

Estimation of In-situ Concrete Flexural Strength using Maturity

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Abstract

Concrete maturity is being recognized as a viable test method to measure in-situ strengths of early age concrete and to assist agencies in making informed decisions on construction schedules. This increased interest is partly due to improved data collection technology in recent years coupled with a better understanding of the effects of construction and curing temperature on early age and long term performance of rigid pavements. The “maturity index”, which is correlated to strength gain in a concrete mixture, is determined from the time-temperature history of the mixture.

This paper presents a study conducted by Caltrans to evaluate the accuracy of this technology in predicting both flexural and compressive strength. The study involved a comprehensive laboratory study using two mix designs cured under four different temperature regimes. The test results indicate that calibration regression equations developed from samples cured in standard room temperature conditions are sufficient to predict concrete strengths associated with both cooler ($\sim 10^{\circ}\text{C}$) and warmer ($\sim 37^{\circ}\text{C}$) curing temperatures with reasonable accuracy. Further, actual field-measured maturity from a recent paving project, using the same mix design as the present study, yielded similarly accurate in-situ concrete strength predictions. The importance of proper curing for accurate strength predictions is demonstrated in the project.

Introduction

In-situ strength estimation using maturity has received widespread attention in recent years as an effective and efficient nondestructive test (NDT) method for quality control and assurance of concrete structures. It has gained preference over traditional strength tests because of the fact that standard beam and cylinder specimens cast during construction are in volumes and curing conditions that are vastly different from the in-situ mass concrete. Strength estimates using traditional test methods, therefore, do not necessarily represent the strength of the in-situ

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structure (ACPA, 2002, Carino, et al., 2001, Rao et al., 2004, Newbolds, et al., 2001, The Transtec Group, 2003). Additionally, in pavements, maturity provides the ability to monitor strength gain in real time to better define appropriate points in times for formwork removal, joint sawing, and opening the roadway to traffic. It is also being viewed as a good tool to adjust the mix design to meet concrete strength requirements in real time as well as to optimize construction schedules.

The American Society for Testing and Materials (ASTM) has standardized the maturity test procedure in ASTM Standard C1074-98 (ASTM 1998). For pavement-specific maturity testing, the American Concrete Pavement Association (ACPA) has developed a guideline, commonly referred to as IS257P (ACPA, 2002). Studies (Hall, 1996, Ansari et al., 1998, Whiting, et al., 1993, Price et al., 1996) have also evaluated the potential to use maturity in early high strength concretes or in projects requiring fast-track construction. Overall, a better understanding of the effects of construction temperature and curing conditions on early age and long-term performance have stimulated more interest in this technology (The Transtec Group, 2003, Yuan et al., 2004). Some researchers (Yuan et al., 2004, Okamoto et al., 1994) have recommended the use of maturity methods to complement other NDT evaluations to estimate in-situ strength properties. Recent surveys (Tikalasky, 2001) have shown that maturity testing is under various different stages of research, and implementation in various State agencies (e.g. TX, IA, PA, IN, TN, CA, etc). Although the concept is familiar to some, lack of prior experience, lack of consensus among all parties involved, and inadequate technology transfer have hindered its widespread use.

Rigid pavement design procedures and current acceptance criteria are based on flexural strengths determined from ASTM C78 or an equivalent test method. However, a majority of studies have focused on predicting the compressive strength of concrete mixtures for structural applications. Moreover, the ASTM C1074 standard, for valid reasons, does not include a precision and bias statement for practitioners to compare against variability in strengths determined from ASTM C78. The effect of mix design parameters, (e.g. cement type, cement content, admixtures, or flyash), and curing conditions on maturity testing is not well understood by end users and, therefore, its widespread use in fast track or conventional construction has been limited to-date. This paper describes a study undertaken by the California Department of Transportation's (Caltrans') Office of Rigid Pavement and Structural Concrete at Translab in Sacramento, California to address the aforementioned issues that arise in technology implementation.

Research Significance

The main objective of this project was to evaluate this test method for use in paving projects that require early opening to traffic. This involved conducting a laboratory study for concrete maturity testing and included portland cement concrete (PCC) mixtures blended with flyash in dosages typically used in California. The main goals were:

- To prove that maturity of concrete can be correlated to flexural strength and that it can be used to predict flexural strength of the mixture.

- To verify that maturity is correlated to compressive strength, for the same mix and at the same curing times. This verification allows a comparison of the strength-maturity models for compressive and flexural strength predictions.
- Evaluate the effect of mix design and curing parameters – flyash content and curing temperature in particular – on maturity measurements.
- Evaluate and compare the performance of the two available methods of calculating maturity (the *Nurse-Saul* vs. the *Arrhenius* function) using an identical set of mixtures and curing conditions.

Concrete Maturity

Concrete maturity is a means to indirectly estimate the strength of a hydrating mixture based on its time-temperature history. This technology has been studied and improved upon over the past five decades. The concept of using the hydration temperature history to predict concrete strength gain was introduced as early as the 1940s by researchers (*Nurse, 1949, Saul, 1951*) working in the area of steam curing processes for fresh concrete. In the 1970s an investigation into serious construction-related accidents in Virginia and West Virginia revealed that insufficient strength gain in concrete as a result of lower curing temperatures was the cause of failures. These investigations, carried out by NIST (then NBS), emphasized the effect of temperature conditions in concrete strength gain and the need for in-situ strength determination (*Carino, et al., 2001*), eventually leading to the development of the ASTM standard procedure for maturity testing, ASTM C1074 (*ASTM 1998*).

The exothermic reaction in the cement hydration process results in the generation of heat concurrently with strength gain. The ability to correlate strength gain or degree of early hydration to the amount of heat generated forms the basis for concrete maturity, as illustrated in Figure 1. The heat generated is estimated from the thermal history monitored for the mixture, which is the temperature data collected as a function of time. Concrete maturity is an index that characterizes the strength gained by a concrete mixture as a function of the combined effects of age and heat released during the hydration process. As such, it is merely an indirect measurement of concrete strength.

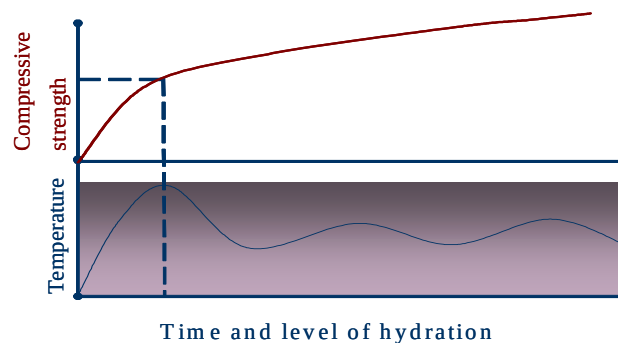


Figure 1 Maturity concept

The current ASTM procedure provides two functions to calculate

maturity—the *Nurse-Saul* function and the *Arrhenius* function. The *Nurse-Saul* function calculates the maturity index known as the temperature-time factor (TTF) expressed in degC-hour. The TTF factor is the area under the time-temperature curve for the mixture as illustrated in figure 2.

The *Nurse-Saul* function is expressed as:

$$M = \sum_0^t (T - T_o) \cdot \Delta t \quad \text{Equation 1}$$

where: M is the TTF maturity index, T is the measured temperature, T_o is the datum temperature, and Δt is the time interval between successive temperature measurements. The datum temperature is essentially the temperature above which the hydrating concrete mixture is considered to accumulate strength. The most commonly recommended datum temperatures are -10°C (14°F) and 0°C (32°F).

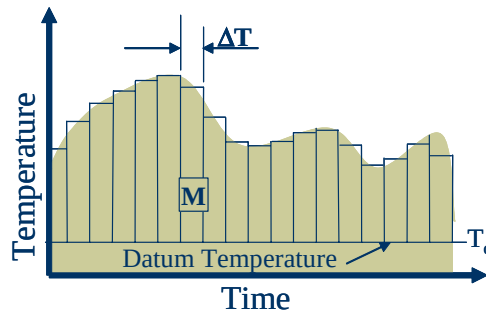


Figure 2 Time-temperature factor calculation

The *Arrhenius* equation calculates the maturity index known as the *Equivalent Age Factor (EAF)* expressed in hours. For a mix undergoing curing at any given temperature, the *EAF* is indicative of the equivalent age of the same mixture cured at a standard reference temperature. The *Arrhenius* equation is expressed as:

$$M = \sum_0^t e^{\frac{-E}{R} \left[\frac{1}{T} - \frac{1}{T_r} \right]} * \Delta T \quad \text{Equation 2}$$

where: M is the *EAF* maturity index, E is the activation energy indicative of the energy required to initiate the hydration reaction process, R is the universal gas constant, T is the average absolute temperature of concrete in time Δt , and T_r is the absolute reference temperature.

Predicting In-situ Strength Using Maturity: Concrete strength prediction involves a lab and a field test procedure. First, the lab procedure involves establishing the mix-specific strength-maturity relationship by correlating strength values at specified ages to the corresponding maturity values. For the strength-maturity relationship, the most commonly used equations is a logarithmic best-fit curve of the form:

$$\text{Strength} = A * \log (\text{maturity}) + B \quad \text{Equation 3}$$

where: *A* and *B* are the regression constants based on the laboratory test data.

The field procedure involves measuring maturity of in-situ concrete to estimate strength based on the lab-developed strength-maturity relationship. Note that the mix design used for the lab procedure has to be identical to that used for construction. Studies (*The Transtec Group, 2003, Tikalasky, et al., 2001, Nomadics, 2003*) have also adopted other maturity function and/or forms of equation for the strength-maturity relationship and reported good predictions of strength in the field. The same procedure can be followed for both compressive and flexural strength estimations.

Test Plan

The test plan was designed for this study to verify that concrete maturity can predict both flexural and compressive strength. Therefore both flexural and compressive strength tests were included in the plan's experimental design. Different curing temperatures and mix designs were included so that the ability of PCC maturity values to recognize and distinguish differences in strengths and rates of strength gain could be evaluated and quantified.

Curing temperatures of 38°C, 23°C, 10°C, along with "ambient" conditions in the month of October in Sacramento, CA, with flyash contents of 15% and 25%, were all considered. Also included in the test plan were maturity calculations using both the *Nurse-Saul* and *Arrhenius* functions for an evaluation of the effectiveness of each analysis method. The plan resulted in a total of 8 different combinations of flyash content and curing temperatures, as seen in table 1.

The samples were initially cured with wet burlap in their respective environments over the first 24 hours, after which they were stripped from the moulds and moist cured until the time of testing. Note that the above test matrix enabled a comparison of maturity predictions for mixes with varying:

- curing temperature (mix 1A vs. 1B vs. 1C vs. 1D, and 2A vs. 2B vs. 2C vs. 2D).
- flyash content (mix 1A vs. 2A, 1B vs. 2B, 1C vs. 2C, and 1D vs. 2D).

Strength Tests and Test Specimens: Compressive and flexural strength tests were performed at 3, 7, 14, and 28 days for all mixes. These test ages include the time range during which the concrete undergoes early-age strength gain, which is very important in defining the shape or slope of the strength gain curve. It also allows for strength evaluation at 28 days, which forms the basis for comparison with the design flexural strength of the concrete mixture. The normally recommended strength parameter is the average compressive strength computed from three trials of compressive strength test specimens (15 x 30 mm or 6 x 12 inch cylinders). Since the variability in flexural strength testing is generally higher, it was recommended that the average flexural strength from four beam tests (15 x 15 x 50 mm or 6 x 6 x 20 inch beams) be used as a representative flexural strength value. The use of four beam specimens in lieu of three also assists in defining the precision associated with

the proposed test method.

Table 1. Mix Design Parameters

Mix ID		Curing condition*	Test ages**
Mix 1: 15% Flyash	Mix 1A	@ 38 ^o C – Immersed in water	3, 7, 14, 28 days
	Mix 1B	@ 23 ^o C - Immersed in water	
	Mix 1C	@ 10 ^o C - Immersed in water	
	Mix 1D	Ambient Conditions	
Mix 2: 25% Flyash	Mix 2A	@ 38 ^o C - Immersed in water	
	Mix 2B	@ 23 ^o C - Immersed in water	
	Mix 2C	@ 10 ^o C - Immersed in water	
	Mix 2D	Ambient Conditions	

* Note that the limewater bath in the 38^oC curing temperature regime was occasionally maintained at a slightly lower temperature, on average around 37^oC. Note as well that the 23^oC curing temperature was closer to 24^oC, on average.

** Note that Mix 2 was tested at 8 days instead of at 7 days and Mix 1 was tested at 29 days instead of at 28 days, in order to accommodate the non-availability of the test apparatus during the testing phase of the project. However, the associated maturity values at the actual time of these tests were used in the data analysis.

The experimental plan covered several batches of concrete mixing. One beam and one cylinder specimen out of those cast were used to install maturity loggers from each batch, which resulted in a total of four beam specimens and four cylinder specimens for each combination of flyash content and curing temperature. Temperature measurements were made in the specimens with maturity loggers every 15 minutes from the time of casting to testing.

Data Analysis

Strength Data: Compressive and flexural strength tests were performed at 3, 7, 14, and 28 days using three and four repetitions for each age of testing. The average strength at each age was subsequently used for the data analysis. The averages computed were all within 10% of the strength of any individual specimen, for each sample. Note that mix 2 was tested at 8 days instead of at 7 days, and mix 1 was tested at 29 days instead of at 28 days to accommodate the non-availability of the test apparatus during the testing phase. However, the associated maturity values at the time of strength tests were used in the data analyses. The average flexural and compressive strengths for mix 1 are summarized in table 2, while those for mix 2 are summarized in table 3.

Table 2. Measured Strengths for Mix 1 with 15% Flyash

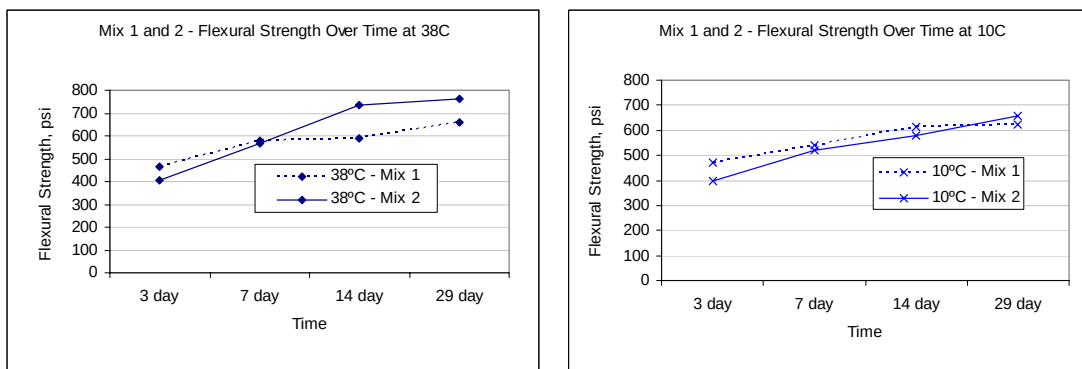
Curing temperature	Flexural Strength, psi				Compressive Strength, psi			
	3 day	7 day	14 day	29 Day	3 day	7 day	14 day	29 day
38 ⁰ C - Mix 1	467	577	587	660	3,500	4,209	4,564	5,277
23 ⁰ C - Mix 1	520	583	603	687	3,401	4,075	4,538	5,008
Ambient - Mix 1	295	450	500	460	3,234	4,027	4,015	4,892
10 ⁰ C - Mix 1	470	540	613	623	2,928	3,847	4,883	4,509

Table 3. Measured Strengths for Mix 2 with 25% Flyash

Curing temperature	Flexural Strength, psi				Compressive Strength, psi			
	3 day	7 day	14 day	29 day	3 day	7 day	14 day	29 day
38 ⁰ C - Mix 2	403	567	733	760	3,051	3,693	5,291	5,056
23 ⁰ C - Mix 2	487	567	623	703	3,258	4,296	4,670	5,540
Ambient - Mix 2	433	527	477	627	2,014	3,631	3,758	4,976
10 ⁰ C - Mix 2	397	520	580	657	2,566	4,154	4,706	5,511

The data in tables 2 and 3 were first examined for outliers. Trends in strength gain over time were observed for all samples. The data were further analyzed to compare the specific strength gain curves over time for mixes 1 and 2 at the various curing temperature regimes. Strength data that appeared to be erroneous or spurious were first identified and eliminated from the analysis. For instance, if the strength data indicated a drop in strength as time progressed, it was evident that the strength gain data was inaccurate. In addition, strength values at 3 days for both mixes 1 and 2 cured at 38⁰C nominal were below the respective strength values for samples cured at 23⁰C under normal laboratory conditions, contradicting expectations. Reasons for low strengths at the high temperature regime are hypothesized in the discussion. Such questionable values appear shaded in tables 2 and 3.

Mixes 1 and 2 had flyash contents of 15% and 25%, respectively, at approximately the same w/c ratios. Accordingly, a comparison of the strength values between these two mixes should indicate a higher rate of strength gain for mix 1 than mix 2 because of the lower flyash content in mix 1. However, the long-term strengths should be nearly the same, or possibly even higher for mix 2 because Class F flyash has very good long-term cementitious properties. For the most part, strength data verified this supposition, as shown in figure 3 for the flexural strength of mixes cured at 10⁰C and 38⁰C.



a) Mix cured at 38°C

b) Mix cured at 10°C

Figure 3. Flexural strength gain for Mixes 1 and 2 cured at 10°C and 38°C

Other Deviations: It was noted that the strength values were erratic in the case of samples cured in ambient conditions, as seen in tables 2 and 3. Questions were raised regarding the curing conditions of these samples, and the curing location on the loading dock at Translab was inspected. There were similar issues with the initial curing conditions of the samples cured at 38°C that were considered highly suspect in the subsequent data analyses. The nominal 38°C beam and cylinder specimens were wet cured under soaked burlap cloth soon after casting; however, the specimens were found to be in a very dry condition by the end of this 24-hour period, after which they were removed from the forms and soaked in limewater. Accordingly, in the analyses process the following assumptions were made:

- For specimens cured under so-called “ambient” conditions, the strength gain values were not indicative of the temperatures recorded from the devices in many instances. Normally “ambient” cured specimens should be stored in sand to retain the hydrating cement’s access to moisture. However, lack of proper curing conditions resulted in samples with strength patterns not representative of well-cured mixture.
- The specimens cured at the 38°C underwent poor curing during the initial 24-hour period and therefore were unrepresentative of the actual 3-day strength characteristics of the mix at that curing temperature. However, since the samples were immersed in water thereafter (@ approx. 36-38°C), the specimens were able to gain sufficient strength to follow typical strength-gain trends at later ages.

Maturity Data: Maturity indices were computed using the time-temperature history data for the 8 sample sets using both the *Nurse-Saul* and *Arrhenius* functions shown by equations 1 and 2 respectively. With the availability of temperature data every 15 minutes, the maturity accumulating in the hydrating mix was calculated at 15-minute intervals over the curing period.

In the preliminary analysis, strength vs. maturity relationships were developed for each of the 8 mixture samples (i.e. Mix 1A through 2D). It was noted that a distinct relationship existed for each curing condition ensued. Next, the data for all

curing conditions were combined for each mixture (data from samples 1A, 1B, 1C, and 1D for Mix 1, and samples 2A, 2B, 2C, and 2D for Mix 2). As a result, the relationships for the combined data had a reasonably good statistical basis to state that the strength-maturity values belonged to the same mix design, even when cured under different temperature regimes. However, it was noted that the quality of these relationships were dependent on the value of the datum temperature and activation energy selected for equations 1 and 2. The analyses performed are discussed in detail for each maturity function.

Nurse-Saul Method: Data analysis using the *Nurse-Saul* method initially focused on selecting the optimum datum temperature value. Datum temperatures values from +10 to -10°C were used in the analysis and it was observed that for the combined data better correlations were derived for datum temperature values on the lower side of 0 to -10°C as seen in Table 4.

Table 4. R-squared of the Strength-Maturity Relationships for Mix 1 and 2 Compressive and Flexural Strength for Varying Datum Temperature Values

Datum Temperature, deg C (deg F)	Flexural Strength		Compressive Strength	
	Mix 1 (15% flyash)	Mix 2 (25% flyash)	Mix 1 (15% flyash)	Mix 2 (25% flyash)
-10°C (14°F)	63.3	89.5	95.3	77.0
-7.5°C (18.5°F)	62.4	89.0	94.9	75.2
-5.0°C (23°F)	61.2	88.2	94.3	72.9
-2.5°C (-27.5°F)	59.5	86.9	93.5	69.9
0°C (32°F)	56.9	84.8	92.3	65.8
2.5°C (36.5°F)	53.1	81.4	90.4	60.1
5.0°C (41°F)	47.1	75.5	87.4	51.7
7.5°C (45.5°F)	36.3	64.3	82.2	38.2
10°C (50°F)	11.2	32.5	69.8	10.4

To evaluate the ability of the maturity method to predict strength, concrete cured at 23°C was used as a control to develop a laboratory-based strength-maturity model. Note that four separate strength-maturity relationships were developed for Mix 1 – flexural strength, Mix 2 – flexural strength, Mix 1 – compressive strength, and Mix 2 – compressive strength. Based on these relationships, the strengths of the samples cured at 10°C and 38°C nominal were predicted using the measured maturity values for each condition. The predicted strengths were then compared to the actual strengths measured in the laboratory to determine prediction accuracy. Comparisons between the actual and predicted strength values were made using the corresponding strength-maturity models. The analyses have been tabulated in table 5.

Predictions for the samples cured in ambient conditions are not presented in the table. The prediction errors for the specimens cured in ambient conditions were as high as 40% for flexural strength and 33% for compressive strength. These huge error terms are attributed to the lack of access to sufficient moisture during the curing

phase. It is to be recognized that maturity equations do not account for moisture effects in strength gain, which in part can be explained by unpredictable strength gain in the vicinity of evaporating surfaces (*Bazant et al., 1972*).

Table 5. Strength Predictions for Mixes Cured at 38°C and 10°C Based on Strength-Maturity Relationships Developed for Mixtures Cured in the Lab at 23°C Using Various Datum Temperature Values

Mix cured at 38C		Mix 1 Comp strength				Mix 2 Comp strength				Mix 1 Flexural strength				Mix 2 Flexural strength		
		Datum Temperature = -10C (14F)														
	age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %
	3 day	3675	3,500	5.0%		3683	3,051	20.7%		541	467	15.8%		520	403	28.9%
	7 day	4340	4,209	3.1%		4572	3,693	23.8%		606	577	5.1%		605	567	6.8%
	14 day	4725	4,564	3.5%		5205	-	-		645	587	9.9%		669	733	-8.8%
	28 day	5238	5,277	-0.7%		5773	5,056	14.2%		695	660	5.4%		724	760	-4.7%
		Datum Temperature = -5C (23F)														
	age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %
	3 day	3708	3,500	6.0%		3740	3,051	22.6%		544	467	16.5%		525	403	30.2%
	7 day	4382	4,209	4.1%		4620	3,693	25.1%		610	577	5.8%		610	567	7.6%
	14 day	4755	4,564	4.2%		5262	-	-		647	587	10.4%		674	733	-8.1%
28 day	5269	5,277	-0.2%		5816	5,056	15.0%		698	660	5.8%		728	760	-4.2%	
	Datum Temperature = 0C (32F)															
age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %	
3 day	3753	3,500	7.2%		3816	3,051	25.1%		548	467	17.4%		532	403	32.0%	
7 day	4437	4,209	5.4%		4684	3,693	26.9%		616	577	6.8%		616	567	8.7%	
14 day	4796	4,564	5.1%		5338	-	-		652	587	11.1%		682	733	-7.1%	
28 day	5310	5,277	0.6%		5875	5,056	16.2%		703	660	6.5%		734	760	-3.4%	
Mix cured at 10C		Mix 1 Comp strength				Mix 2 Comp strength				Mix 1 Flexural strength				Mix 2 Flexural strength		
		Datum Temperature = -10C (14F)														
	age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %
	3 day	3077	2,928	5.1%		2749	2,566	7.1%		483	470	2.7%		431	397	8.7%
	7 day	3661	3,847	-4.8%		3686	4,154	-11.3%		542	540	0.3%		523	520	0.6%
	14 day	4156	-	-		4282	4,706	-9.0%		587	613	-4.4%		579	580	-0.1%
	28 day	4648	-	-		4950	5,511	-10.2%		637	623	2.2%		643	657	-2.1%
		Datum Temperature = -5C (23F)														
	age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %
	3 day	2996	2,928	2.3%		2633	2,566	2.6%		475	470	1.1%		420	397	5.9%
	7 day	3575	3,847	-7.1%		3555	4,154	-14.4%		534	540	-1.2%		511	520	-1.8%
	14 day	4069	-	-		4161	4,706	-11.6%		577	613	-5.9%		568	580	-2.1%
	28 day	4553	-	-		4820	5,511	-12.5%		628	623	0.8%		630	657	-4.0%
		Datum Temperature = 0C (32F)														
	age	predicted	actual	error %		predicted	actual	error %		predicted	actual	error %		predicted	actual	error %
	3 day	2866	2,928	-2.1%		2445	2,566	-4.7%		463	470	-1.6%		402	397	1.3%
	7 day	3432	3,847	-10.8%		3336	4,154	-19.7%		521	540	-3.6%		490	520	-5.7%
	14 day	3926	-	-		3962	4,706	-15.8%		562	613	-8.4%		548	580	-5.5%
28 day	4392	-	-		4602	5,511	-16.5%		612	623	-1.8%		608	657	-7.4%	

From the results shown in table 5, the following observations can be made:

- Based on the above analyses that considered predictions for both Mix 1 and Mix 2 at low and high temperatures, a datum temperature of -10°C (+14°F) is the most appropriate for use for both the mixes used in this study when used to predict strength values over the first 28 days of curing at all temperatures. The overall prediction errors are the least for a datum temperature of -10°C.
- At a datum temperature of -10°C, both the predicted flexural and compressive strengths are close to the actual strength for Mixes 1 and 2 at all ages. Note that negative errors in the table correspond to underpredicted strength values, while positive errors correspond to overpredicted strength values. Accord-

ingly, it can be seen that negative errors are on the conservative side, especially for the 14-day and 28-day strength values, which coincide with typical times and strength gain levels required for opening the pavement to traffic. The typical time for opening the pavement to traffic is about 10 days after construction, after requisite strength levels are achieved.

- The 3-day flexural strengths are generally overpredicted for the samples cured at nominal 38°C for both Mix 1 and Mix 2. As discussed earlier, there was a fundamental problem in the 3-day strength data obtained from the 38°C curing conditions for both Mixes 1 and 2, as the measured strengths are higher for the lower temperature curing conditions – just the opposite of what would be expected. These errors in prediction, although high, were disregarded because the actual data against which the prediction is being compared were questionable. Also, strength values of significance to design or roadway opening are attained at relatively later ages. Note that all other predictions are within a ± 10 percent error.

The strength-maturity relationships for flexural strength and compressive strength have been plotted in figures 4 and 5 respectively. Each figure shows the strength-maturity model developed for the Mix 1 and Mix 2 samples cured at 23°C. The data points for the samples cured at 38°C and 10°C are plotted on the figures to graphically illustrate how closely the data follow the model.

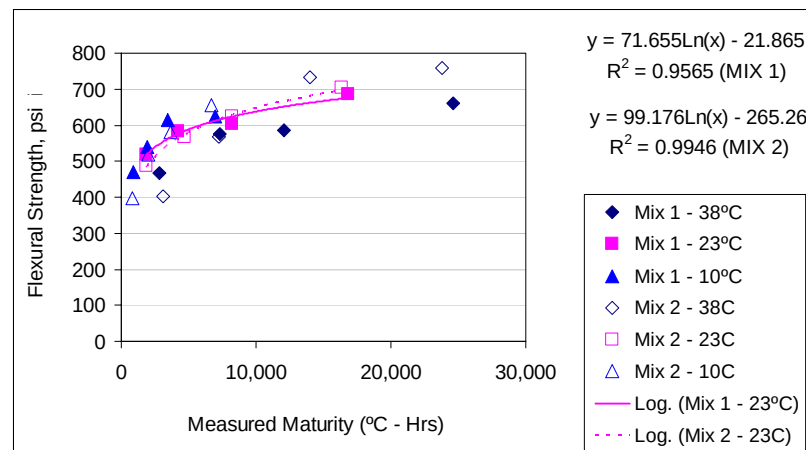


Figure 4. Flexural strength model and predictions for Mix 1 and Mix 2 using the Nurse-Saul function

Arrhenius Method: Data analysis using the *Arrhenius* method initially focused on identifying the optimum activation energy. The activation energy is a key input to the *Arrhenius* equation to compute the equivalent age of the concrete mixture. Although ASTM recommends a standard activation energy value for all mixtures being evaluated using maturity concepts, it is to be recognized that for accurate predictions, the activation energy must be determined in the lab for each specific mixture. The measured activation energy for an identical mixture in a second laboratory was determined to be 13 KJ/mole. An analysis similar to that carried out

for the *Nurse-Saul* method, above, showed that the optimum value for the activation energy of these mixtures was 30 KJ/mole. It should be noted that this activation energy is also in line with those mentioned in the literature.

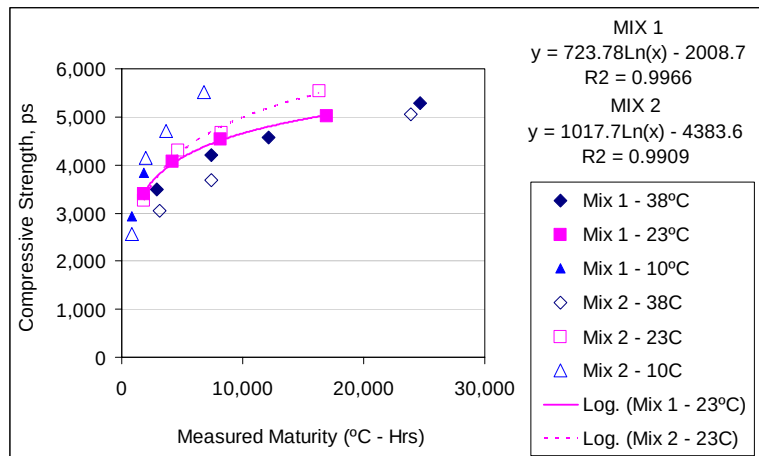


Figure 5. Compressive strength model and predictions for Mix 1 And Mix 2 using the *Nurse-Saul* function

Similar to the previous exercise, the strength-maturity relationships were developed for Mix 1 and Mix 2 using the samples cured at 23°C and strength predictions were made for samples cured at 38°C and 10°C based on lab measured maturity values. These strength predictions were compared to lab measured strength values. Predictions and the resulting errors are shown in table 6 for flexural strength of mixtures cured at 10°C and 38°C respectively. The results for the compressive strength are shown in table 7. Again, the errors in the strength predictions of the samples cured in ambient conditions were as high as 70% for flexural strength and 50% for compressive strength. Recall that these samples did not receive the consistent curing that the samples cured in temperature controlled conditions received. The maturity index used here is the equivalent age factor calculated using an activation energy value of 30 KJ/mole.

Based on the results shown in tables 6 and 7, it can be inferred that the predictions using the *Arrhenius* function were close to the actual strengths, and in most cases the errors were on the conservative side for the compressive strengths. However, the early age strength of the mixture cured at 38°C was overpredicted due to the fact that the specimens underwent poor curing (dried out at the surface) during the initial 24 hours. Figures 6 and 7 show the strength-maturity relationships using the *Arrhenius* function for both flexural and compressive strength respectively. The models are created for the data from the lab-cured samples at 23°C, while the data for the specimens cured at 10°C and 38°C, respectively, are plotted to visually present the quality of predictions.

Table 6. Flexural Strength Predictions For Mix 1 and Mix 2 Samples Cured at 10°C and 38°C Using the Arrhenius Function for Maturity Prediction

Age		Mix 1 flexural strength, psi			Mix 2 flexural strength, psi		
		Predicted	Actual	Error	Predicted	Actual	Error
10°C	3 day	495	470	5.2%	448	397	12.9%
	7 day	554	540	2.5%	542	520	4.2%
	14 day	600	613	-2.1%	597	580	3.0%
	28 day	651	623	4.5%	663	657	0.9%
38°C	3 day	538	467	15.4%	517	403	28.2%
	7 day	604	577	4.7%	602	567	6.2%
	14 day	642	587	9.4%	665	733	-9.3%
	28 day	693	660	4.9%	720	760	-5.2%

Table 7. Compressive Strength Predictions for Mix 1 and Mix 2 Samples Cured at 10°C and 38°C Using the Arrhenius function for maturity

Age		Mix 1 compressive strength, psi			Mix 2 compressive strength, psi		
		Predicted	Actual	Error	Predicted	Actual	Error
10°C	3 day	3,077	2,928	4.9%	2,749	2,566	6.7%
	7 day	3,661	3,847	-5.1%	3,686	4,154	-12.7%
	14 day	4,156	-	-	4,282	4,706	-9.9%
	28 day	4,648	-	-	4,950	5,511	-11.3%
38°C	3 day	3,199	2,928	9.3%	2,925	2,566	14.0%
	7 day	3,792	3,847	-1.4%	3,886	4,154	-6.5%
	14 day	4,287	-	-	4,465	4,706	-5.1%
	28 day	4,792	-	-	5,148	5,511	-6.6%

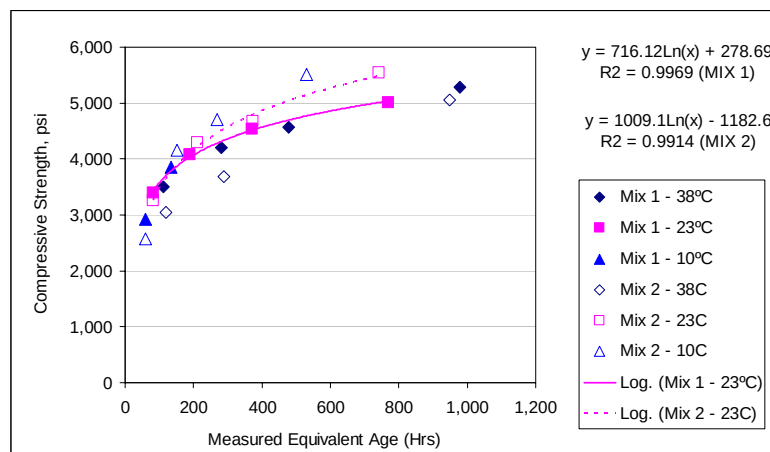


Figure 6. Flexural strength model and predictions for Mix 1 and Mix 2 using the Arrhenius function

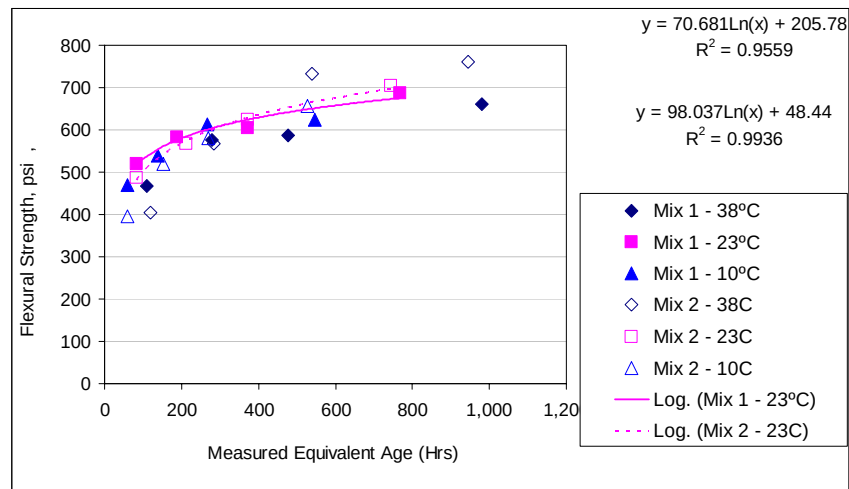


Figure 7. Compressive strength model and predictions for Mix 1 and Mix 2 using the Arrhenius function

Field Validation

The ultimate application for the concrete maturity technology is in predicting in-situ strength values based on field maturity measurements and the lab developed strength-maturity calibration model. A mixture design identical to that used in Mix 2 in this study was used on a prior paving project in Victorville, CA. During this construction project, temperature measurements were made for the hydrating concrete mixture in the pavement section itself, and maturity values from the *Nurse-Saul* function were calculated using a datum temperature of -10°C . Lab strength tests were also performed on companion specimens cast during the paving operation.

The maturity values at different ages along with the corresponding lab-measured strength values were made available for use in the current study. In principle, the calibration curves developed for flexural strength and compressive strength using a datum temperature of -10°C can be used to predict the in-situ strengths of the field slabs cast during the construction of the Victorville project. A verification exercise was conducted, and the strength predictions were quite close to the actual measured strengths as shown in table 8. As can be seen, the strength-maturity calibration curve derived using a mixture cured under standard laboratory conditions (with good curing) can be used to predict in-situ strengths.

Table 8. In-Situ Strength Predictions from Field Measured Maturity Values Using the Strength-Maturity Relationship Derived for Mix 2 Cured at 23°C

Field TTF	Flexural Strength, psi			Compressive Strength, psi		
	Predicted	Actual	Error	Predicted	Actual	Error
2564	480	392	22.7%	3322	3408	-2.5%
6689	575	537	7.1%	4235	4597	-7.9%
9732	612	595	2.9%	4615	4872	-5.3%
27516	714	638	11.9%	5666	5394	5.1%

Conclusions

Based on tests and the data analysis performed, the study concludes as follows:

- Concrete strength gain can be related to the thermal history of the mixture as it hydrates. The two maturity indices calculated using the *Nurse-Saul* function and the *Arrhenius* function, the temperature-time factor and the equivalent age respectively, are both effective in estimating flexural as well as compressive strengths. The benefit from additional lab tests for the *Arrhenius* function was not evident in this study.
- Strength-maturity relationships derived for estimating the flexural strength of concrete mixtures can be used to predict the flexural strength of in-situ concrete to a reasonably accurate degree. The errors in prediction are within the tolerance specified by standard strength tests.
- Concrete maturity can be used to predict the compressive strength of a concrete mixture.
- Strength-maturity relationships must be developed for each specific concrete mixture to increase the accuracy and reliability in strength predictions.
- The selection of the right datum temperature in the *Nurse-Saul* function is crucial to achieving good quality strength predictions. The optimum datum temperature may change with the mix design. For the mix designs used in this study, the optimum datum temperature was determined to be -10°C . The ability to predict both flexural and compressive strength was considered in establishing this value.
- Likewise, the selection of the appropriate activation energy is important for reliable predictions using the *Arrhenius* function. For the mix designs used in this study, the optimum activation energy was determined to be 30,000 joules/mole, resulting in minimal overall errors in strength predictions.
- The logarithmic model for strength determination was found to be adequate to define the strength-maturity relationships.
- For properly cured concrete, the effects on strength development of different mix design parameters and curing conditions can be traced through maturity recordings. In this test plan, the strength predictions in Mix 1 vs. Mix 2 were as expected. The higher percentage of flyash in Mix 2 resulted in lower strength gains in the early ages; however, these strength gains were higher in the long-term relative to Mix 1. The strength predictions clearly show these trends. Similarly, mixtures cured at higher temperatures should gain higher early-age strengths than mixtures cured at lower temperatures. The predicted strengths clearly show these trends as well.
- Maturity is applicable only for mixtures that have sufficient moisture to hydrate and gain sufficient strength during the curing period. An increase in mixture temperature without an associated potential for strength gain, i.e. due to the lack of water for proper hydration, is not reflective of a higher maturity of the mixture.
- The curing conditions provided are, in effect, built into the strength-maturity

relationships. Therefore, it is imperative to provide optimum curing conditions for maximum strength gain as well as to reflect the actual in-situ curing conditions. Likewise, the maturity relationship developed for a control mixture under laboratory conditions is only applicable for predicting strengths in identical mixtures that are cured under similar conditions. For example, high early-age temperatures may tend to distort the strength-maturity relationship because the mixture attains higher early age strengths and lower ultimate strengths. However, based on the findings of this study, this distortion is insignificant, at least for curing temperatures that range between 10°C and 38°C (50°F and 100°F). Note that the selection of the appropriate datum temperature for the *Nurse-Saul* maturity function of -10°C and a previously determined activation energy of 30 KJ/mole for the *Arrhenius* function also account for any divergence resulting from different initial curing conditions.

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