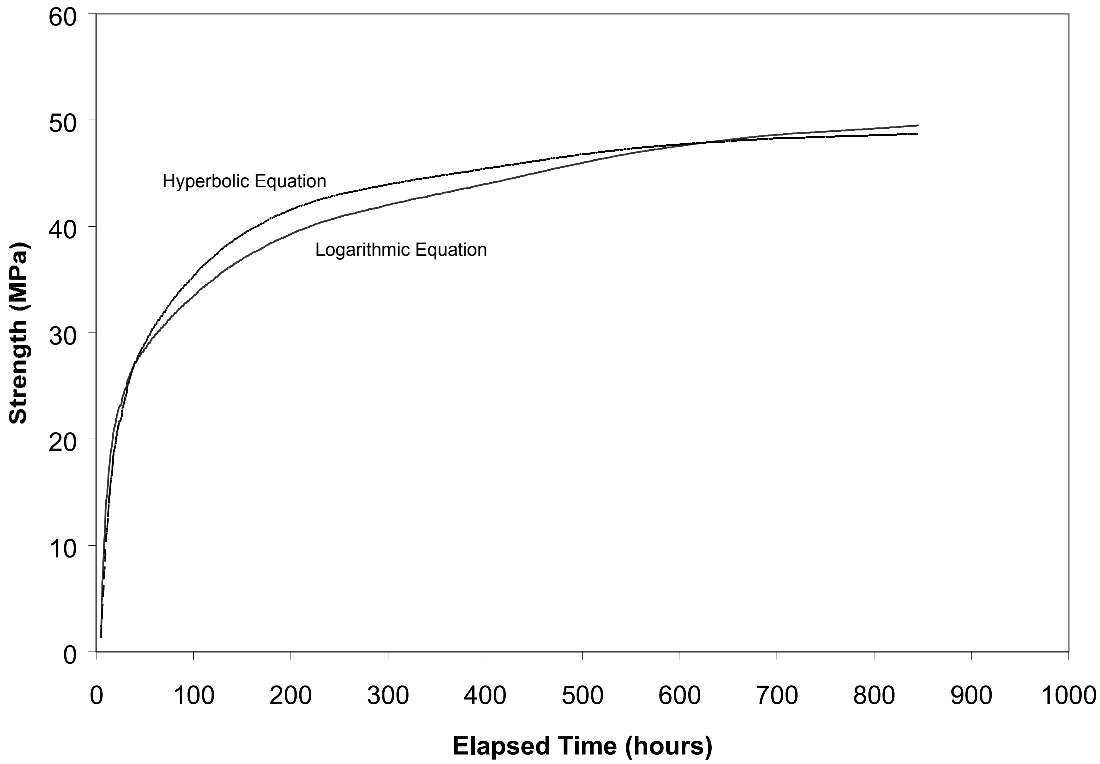


Figure 4.8: Comparison between the logarithmic and hyperbolic prediction functions based on equivalent age method shown in Figure 4.4 applied to data from location #2

4.4 MATURITY CHARACTERISTICS

As of 2000, thirteen states have instituted protocols for using the maturity method primarily to accelerate the opening of construction projects (*Tikalsky, et. al. 2001*). Though Oregon does not use the maturity method, the Federal Highway Administration conducted a demonstration project on the Alsea Bay Bridge project in 1991 (FHWA 1991). One of the conclusions from that project states, "…maturity could be used reliably to predict the compressive strength of concrete in the field." A draft test method for Oregon based on work by Tikalsky, et. al. (*2001*) and ideas from state protocols is included in Appendix D.

The maturity method provides a more realistic estimation of strength development than separately cast test specimens (cylinders or beams). Often, application of the maturity method allows subsequent construction activities to proceed earlier than if such decisions were based on the results of the separately cast test specimens. Consequently, project schedules can be accelerated resulting in cost-savings.

The correlation curve that is developed for a specific mixture and supplier is a “fingerprint” for that mixture; consequently, maturity is a powerful quality assurance tool. Monitored maturity behavior that deviates from the correlation curve indicates that the placed concrete is not the intended mixture, the characteristics of the components have changed, or the placed concrete was exposed to curing conditions outside acceptable limits.

A disadvantage of the maturity method is the effort needed to develop and maintain the correlation curves. Each mixture design from each concrete plant requires a separate correlation curve. However, for large projects, the curve can be developed at the outset and used for subsequent placements. A high level of quality control is required at the concrete plant in order to produce batches truly representative of the mixture design for the correlation curve and the construction project. Periodic verification of the correlation curve is required.

5.0 SUMMARY

The maturity method investigation showed the following:

- The study points out the need for strict control of the maturity method procedure including, determining the maturity constants, generating and verifying the correlation curve, and acquiring the in situ temperature data.
- The method may be useful on large projects where the time and expense of conducting the calibration and verification is justified. The method may also be useful on small projects in which the correlation curve for the concrete mixture already exists.
- Without the verification results from this study, Oregon will need to rely on the experience of other states and the ASTM specifications to incorporate the maturity method into its construction specifications.
- The equivalent age method in conjunction with a hyperbolic prediction equation should produce the most accurate strength estimates

6.0 REFERENCES

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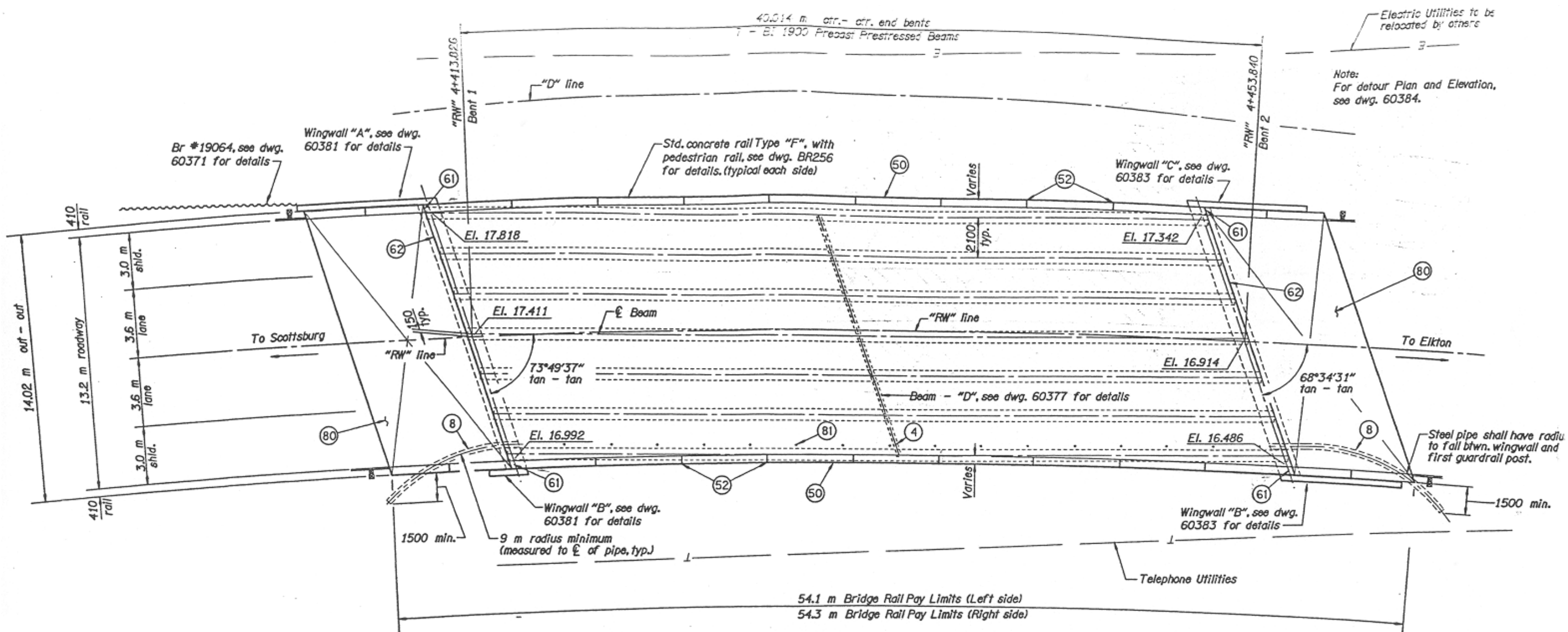
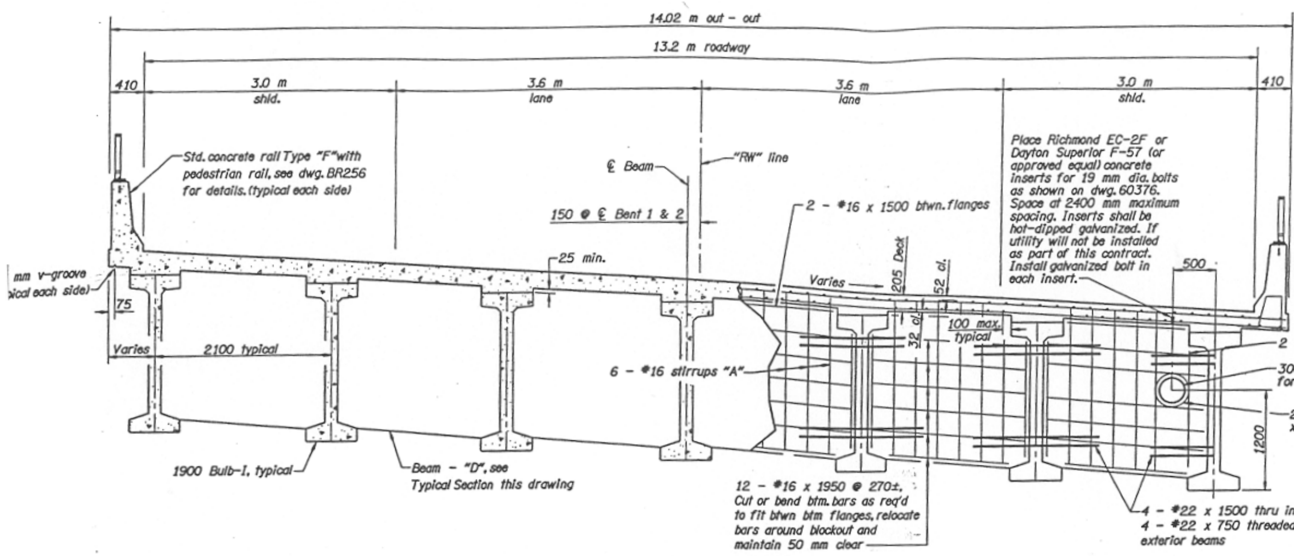
APPENDICES

APPENDIX A

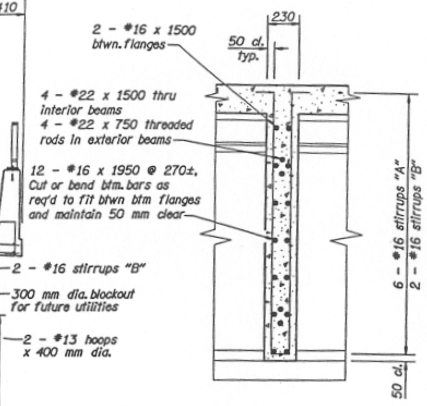
WELLS CREEK BRIDGE DECK PLAN



DECK PLAN
Scale 1:100



TYPICAL DECK SECTION
Scale 1:25



TYPICAL SECTION
BEAM - "D"
Scale 1:25

DECK REINFORCEMENT NOTES:

Longitudinal

Top #13 @ 200 (epoxy coated)

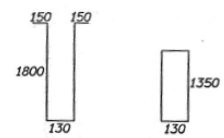
Bottom #13 @ 190

Transverse

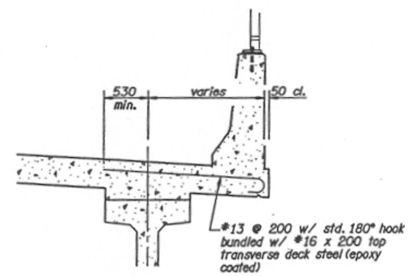
Top & Bottom #16 @ 200 (epoxy coat top)

See Overhang Details, this drawing.

Stagger top & bottom bars as much as practical to facilitate placement of concrete.



STIRRUP "A" STIRRUP "B"



OVERHANG DETAIL
Scale 1:15

APPENDIX B

CONCRETE MIXTURE DESIGN

Project: Wells Creek

Contractor: Carter & Co   Contract No. C12640

Concrete Mix Design No. SCM-30U DECK   Strength 30Mpa @28 days

Design Slump 100mm   W/C Ratio 0.37   Unit Wt./Density 2312 Kg/m3

CONTENTS	Sieve Size	S.P.G.	SSD WTS.	VOLUME	AGGR. %
Cement: Ashgrove		3.150	372	0.118	
Fly Ash ISG		2.250			
Silica fume Masterbuilders		2.200			
Coarse Aggregate					
Source	Sieve Size				
Wahl's Pit	3/4-#4	2.606			
Elliot Bar	"	2.685			
Umpqua	"	2.660	1051	0.395	57.8
Umpqua	1/2"-#4	2.640			
Elliot Bar	3/8"-#4	2.670			
Fine Aggregate					
Source	Sieve Size				
Wahl's Pit	#4-0	2.583			
Elliot Bar	"	2.566			
Umpqua	"	2.606	753	0.289	42.2
Water City of Coos Bay		1.000	136	0.136	
Air 6.2 %				0.062	
TOTALS			2312	1.000	

Admixtures: Type	Brand	Dosage
glennium 3000	Masterbuilders	520ml/100kg
mbae90	"	var.
polyheed 997	"	260ml/100kg
NC-534	"	var.
Delvo	"	var.

APPENDIX C

BATCHER SLIP AND FIELD TEST DATA FOR THE ABUTMENTS AND DECK

Date:
9/4/02
Abutment

Coarse Aggregate (kg)	Moisture (%)	Batch Ticket Fine Aggregate (kg)	Moisture (%)	Cement (kg)	Water (L)	MBAE-90 (mL)	Pollyheed (mL)	Glenium (mL)	Batch Size (m3)	Field Tests Ambient Temp (°C)	Concrete Temp (°C)	Slump (mm)	Air (%)	Density (kg/m3)	Cement Content (kg/m3)	W/C Ratio
8190	1.6	5922	2.5	2850	666	355	7334	14787	7.65	19	22	115	6	2319	374	0.34
8190	1.6	5922	2.5	2855	727	355	7334	14787	7.65							
8190	1.6	5922	2.5	2850	666	355	7334	14787	7.65							
8190	1.6	5922	2.5	2850	666	355	7364	14787	7.65							
8190	1.6	5940	2.5	2860	651	355	7364	14787	7.65							
8190	1.6	5868	2.5	2855	636	355	7364	14787	7.65							
3312	1.6	2412	2.5	1160	273	118	2987	6033	3.10							
2898	1.6	2088	2.5	1005	235	118	2602	5264	2.70							

Date:
10/1/02
Deck

Coarse Aggregate (kg)	Moisture (%)	Batch Ticket Fine Aggregate (kg)	Moisture (%)	Cement (kg)	Water (L)	MBAE-90 (mL)	Pollyheed (mL)	Glenium (mL)	Batch Size (m3)	Field Tests Ambient Temp (°C)	Concrete Temp (°C)	Slump (mm)	Air (%)	Density (kg/m3)	Cement Content (kg/m3)	W/C Ratio
8136	0.9	5886	2.1	2845	784	355	7393	14728	7.65	17	21	125	6	2305	371	0.35
8136	0.9	5886	2.1	2845	784	384	7393	14787	7.65							
8136	0.9	5886	2.1	2850	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2850	784	355	7364	14787	7.65							
8136	0.9	5886	2.1	2845	784	355	7393	14787	7.65	18	21	110	5.5	2314	372	0.35
8136	0.9	5886	2.1	2845	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2850	784	355	7393	14846	7.65							
8136	0.9	5886	2.1	2855	784	355	7393	14757	7.65	18	21	150	5.7	2311	373	0.35
8136	0.9	5904	2.1	2850	784	355	7393	14728	7.65							

8136	0.9	5886	2.1	2855	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2855	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2840	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2845	784	355	7393	14787	7.65							
8136	0.9	5886	2.1	2855	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2845	784	355	7393	14787	7.65	19	21	125	6.1	2307	372	0.35
8136	0.9	5886	2.1	2845	784	355	7393	14787	7.65							
8118	0.9	5886	2.1	2860	784	355	7364	14787	7.65							
8136	0.9	5886	2.1	2845	784	355	7393	14787	7.65							
8136	0.9	5886	2.1	2850	784	355	7364	14787	7.65							
8136	0.9	5886	2.1	2845	784	355	7364	14787	7.65	19	21	100	5.8	2315	373	0.35
8136	0.9	5886	2.1	2845	784	355	7393	14787	7.65							
8136	0.9	5886	2.1	2855	784	355	7393	14787	7.65							
8136	0.9	5886	2.1	2855	780	355	7393	14787	7.65							
8136	0.9	5886	2.1	2850	784	355	7364	14787	7.65							
8136	0.9	5886	2.1	2855	784	355	7364	14787	7.65							
8118	0.9	5904	2.1	2845	784	355	7393	14787	7.65							
1584	0.9	1152	2.1	555	148	59	1449	2957	1.5							

APPENDIX D

DRAFT ODOT TEST METHOD

Draft ODOT Test Method

Adapted from "Using Concrete Maturity Meter for QA/QC" (*Tikalsky, et. al. 2001*)

Method of Test for
ESTIMATION OF CONCRETE STRENGTH BY THE MATURITY METHOD

SCOPE

This method describes a procedure to estimate in real-time the in-situ strength of portland cement concrete. The method is acceptable for determining when strength-based actions can be performed and for quality assurance. It does not replace the need for testing cylinders at 28 days to measure compressive strength for acceptance.

BACKGROUND

The maturity method is based on the temperature history of hydrating concrete. Conducting the maturity method consists of three steps:

1. Develop strength-maturity relationship
2. Estimate the strength of in-place concrete
3. Verify strength-maturity relationship

A separate strength-maturity relationship must be developed for each mixture design from each supplier. Furthermore, a new strength-maturity relationship must be created if the source of the constituents changes.

The limitations of the maturity method are the following:

1. Can not account for errors in batching. Results are invalid if the field-placed concrete does not have the same constituents and proportions as the concrete used to create the strength-maturity relationship.
2. Can not account for poor placement or curing.
3. Differences in early-age temperature histories will alter the strength-maturity relationship.
4. Only valid if the concrete continuously hydrates during the time of testing.
5. Does not measure the strength of concrete but predicts it based on several assumptions. Results should be treated as such. The Engineer may choose to specify other forms of testing to verify the results from the maturity method.

For this test method, the maturity will be calculated using the Arrhenius relationship for equivalent age:

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

where:

t_e = equivalent age at a specified temperature T_s, in days or hours,
Q = activation energy divided by the gas constant, in K,
T_a = average temperature of concrete during time interval Δt, in K,
T_s = specified temperature, in K, and
Δt = time interval, in days or hours.

APPARATUS

Commercial, battery-powered maturity meters that meet ASTM C 1074 specifications and are capable of computing Arrhenius equivalent age with variable activation energy values are acceptable. An example of an acceptable meter is the Humboldt 4101 4-channel maturity meter. The meter uses type-T thermocouple wire. An acceptable gauge of wire is 24.

A computer program for determining the best-fit, logarithmic curve is required. If the temperature of concrete hydration is outside the range of 0^{o}C to 45^{o}C, or if the apparent activation energy constant is determined without completing final set tests (as specified in ASTM C 1074), a computer program with capabilities for determining a best-fit, hyperbolic curve is required. The program must be capable of generating an equation and the corresponding regression coefficient.

APPARATUS PREPARATION

Inspect, calibrate, and prepare the equipment as follows:

- Meters are to be inspected prior to each use to ensure sufficient battery power is available to complete testing.

- Meters are to be inspected prior to each use to ensure that proper activation energy values indicative of the tested concrete are inputted.

- Meters shall be inspected every six months at minimum to ensure that temperatures being outputted are correct. This can be done by inserting the sensors into a water bath of known temperature. If deviations greater than 1^{o}C are noticed, the device should be re-calibrated according to the manufacturer.

- Meters should be protected from moisture, extreme heat, extreme cold, and theft when left in the field during testing. Each meter should be maintained in a manner consistent with manufacturer's specifications.

- If a maturity meter that employs the use of thermocouples is used, then the wire tips at the temperature-sensing end of each thermocouple must be soldered or spot welded together.

CORRELATION CURVES

Correlation curves are made for each mixture that will be used in the field. Acceptable tolerances between the calibration mixture and field mixture are 5 percent for all constituents except air-entraining admixtures. Air-entraining admixtures are to be proportioned so that both the calibration and field-delivered concrete have the same design air content. The procedures for determining curves are as follows:

Determine the activation energy, Q, according to ASTM C1074 for the equivalent age equation. The specified temperature, T_s, in the equation is 293.15 K.

Prepare at least 17 cylindrical concrete specimens (152 mm x 304 mm) from a batch of concrete that is approximately 3.5m^3 (4.6 yd^3) in size or larger according to the procedures outlined in ASTM C 192. Record mixture proportions and constituents, slump, air content, initial temperature, and mixture proportions. Embed temperature sensors into the center of two of the cylindrical specimens. Immediately connect the temperature sensors to the maturity meter and begin data acquisition. Include a sensor to record the ambient temperature that the specimens are exposed to during the test. Data collection must continue uninterrupted for the duration of the test.

Moist-cure the specimens in a condition that will allow the concrete to experience approximately the same temperatures as the field-placed concrete. Cure the specimens in this manner for 8 to 12 hours. After this time, the specimens should be moist-cured according to ASTM C511. Demold the cylinders after 24 hours and return them to the prescribed conditions.

Perform compression tests at the ages of 1, 3, 7, 14, and 28 days according to ASTM C 39 procedures. In the event that strength estimation will be required for extended periods, complete testing to encompass the range of maturity values expected. At each age, test two specimens and record the individual and average compressive strengths. If the range of the test results is greater than 10 percent of the average, test a third cylinder and average the strengths from all three specimens. If any specimen is obviously defective, discard it. The cylinders with temperature sensors may be tested for the final two tests if required.

At the time of each test, record the two equivalent age values and the average value.

Use the curve-fitting computer program to plot the average strengths as a function of the average equivalent age values and draw the best-fit curve based on one of the following relationships:

Hyperbolic equation:

$$S = \frac{S_u \cdot K \cdot (t_e - t_{eo})}{1 + K(t_e - t_{eo})}$$

where:

S = average cylinder compressive strength
S_u = limiting strength of the concrete
t_e = equivalent age
t_{eo} = equivalent age when strength development begins
K = rate constant

The computer program will calculate S_u, t_{eo}, and K.

Logarithmic equation:

$$S = A + B \cdot \log(t_e)$$

where A and B are constants calculated by the computer program.

If the in-situ hydration temperature of the concrete structure is anticipated to hydrate outside the range 0 to 45 ^oC (30 to 110 ^oF), then the hyperbolic strength-maturity relationship should be used. If the in-situ hydration temperature of the concrete structure is anticipated to hydrate within the range 0 to 45 ^oC (30 – 110 ^oF), then either the logarithmic or the hyperbolic strength-maturity relationship can be used. Record the equation and R^2 value for the curve. For an R^2 value of 0.95 or greater, the strength-maturity curve and corresponding equation are considered valid. For an R^2 value less than 0.95, the Engineer should determine the reason for the large variation. No points should be disregarded without a statistically valid reason (i.e. faulty specimen). If removing outliers cannot be statistically justified, the entire strength-maturity relationship must be redone.

IN-PLACE CONCRETE STRENGTH ESTIMATION

In the days prior to concrete placement, instrument the structure with temperature sensors compatible with the maturity meter(s). The sensor wires should be attached to reinforcing bars with ties and led out either through or underneath formwork. The wires should be networked through the structure using the reinforcing bars. In instances when the wires are not tight against the reinforcement, sufficient slack should be left so that the weight of concrete will not tear the wire. The exposed end of the sensors should not touch the reinforcement. Label both ends of each sensor to avoid uncertainty in wire placement. It is advantageous to provide duplicate sensors in critical locations. More thermocouples than available maturity channels should be placed in the structure so that if any sensors are destroyed during placement, the other leads can be used. The ends of the wires that are placed into the maturity meters should be protected from any adverse weather conditions. In the event that the element is not reinforced, thermocouples can be either connected to a steel bar placed into the sub-base, attached to formwork, or inserted directly into a fresh concrete surface.

The thermocouples should be placed in the locations where strength estimation is required and/or in the positions that are anticipated to hydrate under the lowest temperatures or are placed last. In general, sensors for the latter purposes should be placed 50 - 100 mm (2 – 4 in) from the surface of the structure and in the portion that will be cast last. The Engineer should be consulted for placement. Record the three-dimensional location of each sensor and reference the location to the sensor label.

When the concrete arrives at the construction site, the batcher slip should be obtained and checked by the inspector. If the concrete is not of the same composition as the correlation mixture, then maturity cannot be used to estimate strength. The inspector may opt to go to the ready-mix plant and specify the constituents and proportions directly.

If possible, connect the sensors to the meters prior to concrete placement. Otherwise, connect the sensors to the meters as soon after placement as possible. One sensor should be located near the structure so that ambient conditions can be monitored. As soon as possible after all of the sensors connected to an individual meter are covered with concrete, activate the maturity meter. As concrete is placed, some of the sensors may break. If this occurs, replace the lead of the broken channels with the extra ones wired into the structure. Under no circumstances should wires be removed or switched for a specific sensor after ½ hour past the time that the concrete was placed around that sensor. Maturity must be monitored in a continuous manner from time of placement. Do not disconnect the sensors or turn off the meters until the target maturity values are reached. The maturity value corresponding to the desired strength as provided by the calibration equation should be recorded and made available to QC/QA personnel.

When a channel displays the target maturity index, it is predicted that the concrete at that location has achieved the corresponding target strength. Data acquisition may be terminated once the desired strength has been estimated for all applicable channels. The wires may be cut flush with the surface.

RELATIONSHIP VERIFICATION

Verify strength-maturity relationships at a frequency specified for the pertinent work.

During the field concrete placement, prepare five 152 x 304 mm (6 x 12 in) cylindrical concrete specimens according to the procedures outlined in ASTM C31. At the discretion of the Engineer, more cylinders may be specified.

Embed temperature sensors into the center of two of the cylindrical specimens. Connect the temperature sensors to the maturity meters and begin data acquisition. Moist-cure the cylinders on site in a manner that will yield approximately the same early-age temperatures prevalent in the concrete structure. In most cases, this will entail capping the cylinders, covering with wet burlap, and then placing them near to the structure. In cases where the in-situ structure is insulated, appropriate procedures shall be applied to the cylinders. At an age of 24 +/- 6 hours, transport the cylinders to the laboratory, demold them, and cure them according to ASTM C511 procedures.

At an age or ages specified by the Engineer, test two of the cylinders in compression according to ASTM C39, and record the strength and maturity at the time of testing. If the range of strength results is greater than 10 percent of the average, test a third cylinder and average the strengths from all three specimens. If any specimen is obviously defective, it shall be discarded.

Use the average maturity value determined through verification to estimate strength based on the correlation curve. If the verification strength is within +/- 5 percent of the predicted strength, then the relationship is verified. If the verification strength is more than +/- 10 percent of the predicted strength, then the correlation curve is no longer valid and must be regenerated. If 2 out of 3 consecutive verification tests are between 5 and 10 percent above or below the predicted strength, then the correlation curve is no longer valid and must be regenerated.