Title

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Publication Date

2004-05-01

UCPRC-RR-2004-02

Evaluation of the Maturity Method for Flexural Strength Estimation in Concrete Pavement

Research Report Prepared for:
California Department of Transportation

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May 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The primary purpose of the work presented in this report is to provide Caltrans with information regarding the accuracy and feasibility of the maturity method for the measurement of concrete flexural strength. Information is also provided regarding use of the maturity method for measurement of compressive strength.

The knowledge of early strength gain in concrete pavement is critical for deciding when a pavement is safe to open to traffic, and to identify the optimal time for transverse joint development/sawing. The knowledge of early strength gain is also critical in structural engineering for determining when formwork can be safely removed. The current practice of estimating in-place concrete strength by testing field cured cylinders and flexural beams has increasingly been found to be inefficient for the following reasons:

- Uncertainty often exists regarding the relationship between the curing histories of beam and cylinder specimens and the pavement slabs or concrete structure, even though great effort is made in trying to obtain similar curing conditions;
- Labor and equipment required to perform sufficient tests to obtain useful results in the field are often costly;
- Preparation, moving, and testing of heavy concrete beams places burdensome physical requirements on staff,
- Logistical problems arise related to the preparation, curing, and testing of large numbers of beams and cylinders on the 24-hour-per-day, 7-day-per-week basis required for many Caltrans construction schedules.

For these reasons, it has become highly desirable to have an alternate method to determine in-situ concrete strength.

The use of the maturity concept for estimating concrete strength has been gaining acceptance across the United States and is under investigation for implementation by Caltrans because of its potential for solving many of the difficulties listed above. The maturity method is a completely non-destructive technique for estimating concrete strength in the pavement slab or concrete structure based on its in-situ temperature history and prior laboratory calibration of temperature history to flexural beam or compressive cylinder laboratory test strength.

A literature review was conducted (Appendix A) to obtain an overview of previous work on the subject of concrete maturity. The literature review led to the formation of three fundamental questions that have yet to be answered regarding the implementation of the concrete maturity method for flexural strength estimation in concrete pavement and concrete structures. These questions are:

1. Is the maturity method applicable to the estimation of flexural strength?
2. Is the maturity method applicable to Caltrans concrete mixes with special cements and/or chemical admixtures?
3. What is the best approach for implementation of the maturity method to meet Caltrans requirements? In particular:
    a. What method should be used to calculate maturity?
    b. How should laboratory calibration be performed?
    c. How should maturity be measured in the field?
    d. Should some beams or cylinders still be tested in the field?

The objective of the work described in this report is to answer these questions. To this end, the Partnered Pavement Research Center (PPRC) performed the following tasks:

- Instrumentation of slabs with four different mixes found at three concrete pavement construction projects in District 8 (one project had two mixes) to measure maturity.
- Laboratory testing of flexural and compressive strength to develop maturity versus strength curves for each of the four mixes, using different curing temperatures,
- Measurement of maturity in field cast beams and cylinders on each of the four field projects, and testing of strength at different time intervals to compare the maturity development in the slab and field cast and cured specimens, and to compare predicted strength from the laboratory calibration with actual beam and cylinder strengths measured in the field cast specimens.
- Analysis of the results and development of conclusions as to whether the maturity method works for the measurement of flexural strength.
- Development of recommendations for implementation of the maturity method in California, if the decision is made to move forward with implementation.

The results of each of these tasks are presented in this report.

2.0 EXPERIMENT DESIGN AND TEST PROCEDURES

This section of the report presents a brief overview of the field and laboratory work performed, followed by a description of the procedure used for the development of the strength-maturity calibration curves and the details of the field and laboratory studies for each mix.

2.1 Overview of the Project and Experiment Design

Four different mix designs were included in the laboratory and field experiments. The three construction projects and four mixes together with their dates of construction are as follows:

- On I-40 at Ludlow, a Type II mix, in April, 2002,
- On SR-91 at Riverside, a Type III mix, in February 2003,
- On SR-91 at Riverside, a Type II/V mix, in February 2003,
- On I-15 at Victorville, a Type II/V mix, in June 2003.

The mix designs are summarized in Table 1. The mix designs used in the laboratory reproduced those of the field mixes. Detailed mix proportions are included in Appendix B.

Table 1 Summary of the Mix Designs and Construction Sites Studied

Design Components	**Mix** (Ludlow) I-40	(Riverside I) SR-91	(Riverside II) SR-91	(Victorville) I-15
Cement Type	Type II	Type III	Type II/V	Type II/V
Cementitious Materials Content (Cement + Fly Ash)	657 lb./cu. yd. (390 kg/m^3)	708 lb./cu. yd. (420 kg/m^3)	600 lb./cu. yd. (356 kg/m^3)	567 lb./cu. yd. (336 kg/m^3)
Water/Cement Ratio	0.41	0.38	0.48	0.47
Mineral Admixtures	Fly Ash (F) 25%	None	Fly Ash (F) 25%	Fly Ash (F) 25%
Chemical Admixtures	HRWR, AEA	HRWR, Retarder, Accelerator	AEA	AEA, HRWR

HRWR = High Range Water Reducer
AEA = Air Entraining Agent

Specimens for each of these mix designs were mixed, cast, and cured in the laboratory under three curing temperatures (10, 23, and 40ºC). Specimens were also cast in the field using concrete taken from in front of the paver and cured in the field buried in wet sand according to CTM 540.

In the laboratory, the samples were stored at their respective curing temperatures immediately after casting. Specimens cured at 23ºC were maintained at 100 percent relative humidity, and specimens cured at 10ºC and 40ºC were immersed in lime-saturated water 24 hours after casting. Concrete specimens were tested immediately after their removal from their respective curing environments, and were not allowed to dry before testing. As highlighted by Mehta and Monteiro (*1*), it has been observed that air-dried specimens show 20 to 25 percent higher strength than corresponding specimens tested in a saturated condition[1].

For both field and laboratory prepared specimens, compressive and flexural strengths were determined, and the temperature history was measured at midpoint in both 150 × 300 mm concrete cylinders and 150 × 150 × 565 mm concrete beams. Temperature history was also measured at different locations and depths in the pavement slabs from which the field mix was obtained (see Section 2.2).

For a given concrete mix, results are presented for each of the eight conditions shown on the right hand side of Figure 1 for both the field and laboratory prepared specimens, for each one of the four different mix designs studied. Reference to this figure will be useful when reviewing the results, which are presented in Appendix C.

[1] The lower strength of the saturated concrete is probably due to the existence of disjoining pressure within the cement paste.

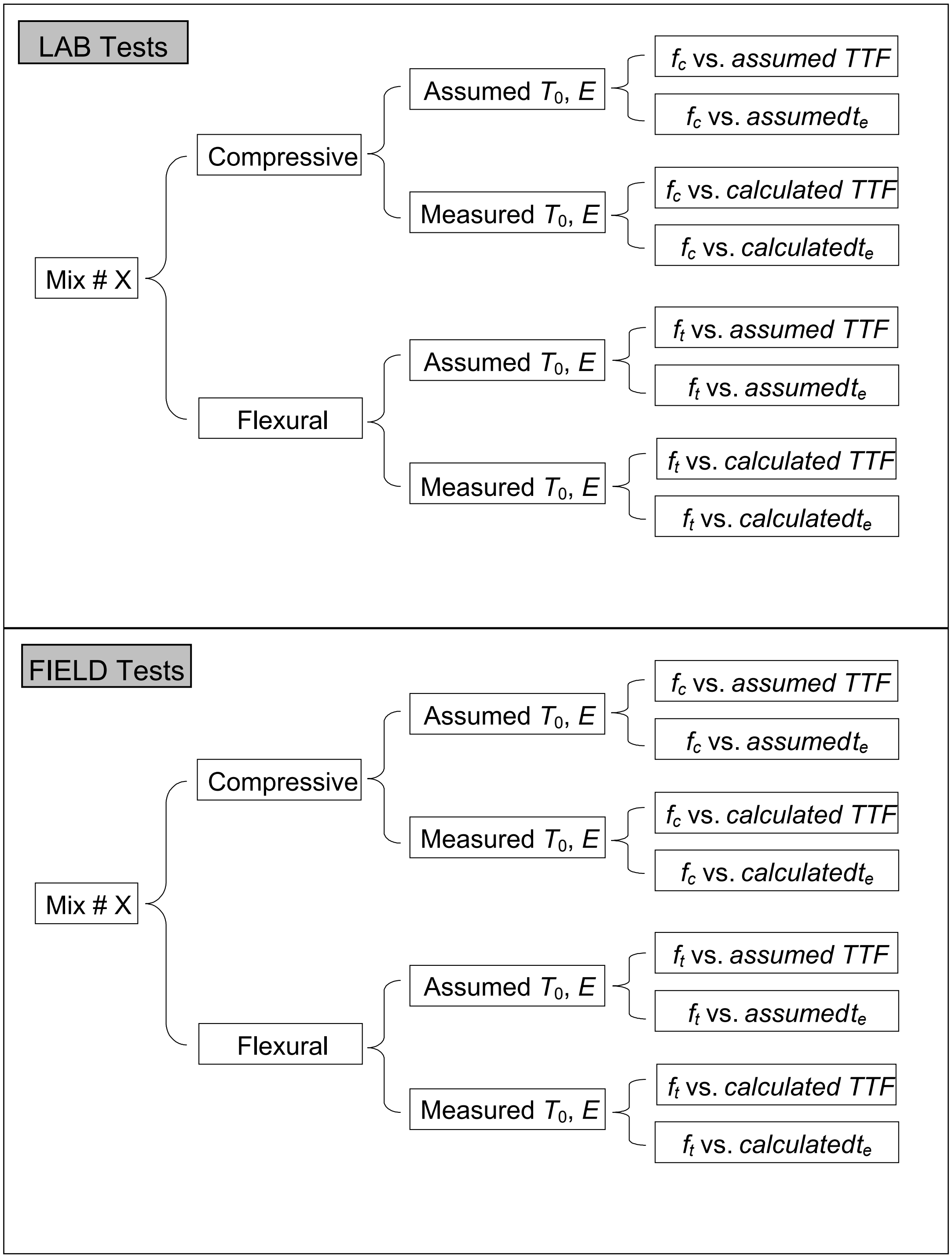

Figure 1. Schematic representation of the variables investigated and tests performed.

Excluding extra replicates and validation mixes, a total of approximately 384 concrete samples (cylinders and beams) and 189 mortar cubes were prepared and tested for this study. These samples are distributed as follows:

- Strength-maturity evaluation in the laboratory (for each of the four mix designs):
    - 36 beams and 36 cylinders cast and cured in the lab
    - 12 beams and 12 cylinders cast and cured in the field
    - Total ~ 192 beams and 192 cylinders
- Determination of activation energy and datum temperature
    - 9 + 54 mortar cubes per mix design
    - Total ~ 189 samples

2.2 Field Instrumentation and Sampling

In all projects, thermocouples were installed in the pavement before the placement of the fresh concrete. Several types of maturity meters were evaluated, as discussed in Section 3.7. Thermocouples were regularly installed in two locations in the slabs (at the center and close to the shoulder, 0.3 m from the edge) and at three different depths for each location (50 mm from the top, mid-depth, and 50 mm from the bottom). In some cases, additional thermocouples were also installed on the traffic side of the slab. Six to seven channels were used for the thermocouple wires embedded in the pavement, and one channel was left to collect ambient temperature data (Humboldt maturity meter, as discussed in Section 3.7). The temperature history was recorded at half-hour intervals for the first 48 hours and one-hour intervals thereafter. Figure 2 illustrates the location of temperatures gauges in the pavement slabs.

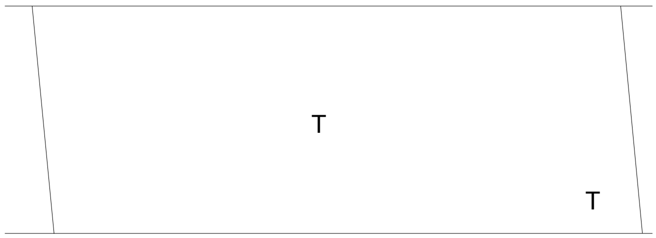

Figure 2a. Plan view of the thermocouple locations on the slab (T = thermocouple location).

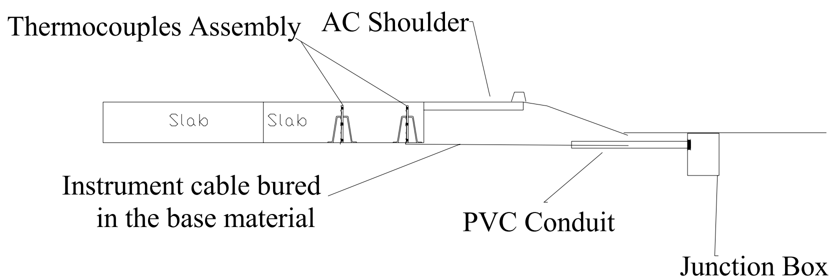

Figure 2b. Cross section of thermocouple wires on wooden dowel at multiple depths.

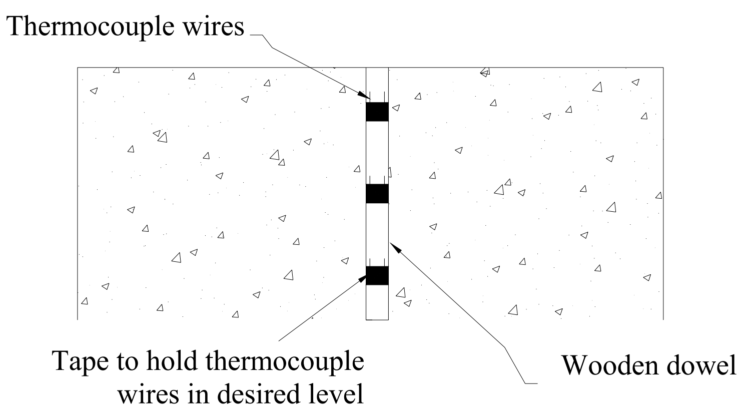

Figure 2c. Cross section of maturity meter thermocouple locations in the slab.

Figure 2. Locations of instrumentations in concrete slabs.

In addition to the slab instrumentation, 12 cylinders and 12 beams were cast during construction as concrete arrived from the batching plant. The field cured beams and cylinders were cast from the same concrete delivery truck that delivered the concrete for the instrumented slabs on each project. Thermocouple wires were placed inside two cylinders and two beams to record the temperature at half-hour intervals for the first 48 hours and one-hour intervals thereafter.

To mitigate the potential of losing or damaging the thermocouple wires during or after construction, they were attached to steel “chairs” and wooden dowels as shown in Figures 2(b) and (c). The steel chairs were nailed to the base to minimize movement during concrete placement, Figure 3. The wires were then buried in the base layer and protected by PVC conduits at the edge of the section. In some cases, in addition to the steel chair, a tin box was used to protect the thermocouple array and the steel chair from the flow of the fresh concrete that may cause the instrument to move, Figure 4. The tin box was pulled out immediately after concrete placement.

Besides the fresh concrete sampling during construction, materials from the batch plants (contractors) were transported to the UC Pavement Research Center Laboratory in Richmond, California for the laboratory tests, so that for each mix, all the experiments were performed with the same materials used in the concrete slabs (fine aggregates, coarse aggregates, cement, mineral and chemical admixtures). In most cases, the laboratory maturity calibration curves were developed after construction because the mix materials were not available to the researchers prior to the beginning of construction. On typical construction projects, the contractor would be required to develop the maturity curve, or submit materials to Caltrans, prior to construction.

Figure 3. Installation of a weather station and field instrumentation.

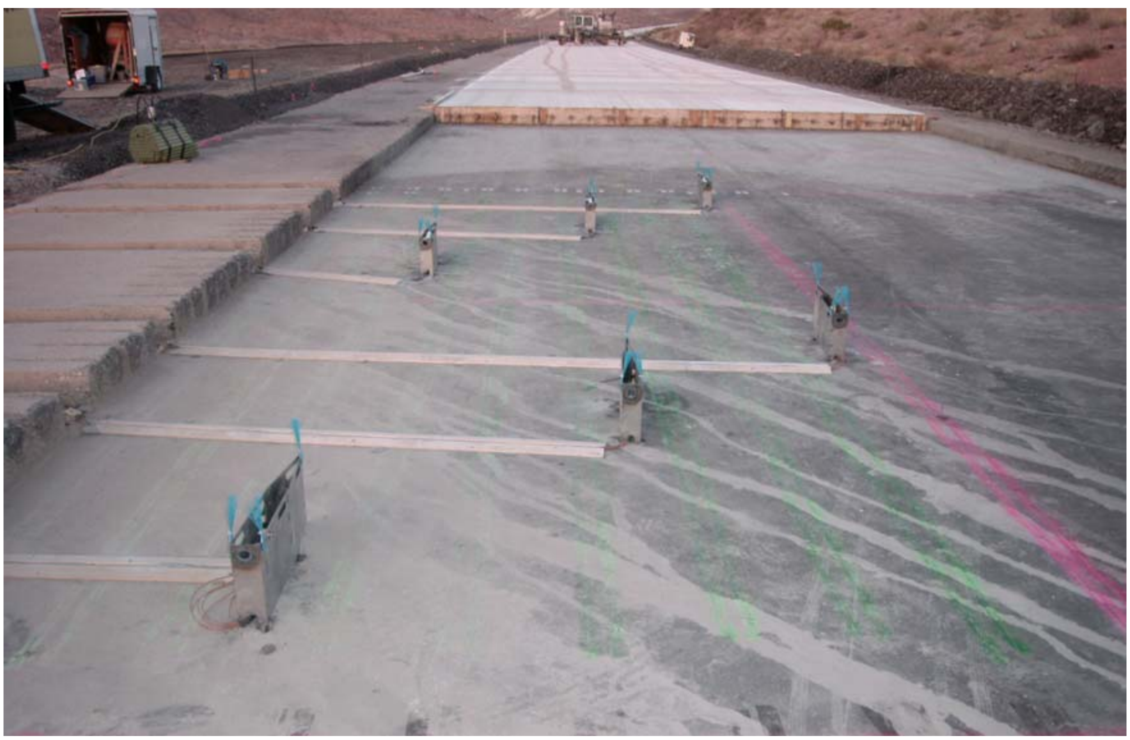

Figure 4. Thermocouples placed in different locations before concrete placement, protected by temporary tin boxes that were removed after placement.

Figure 5 shows a plot of time versus maturity, and it can be observed that essentially no difference was observed in the maturity index values measured in the various locations across the slab. Based on such plots, and considering the levels of stress distribution in the slab, it is recommended that the maturity meter should be installed close to the shoulder, on the upper third of the depth ("shoulder top" location).

2.3 Laboratory Work

For all projects, the concrete mixes prepared in the laboratory used the same materials and duplicated the mix proportions used by the contractors. All specimens were cured under controlled temperature conditions, as discussed in Section 2.1. For each mix, and for each curing condition, four samples (two beams and two cylinders) were instrumented with maturity meters, and compressive and flexural strength were measured at specified time intervals.

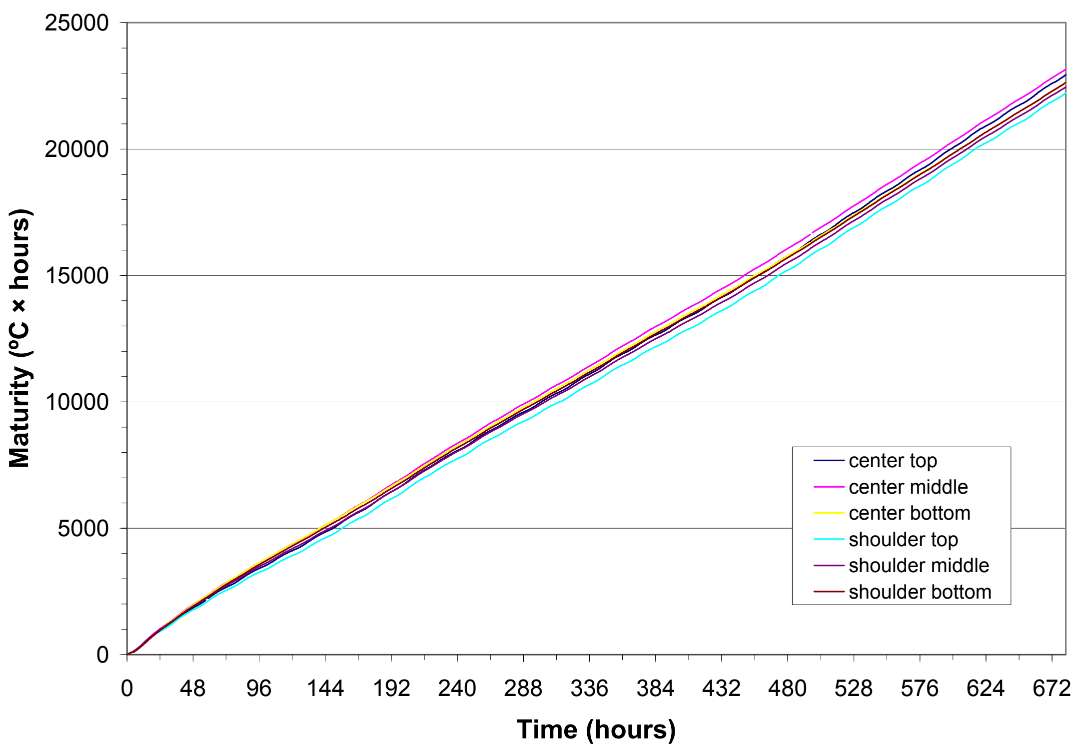

Figure 5. Example of maturity over time for several locations within the slab.

Compressive strength tests were performed according to ASTM C 39. The general guideline for evaluation of the results (besides verifying standard deviation and coefficient of variation) as stated by ASTM 1074 is that individual results should be within 10 percent of the calculated average. Flexural strength tests were performed according to ASTM C 239 (third point loading).

The procedure used to develop the strength-maturity relationships and to estimate in-situ strength generally followed the ASTM 1074 procedure. However, for this study, additional variables were evaluated. These included several curing temperatures, use of both the Nurse-Saul and Arrhenius methods, and use of measured and assumed datum temperatures and activation energies (see Section 2.4).

2.4 Calculating the Maturity Index

There are basically two accepted methods used to calculate the maturity index: the Nurse-Saul maturity function, used to determine a Time-Temperature Factor (*TTF*), and the Arrhenius equation, used to calculate the Equivalent Age term (t_e). Equation 1 shows the Nurse-Saul maturity function (time-temperature factor):

$$M(t) = \sum (T_a - T_0)\Delta t \qquad \textbf{(1)}$$

Where,
$M(t)$ = temperature-time factor (degree-hours)
Δt = time interval (hours)
T_a = average concrete temperature during interval (ºC)
T_0 = datum temperature (ºC)

This function is simple to use. It assumes that the initial strength gain is a linear function of temperature, but independent of the temperature variation. It applies well only to curing conditions in which the curing temperature does not vary over a wide range. Generally, the datum temperature (T_0) (the temperature at which there is no strength development in the concrete) is assumed to be –10ºC (14ºF).

The equivalent age is calculated by the Arrhenius equation (Equation 2):

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

Where,
t_e = equivalent age at specified temperature (hours)
T_a = average temperature of concrete during interval (K)
T_s = specified temperature (K)
Δt = time interval (hours)
Q = activation energy divided by gas constant (E/R)

The Nurse-Saul equation requires a datum temperature (T_0) for concrete hydration, which can be measured in the laboratory or estimated from standard references. The Arrhenius equation requires the activation energy (Q) which can also be measured in the laboratory or estimated from standard references (note that in practice, as in the rest of this study, the activation energy is referenced by the numerator E rather than Q). The Nurse-Saul equation is simpler and easier to use than the Arrhenius equation. The laboratory measurement of datum temperature is time-consuming and difficult, and the measurement of activation energy is even more so.

These maturity indexes (*TTF* and t_e, described in detail in Appendix A) were used to evaluate the strength-maturity relationships, and these maturity indexes were calculated using both assumed typical values of datum temperature (T_0) and equivalent energy (E) (T_0 = –10ºC and E = 48 kJ/mol), and experimentally measured values, determined according to the procedure described in the appendix of ASTM C 1074.

3.0 LABORATORY AND FIELD TEST RESULTS

Results based on the methods and procedures described in Section 2 are summarized in this section. For each mix design, eight plots were generated (Appendix C) in order to permit comparison of: 1) compressive strength versus maturity and flexural strength versus maturity correlations; 2) maturity indexes calculated with assumed and measured values of T_0 and E; and 3) the Nurse-Saul function (*TTF*) and the Arrhenius function (t_e). Figures C2-1 through C2-4 for both laboratory and field-developed curves are contained in Appendix C2.

In each plot, the coefficient of determination, R^2, has been determined. The results (R^2 grater than 0.7) demonstrates good relationships between maturity and strength.

3.1 Activation Energy and Datum Temperature

As noted in Section 2.4, the datum temperature (T_0) and activation energy (E), can be experimentally measured for a specified concrete mix in order to calculate the maturity indexes. These two parameters were determined for each of the mixes evaluated according to ASTM C1074. In this procedure, K-values are first determined which are defined as the "rate constant for strength development." The K-values are then graphically used to determine T_0 and E. Until the final set of calculations, the activation energy is computed in the same manner as datum temperature. The K-values can be determined experimentally as follows:

- Prepare a mortar mix
    - FA/C = Fine Aggregate/Cement ratio of the concrete being studied
    - CA/C = Coarse Aggregate/Cement ratio of the concrete being studied
    - W/C ratio = water/cement ratio of the concrete being studied
    - Proportions of admixtures = proportions of admixtures of the concrete being studied

- Prepare 3 temperature baths
  - 10ºC = the lowest concrete temperature expected in-situ
  - 40ºC = the highest concrete temperature expected in-situ
  - 25ºC = a midway temperature between the lowest and highest expected in-site concrete temperatures
- Prepare 50-mm mortar cubes
  - 3 sets (one for each temperature bath)
  - 18 cubes per set (plus a few (e.g., 9) to determine *t* to reach 4 MPa)
  - 3 replicates in each test
- Conduct compressive tests
  - Determine the time at which each mix reaches about 4 MPa
  - Perform next tests always at twice the age of previous test
- Determine K-values
  - S_u = limiting strength: y-intercept from 1/strength versus 1/age plot from last 4 tests
  - $A = S/(S_u – S)$, S = strength at age t, from the first 4 tests
  - Plot A versus 1/age for the first four test for each curing condition
  - K value = slope of best fit lines.
- Determine datum temperature
  - Plot K versus temperature
  - The x intercept = datum temperature
- Determine activation energy
  - Plot K versus 1/temperature

· The Q = –slope

An example of this approach is illustrated in Figure 6. All the data developed following the above procedure are included in Appendix C.

It is important to note that the experimentally determined values for E and T_0 can vary significantly from the typically assumed values. In order to evaluate the influence of such values on the quality of the strength-maturity correlations, and ultimately on the accuracy of the strength estimates, both measured and typically assumed values were used and compared in the development of the laboratory curves and strength prediction. The assumed values were T_0 = –10ºC and E = 48 kJ/mol. While the measured values are summarized in Appendix C, Table 2 contains a summary of measured values for T_0 and E and Q for the 4 mixes.

Table 2 Measured Datum Temperatures and Activation Energies for the Four Mixes Included in This Study

Mix	**Datum Temperature T_0, ºC**	**Activation Energy *E*, kJ/mol**	**E/R (Q) in ºK**
Mix #1, Ludlow	-2.0	29.5	3543
Mix #2, Riverside I	-100.7	6.0	709.6
Mix #3, Riverside II Mix # 4, Victorville	-38.8	13.2	1588

3.2 Laboratory Calibration Curves

The laboratory calibration curves are presented in the following sections, with sub-items divided by type of mix (from #1 to #4) and strength parameter (compressive or flexural). Refer to Appendix A for the description and definition of terms used here, and to Section 2 for a description of the experimental method and procedures.

Note that three curing temperatures were used in the laboratory (10, 23, and 40ºC), as described in Section 2.1. Initially, in order to obtain the most general strength-maturity

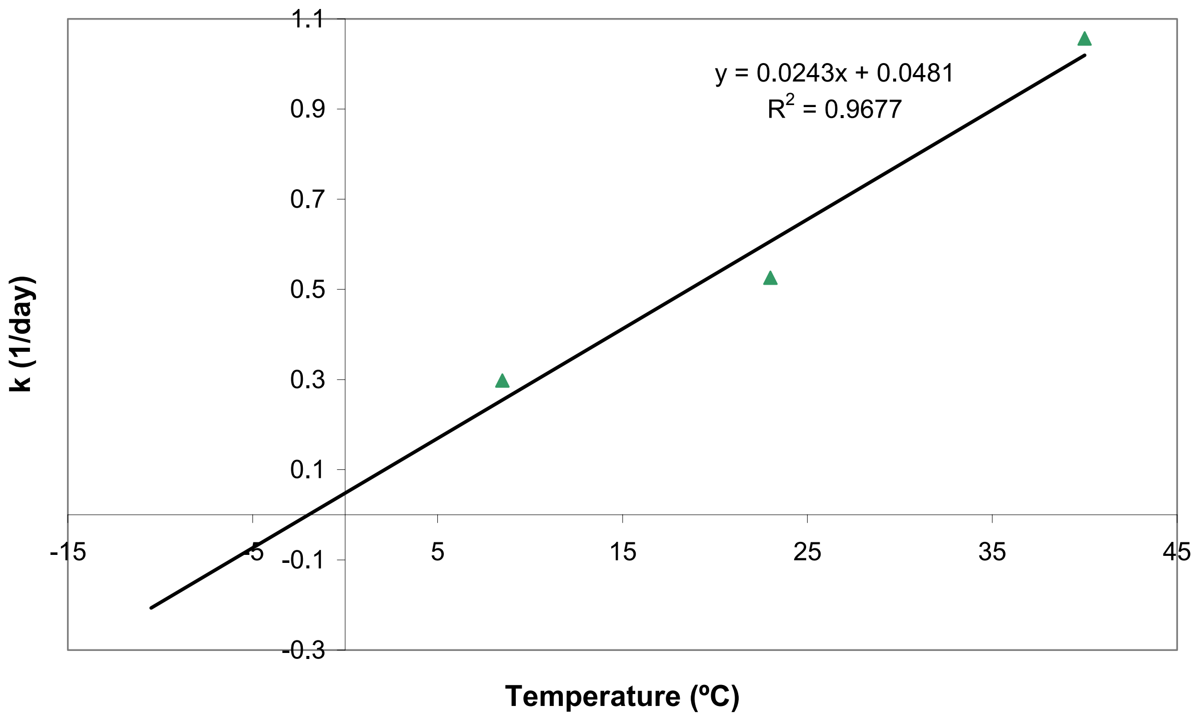

Figure 6a. Determination of datum temperature, T_0 for Ludlow mix.

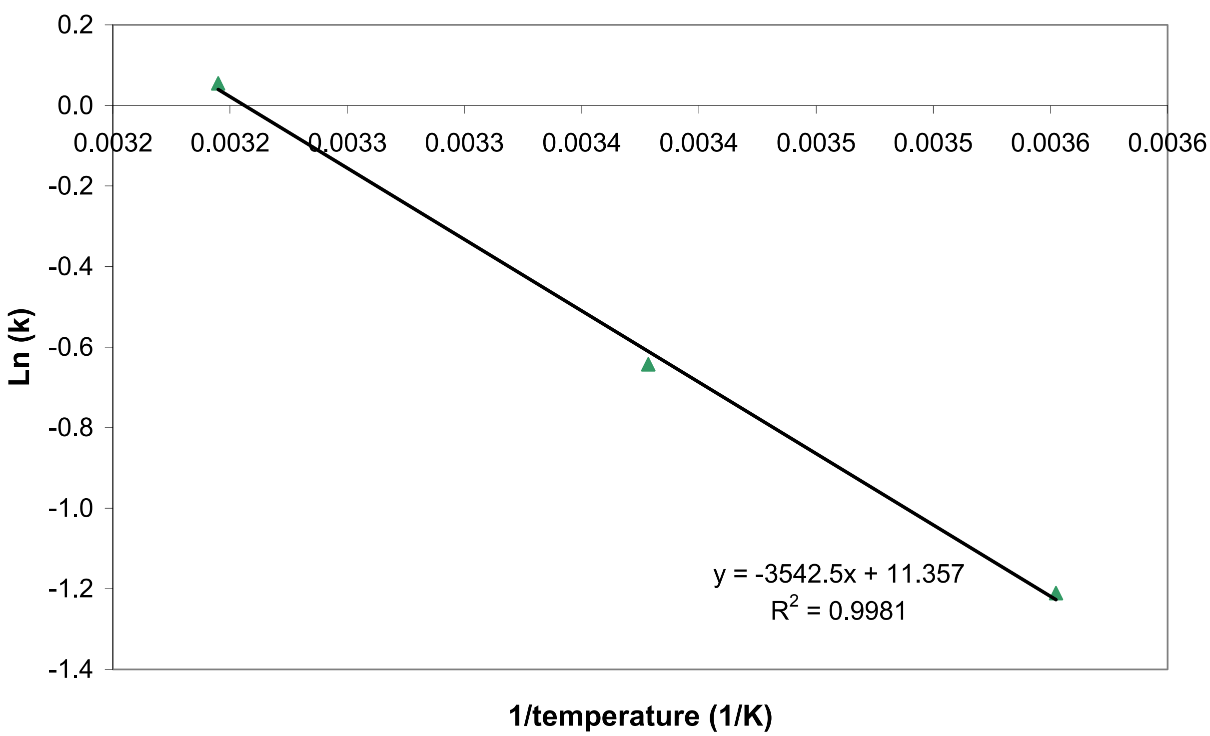

Figure 6b. Determination of activation energy, *E* for Ludlow mix.

Figure 6. Determination of T_0 and *E* for Mix #1, Ludlow.

relationship and disregarding any possible dependency of such relationship on the curing temperature, single lab curves were fitted using data from samples exposed to all curing temperatures. An example is provided in Figures 7 and 8 for Mix #1, Ludlow illustrating the development of compressive and flexural strengths based on assumed values of T_0 and E. Similar data are shown in Figures 9 and 10 using individual temperatures and assumed values for T_0 and E.

3.3 Field Calibration Curves

Field calibration curves for the 4 mixes are briefly described in this section. As with the laboratory curves, relationships were developed for both compressive and flexural strength. The field specimens were cast during construction of the pavements and cured in the field according to the Caltrans method (i.e., buried in wet sand and exposed to the local variations in temperature). Appendix C4 contains a summary of these field measurements.

In one of the projects, (Riverside II – Mix #3), a different maturity meter was tested, and this meter did not provide the temperature history of the concrete. Instead, it only calculated *TTF* values at a few programmed ages. Unaware of the limitations of this meter, the strength tests in the field, performed by a third party laboratory, were performed at different ages. This made it impossible to plot the field curves for this particular mix (see Appendix C4).

Figures 11 and 12 illustrate the relationship between compressive strength and maturity based on assumed values of T_0 and E.

Similar data are shown in Figures 13 and 14 flexural strength and maturity based on measured values of T_0 and E. Appendix C4 contains all of the available relationships for the field mixes (except Mix #3, the reason for which was stated earlier).

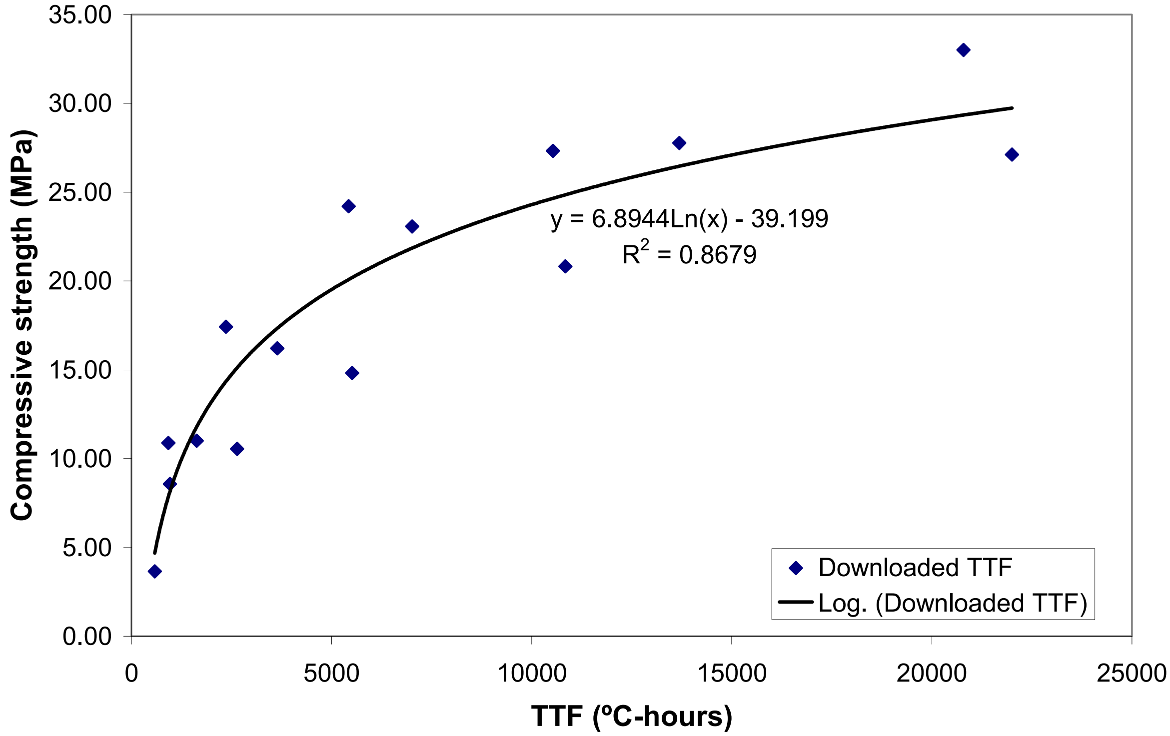

Figure 7a. Compressive strength vs. TTF (based on assumed T_0)

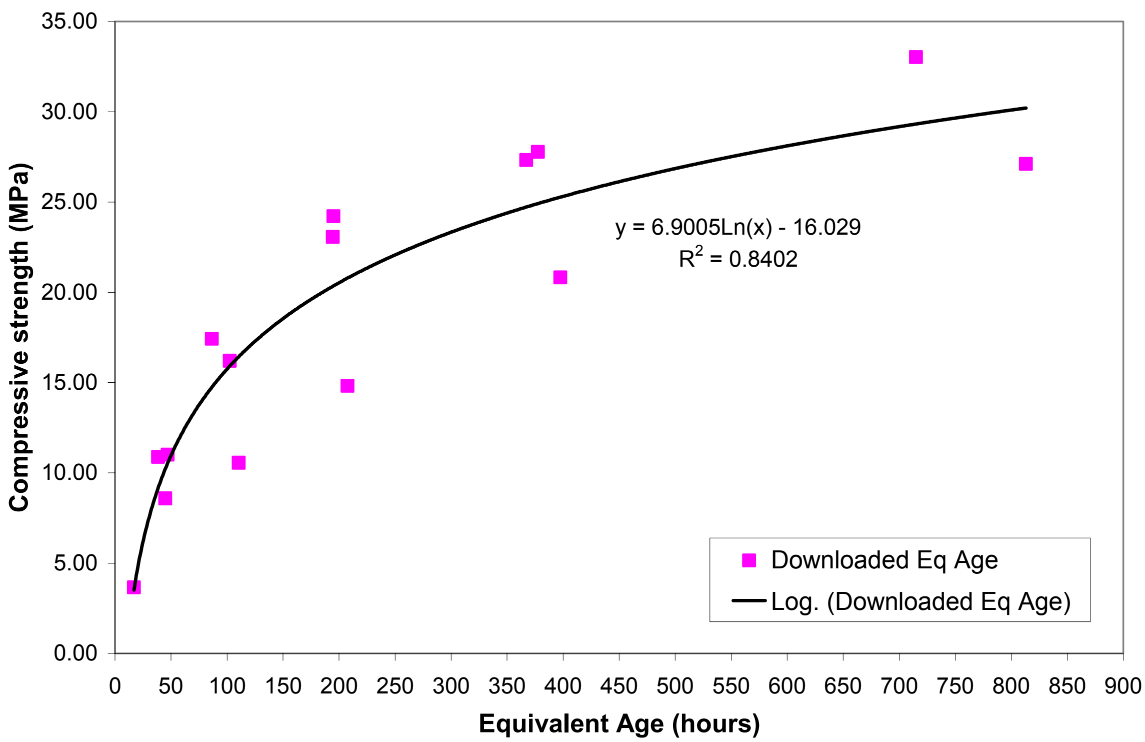

Figure 7b. Compressive strength vs. t_e (based on assumed E)

Figure 7. Compressive strength versus maturity relationships for Mix #1, Ludlow, based on assumed values of T_0 and E.

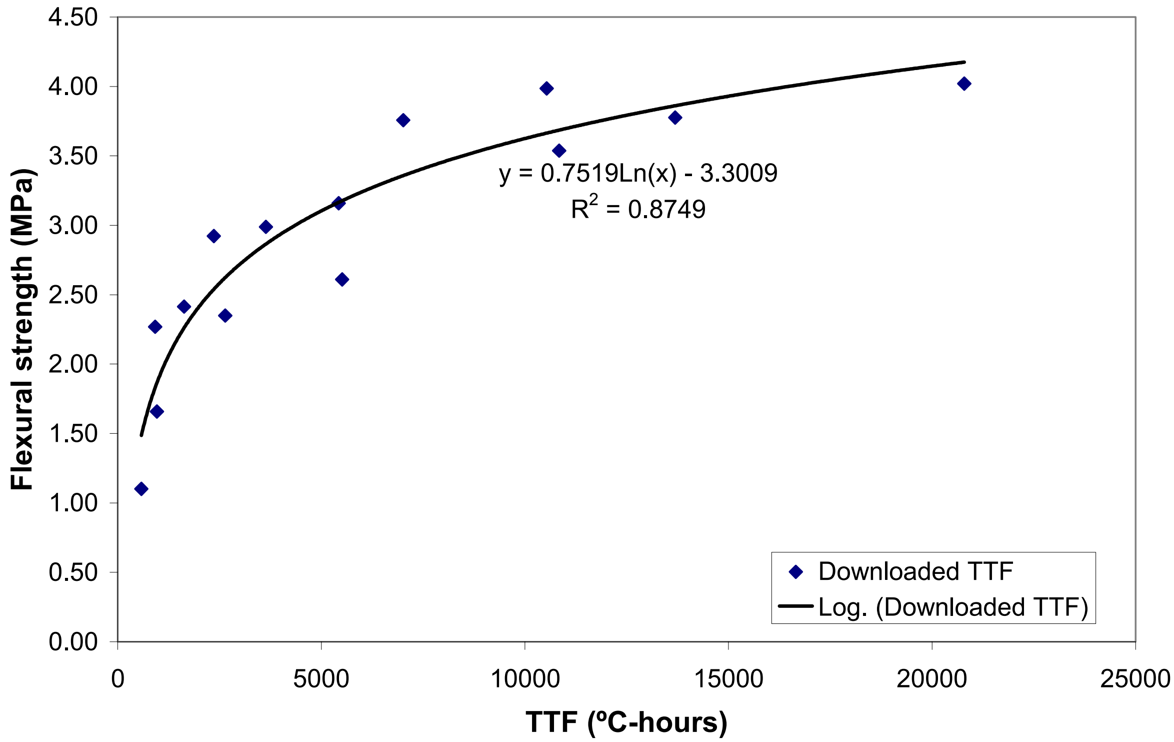

Figure 8a. Flexural strength vs. TTF (based on assumed T_0)

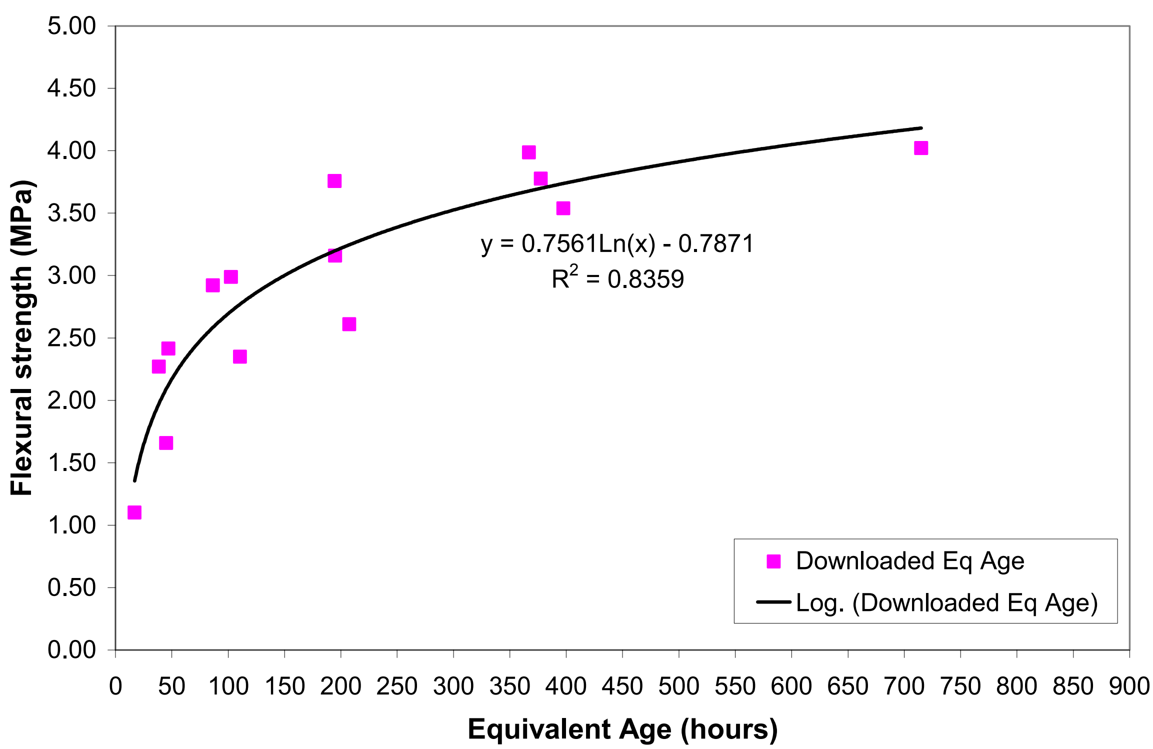

Figure 8b. Flexural strength vs. t_e (based on assumed E)

Figure 8. Flexural strength versus maturity relationships for Mix #1, Ludlow, based on assumed values of T_0 and E.

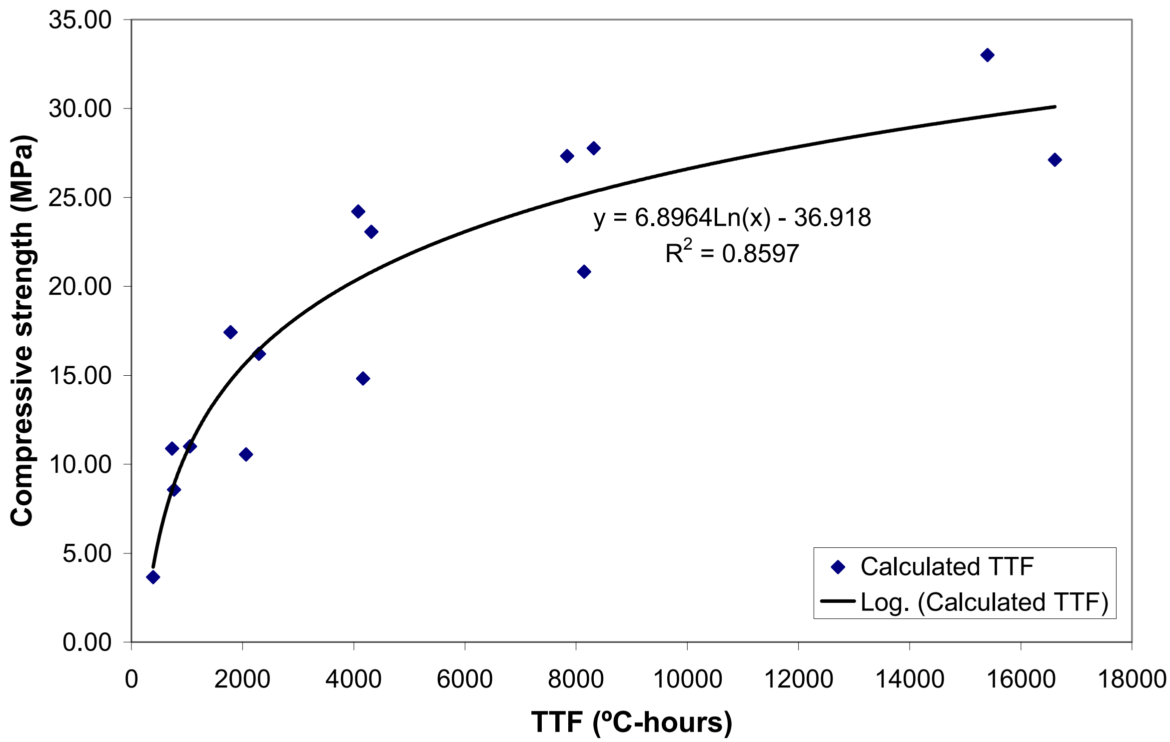

Figure 9a. Compressive strength vs. TTF (based on assumed T_0)

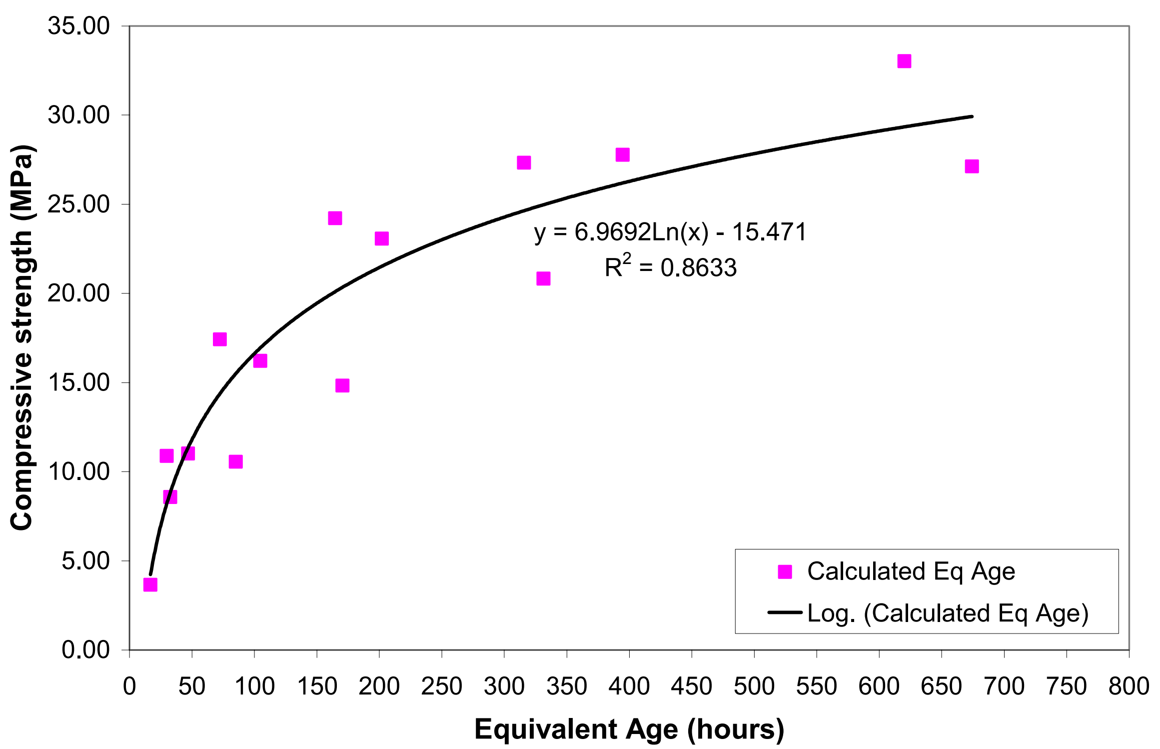

Figure 9b. Compressive strength vs. t_e (based on assumed E)

Figure 9. Compressive strength versus maturity relationships for Mix #1, Ludlow, based on measured values of T_0 and E.

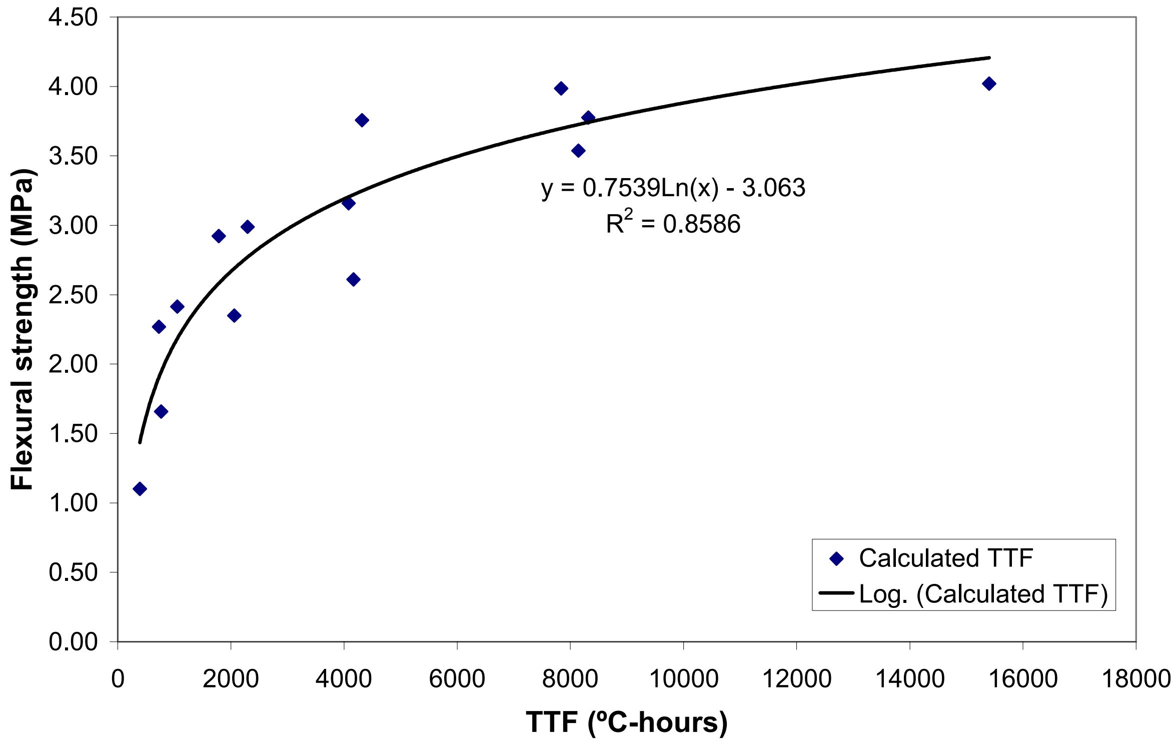

Figure 10a. Flexural strength vs. TTF (based on assumed T_0)

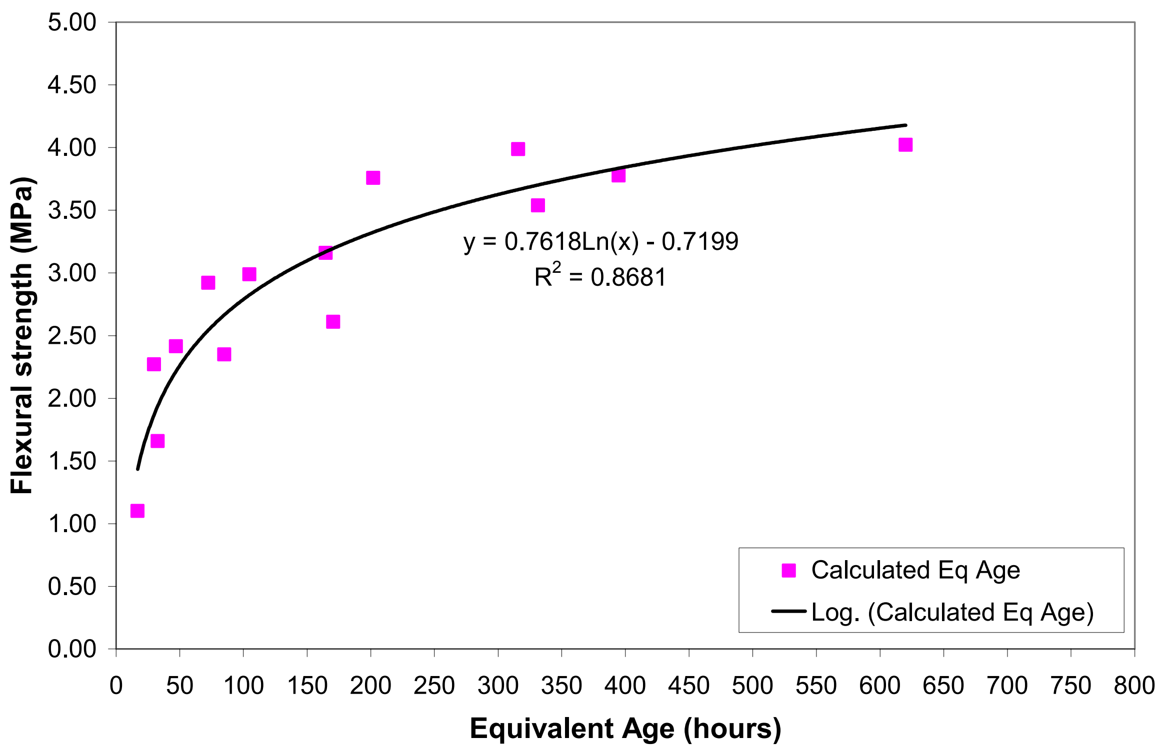

Figure 10b. Flexural strength vs. t_e (based on assumed E)

Figure 10. Flexural strength versus maturity relationships for Mix #1, Ludlow, based on measured values of T_0 and E.

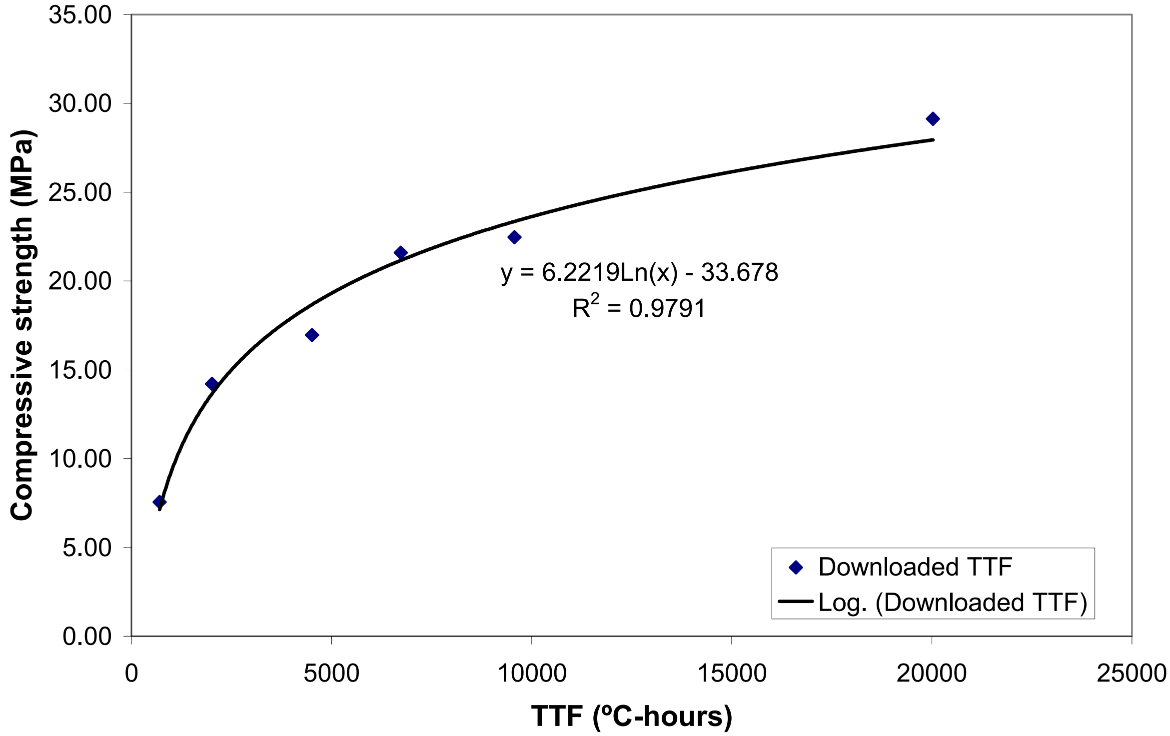

Figure 11. Correlation between compressive strength and *TTF,* assumed T_0 (Mix #1, field cylinders).

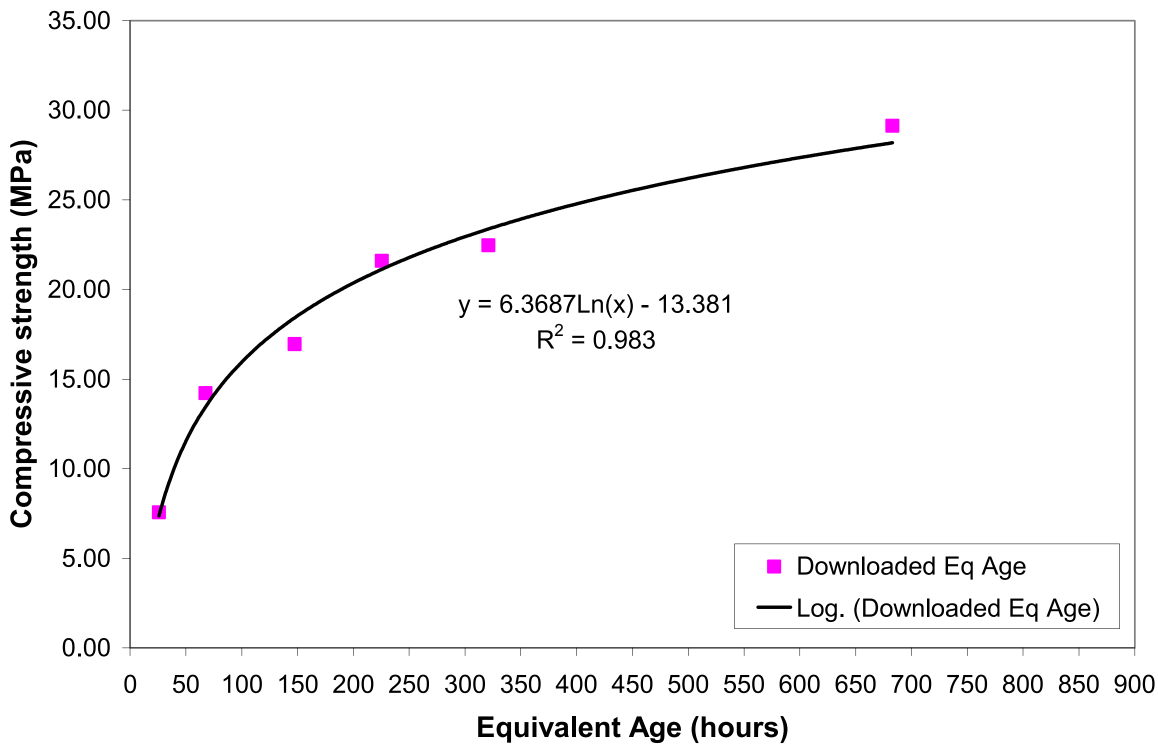

Figure 12. Correlation between compressive strength and t_e, assumed *E* (Mix #1, field cylinders).

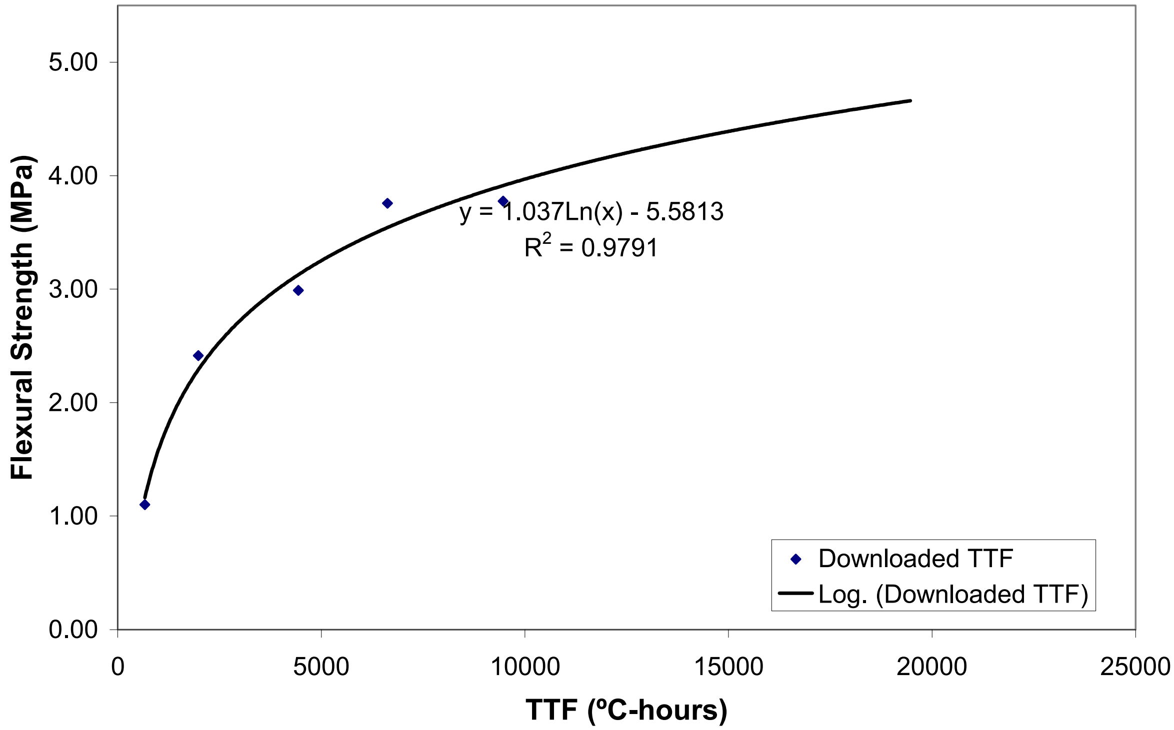

Figure 13. Correlation between flexural strength and *TTF*, assumed T_0 (Mix #1, field beams).

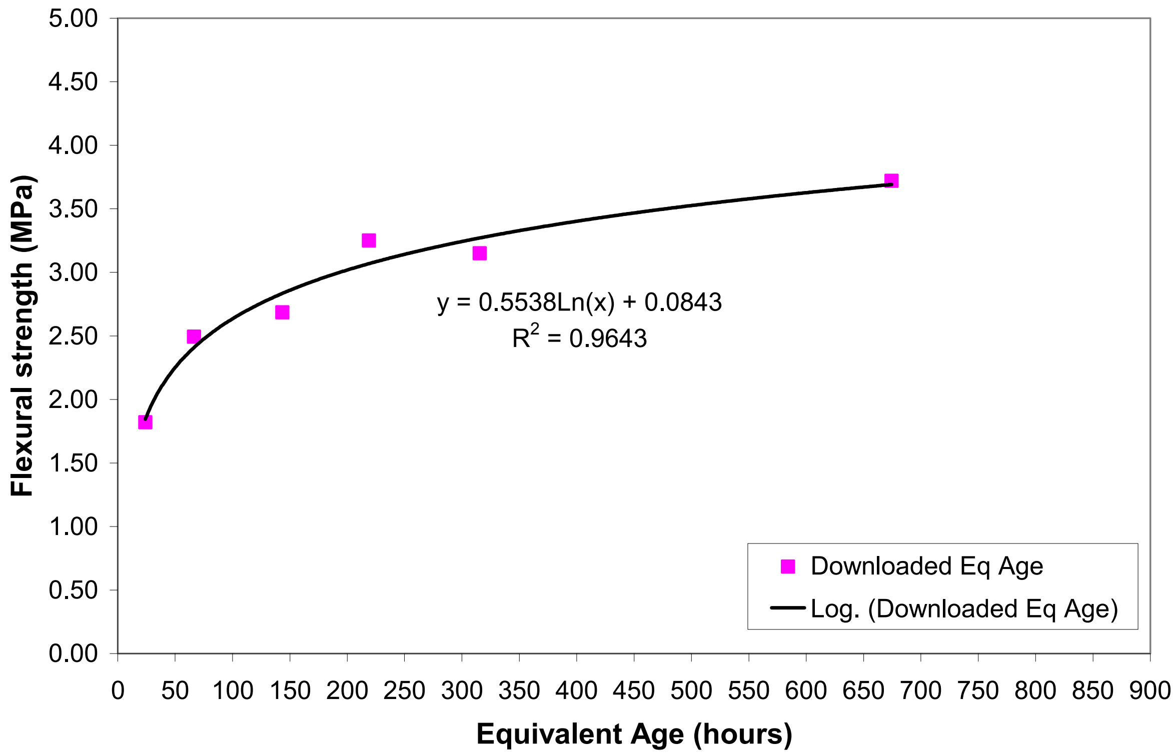

Figure 14. Correlation between flexural strength and t_e, assumed *E* (Mix #1, field beams).

3.4 Strength Estimates of Field Specimens Based on the Laboratory Curves

Maturity-strength curves developed in the laboratory (Section 3.2) were used to estimate the strength of concrete beams and cylinders cast during construction and cured in the field. The lab estimated value was then compared to the measured strength of the field specimens. As before, "assumed" refers to maturity indexes based on assumed values of T_0 and E, while "calculated" refers to the determination of the maturity indexes based on the measured values of T_0 and E. It can be seen that in many cases the experimental determination of such parameters did not improve the accuracy of strength estimates.

Initially, estimates were calculated based on the strength-maturity relationships developed from data for all curing temperatures (Appendix C5, Tables C5-1 through C5-6). Estimates were also calculated based on the correlations obtained from 23ºC data only (Appendix C5, Tables C5-8 through C5-13).

Tables 3 and 4 contain summaries of the flexural and compressive strengths measured in the field beams and predicted for the same maturities using the laboratory calibrated curves for Ludlow (Mix #1), Riverside I (Mix #2), and Victorville (Mix #4). For Victorville, the laboratory curve using the early-age data is used for comparison since correlations between flexural strength and maturity are affected by strengths at later ages. Considering the ages up to 14 days resulted in stronger relationships.

3.5 Estimates of Strengths of Laboratory Specimens at 10ºC and 40ºC Based on 23ºC Laboratory Relationships

In order to obtain additional insight on the influence of curing temperatures on the development of strength-maturity relationships, some additional estimates were performed. Appendix C6 contains the results of these analyses. The laboratory relationships developed based

Table 3 Summary of Percent Differences between Measured and Predicted Strengths for the Projects Studied (Developed from 10, 23, and 40ºC Data)

Ludlow									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
7.56	6.02	6.45	-20.5%	-14.7%	1.82	1.59	1.62	-12.7%	-11.3%
14.21	13.25	13.04	-6.8%	-8.3%	2.49	2.41	2.39	-3.6%	-4.3%
16.96	18.81	18.43	10.9%	8.7%	2.69	3.01	2.97	12.2%	10.5%
21.59	21.57	21.36	-0.1%	-1.1%	3.25	3.31	3.29	2.0%	1.1%
22.46	24.00	23.80	6.8%	5.9%	3.15	3.58	3.56	13.8%	13.2%
		Avg. Diff. =	**-1.9%**	**-1.9%**			**Avg. Diff. =**	**2.4%**	**1.9%**
Riverside I									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
15.37	15.71	14.51	2.2%	-5.6%	2.41	2.47	2.22	2.7%	-7.7%
28.41	25.23	23.54	-11.2%	-17.1%	2.94	3.86	3.52	31.5%	19.8%
28.96	30.45	28.32	5.1%	-2.2%	3.86	4.63	4.21	19.8%	8.9%
30.27	33.56	31.30	10.9%	3.4%	-	5.08	4.64	-	-
31.75	38.46	36.06	21.1%	13.6%	3.84	5.80	5.32	51.1%	38.7%
		Avg. Diff. =	**5.6%**	**-1.6%**			**Avg. Diff. =**	**26.3%**	**14.9%**
Victorville									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
23.5	16.17	16.45	-31.2%	-30.0%	2.7	2.86	2.88	6.0%	6.8%
31.7	23.02	23.04	-27.4%	-27.3%	3.7	3.62	3.58	-2.1%	-3.3%
33.6	25.74	25.48	-23.4%	-24.2%	4.1	3.92	3.84	-4.5%	-6.5%
37.2	33.66	32.76	-9.5%	-11.9%	4.4	4.74	4.60	7.7%	4.6%
		Avg. Diff. =	**-22.9%**	**-23.4%**			**Avg. Diff. =**	**1.8%**	**0.4%**

Table 4 Summary of Percent Differences between Measured and Predicted Strengths for the Projects Studied (Developed from 23ºC Data)

Ludlow									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
7.56	9.08	8.31	20.0%	9.8%	1.82	2.12	1.87	16.6%	2.8%
14.21	16.45	15.42	15.7%	8.5%	2.49	2.76	2.50	10.7%	0.3%
16.96	22.11	21.24	30.4%	25.3%	2.69	3.24	2.98	20.5%	10.9%
21.59	24.93	24.41	15.4%	13.0%	3.25	3.47	3.24	6.8%	-0.3%
22.46	27.40	27.04	22.0%	20.4%	3.15	3.68	3.47	16.9%	10.1%
		Avg. Diff. =	**20.7%**	**15.4%**			**Avg. Diff. =**	**14.3%**	**4.8%**
Riverside I									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
15.37	16.13	16.43	4.9%	6.9%	2.41	3.19	3.19	32.6%	32.5%
28.41	26.32	25.96	-7.4%	-8.6%	2.94	3.91	3.87	33.1%	31.9%
28.96	31.91	31.01	10.2%	7.1%	3.86	4.30	4.24	11.4%	9.7%
30.27	35.24	34.14	16.4%	12.8%	-	4.54	4.46	-	-
31.75	40.48	39.18	27.5%	23.4%	3.84	4.91	4.83	28.0%	25.8%
		Avg. Diff. =	**10.3%**	**8.3%**			**Avg. Diff. =**	**26.3%**	**25.0%**
Victorville									
Compressive Strength					Flexural Strength				
Measured	Estimates		Difference		Measured	Estimates		Difference	
(MPa)	TTF	t_e	TTF	t_e	(MPa)	TTF	t_e	TTF	t_e
23.5	15.69	14.74	-33.2%	-37.3%	2.7	3.15	3.07	16.7%	13.7%
31.7	21.72	21.88	-31.5%	-31.0%	3.7	3.91	3.89	5.8%	5.0%
33.6	24.11	24.53	-28.3%	-27.0%	4.1	4.21	4.19	2.7%	2.2%
37.2	31.07	32.42	-16.5%	-12.8%	4.4	5.04	5.09	14.5%	15.7%
		Avg. Diff. =	**-27.4%**	**-27.0%**			**Avg. Diff. =**	**9.9%**	**9.2%**

Table 5 Compressive Strength Estimates Based on Laboratory Curves

Site	TTF (ºC-hours)	Equiv Age, t_e (hours)	Estimated Compressive strength, TTF (MPa)	Estimated Compressive strength, t_e (MPa)	Difference between TTF an t_e
Mix #1 (Ludlow)	924	41	10.18	10.41	-2.3%
	2544	103	17.16	16.83	1.9%
	5370	198	22.31	21.38	4.2%
	7752	287	24.84	23.97	3.5%
	10686	389	27.06	26.09	3.6%
	21881	812	32.00	31.22	2.4%
Mix #2 (Riverside I)	812	26	15.89	13.57	14.6%
	2798	79	25.17	22.12	12.1%
	5894	156	30.75	27.33	11.1%
	9035	237	33.95	30.51	10.1%
	17439	450	38.88	35.38	9.0%
Mix #3 (Riverside II)	1414	40	6.37	5.87	7.8%
	2558	69	8.87	8.14	8.2%
	5869	160	12.37	11.66	5.8%
	9330	257	14.32	13.64	4.8%
Mix #4 (Victorville)	5023	83	16.09	16.22	-0.8%
	12068	201	23.01	23.16	-0.7%
	17261	287	25.83	25.98	-0.6%
	49000	817	34.07	34.22	-0.5%

Table 6 Flexural Strength Estimates Based on Laboratory Curves

Site	TTF (ºC-hours)	Equiv Age, t_e (hours)	Estimated Flexural strength, TTF (MPa)	Estimated Flexural strength, t_e (MPa)	Difference between TTF an t_e
Mix #1 (Ludlow)	924	41	2.12	2.14	-0.8%
	2544	103	2.81	2.78	1.3%
	5370	198	3.32	3.23	2.8%
	7752	287	3.57	3.49	2.4%
	10686	389	3.79	3.70	2.5%
	21881	812	4.28	4.21	1.7%
Mix #2 (Riverside I)	812	26	2.57	2.09	18.9%
	2798	79	4.20	3.32	21.1%
	5894	156	5.18	4.07	21.5%
	9035	237	5.74	4.52	21.2%
	17439	450	6.61	5.22	20.9%
Mix #3 (Riverside II)	1414	40	1.59	1.52	4.4%
	2558	69	1.96	1.86	5.3%
	5869	160	2.49	2.39	4.1%
	9330	257	2.78	2.68	3.5%
Mix #4 (Victorville)	5023	83	2.38	2.42	-1.6%
	12068	201	4.06	4.10	-0.9%
	17261	287	4.75	4.78	-0.7%
	49000	817	6.74	6.77	-0.4%

on the 23ºC data were used to estimate the strength of the samples cured at 10ºC and 40ºC in the laboratory.

The temperature histories over the first 28 days for the field slabs and beams are shown in Figures 15, 16, and 17 for Ludlow, Riverside I and Victorville, respectively. It can be seen that the temperature ranges in which the concrete developed strength are different for the each project. At Ludlow, the concrete temperatures were generally between 10 and 30ºC, at Riverside between 10 and 25ºC, and at Victorville between 25 and 40ºC. The laboratory maturity calibrations were performed by combining data from beams cured at 10, 23 and 40ºC.

The assumption of maturity is that these data should collapse into one curve. However, the results of this study indicate that this assumption is not completely valid, as is shown in Appendix C2 (Strength versus Maturity Relationships—Individual Curing Temperatures). The

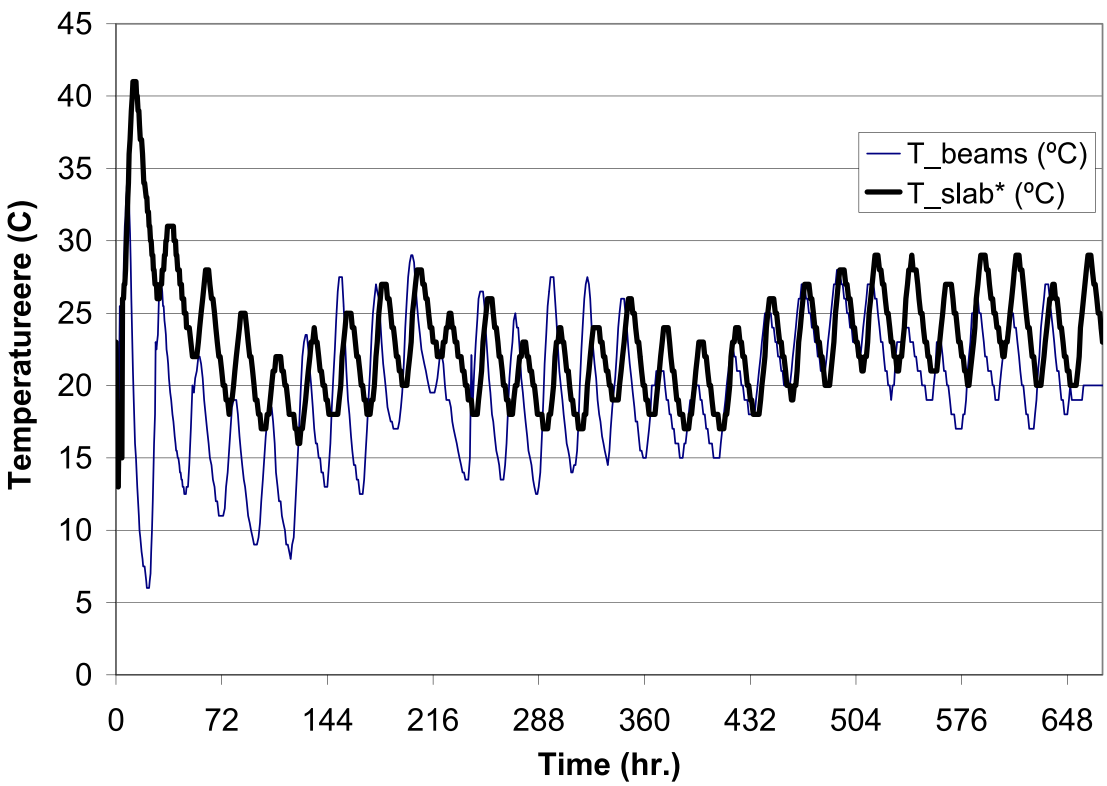

Figure 15. Temperature history for first 28 days for Ludlow beams and slab.

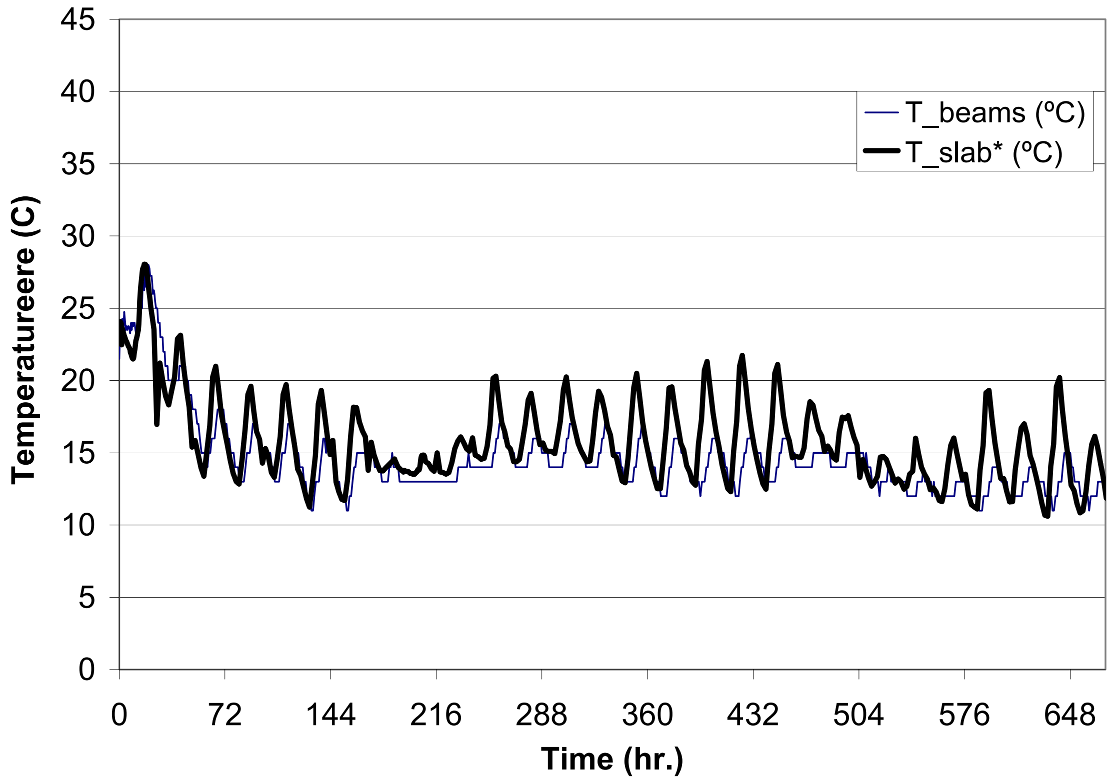

Figure 16. Temperature history for first 28 days for Riverside I beams and slab.

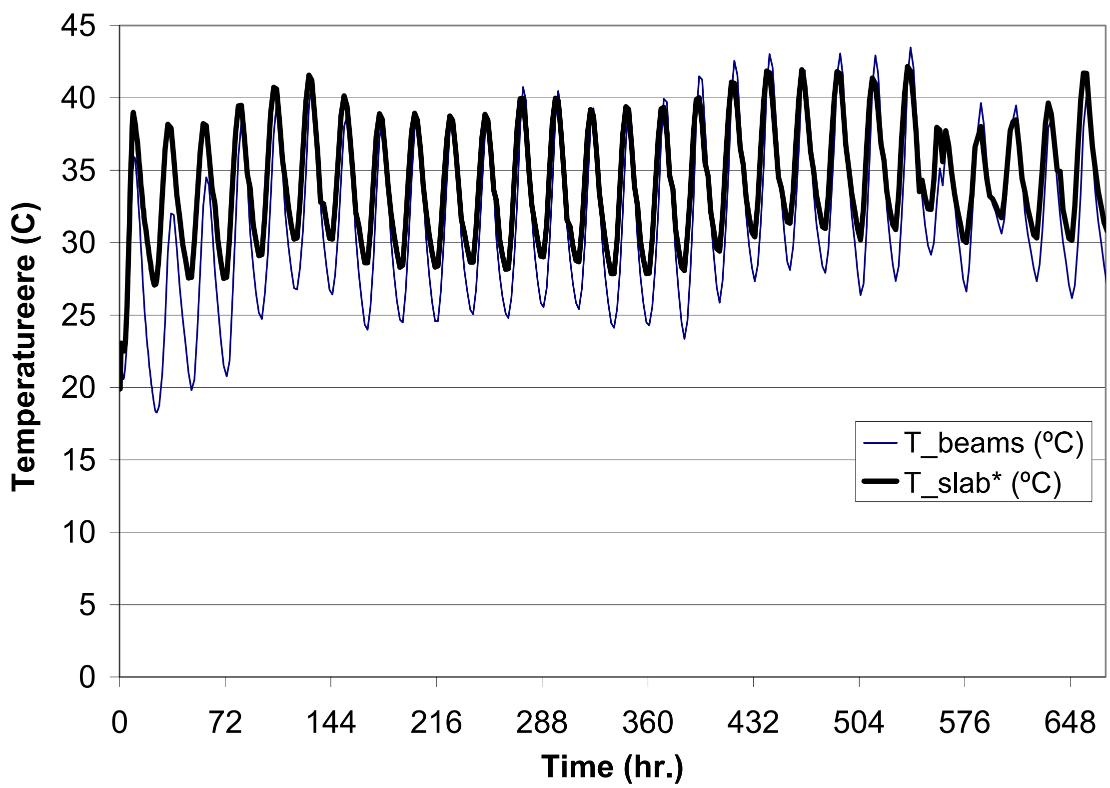

Figure 17. Temperature history for first 28 days for Victorville beams and slab.

influence of curing temperature on the maturity-versus-strength curve may need to be taken into consideration when predicting field strengths based on maturity. This question warrants further investigation.

3.6 Maturity Gauges Used in this Study

Table 7 provides a summary of the maturity gauges included in this study and their features. Wireless sensors read with a PDA equipped with an antenna were found by the field researchers to be the most convenient for field use. Sensors that require wires coming from the slab had the wires cut by construction equipment or laborer's tripping over them several times during the study. Several data collection devices left near the slab were damaged by construction equipment or stolen during this study.

Table 7 Comparison of Maturity Meters Used in this Study

Meter Name	**Connection**	**Functions**								
		Sensors	**Temperature History**	**Change of constants (Activation Energy and Datum Temperature)**	**Minimum Recording Interval**	***TTF* & Equivalent Age (Arrhenius)**	**Battery Life**	**Shelf Life**	**Advantages**	**Disadvantages**
Humboldt	Embedded Thermocouple Wires	4 Channels	Continuously Record	Can be changed	30 minutes only	Computes	2-1/2 months	N/A	Easy to install (in the lab), easy to read and download	Potential for theft, run over or damage
IRD	Wireless (Read by PDA with antenna)	Uses Tags	Continuously Record	Can be changed	Any time	Computes	5 years	N/A	Easy to install, easy to read, embed, and download	Antenna range is very short and can be time consuming
Nomadics	Semi-Wireless (Read with handheld device)	Logger with thermocouple Wire	Continuously Record	Can be changed	30 minutes only	Computes	3 Months	5 Years	Easy to install, easy to read and download	Records temperature 30 minutes interval (Wires sticking out of pavement)
Nomadics	Semi-Wireless (Read with handheld device)	Logger with thermocouple Wire	Does not record temperature history	Can be changed	4 hrs	Computes *TTF*	3 Months	5 Years	Easy to install, easy to read and download	Records temperature 4 hrs interval (Wires sticking out of pavement)

4.0 CONCLUSIONS AND SUMMARY OF RECOMMENDATIONS

The results presented in this study address the main concerns regarding the application of the maturity method for flexural strength estimation in concrete pavements, and the applicability of the maturity method for compressive strength of Caltrans mixes. The following are the conclusions and recommendations answering the questions posed in the objectives of this study.

4.1 Is the Maturity Method Applicable to Flexural Strength Estimation?

- The results presented in this report indicate that it was possible to establish reasonable correlations between maturity indexes (*TTF* and t_e) and Flexural Strength during laboratory calibration of maturity curves, for all four mixes included in the study.
- Flexural strengths measured in field beams and flexural strengths predicted from the laboratory maturity curves were similar at early ages for the two Type II mixes checked against field beams. For the Type III mix, the field beams had lower strengths than were predicted using the laboratory calibrated maturity curve.
- However, maturity curves calibrated using data that included later age laboratory beam strengths tended to predict beam strengths that were greater than those measured in the field cured beams in some cases. This may be partly due to the temperature ranges experienced by the field beams as they developed strength being at the extremes of the temperatures used in the calibration of the laboratory maturity curves. It may also be due to differences in moisture conditions between the field and laboratory curing conditions. Field curing under wet sand may produce less humid conditions than the laboratory condition, resulting in lower tensile strengths due to drying shrinkage. Moisture conditions in the slab may be more similar to the laboratory curing conditions.

- The use of laboratory established compressive strength versus maturity curves to estimate the flexural strength is not recommended, because the relation between compressive strength and flexural strength are not consistent across different mixes, and for a given mix vary considerably with age and other variables.
- These results indicate that the maturity method can be implemented for estimating flexural strengths for pavement construction. Additional work will be necessary for successful implementation, especially for Type III and other high early strength mixes.

4.2 Is the Maturity Method Applicable to Caltrans Concrete Mixes with Special Cements and/or Chemical Admixtures?

- Good correlations were found between maturity indexes (*TTF* and Equivalent Energy) and compressive strength of concrete during laboratory calibration of the maturity curves.
- Compressive strengths measured in field cylinders and compressive strengths predicted from the laboratory maturity curve matched well for one of the Type II mixes and the Type III mixes. For the other Type II mix (Victorville) observed in the field, the maturity method underestimated the compressive strengths of the field cylinders. These results indicate that the maturity method is probably applicable to Caltrans mixes with special cements and/or chemical admixtures.

4.3 What is the Best Approach for Implementation of the Maturity Method to Meet Caltrans Requirements?

4.3.1.1 Which method should be used to calculate maturity?

- The Nurse-Saul (*TTF*) method provided similar results to the more complex Arrhenius (t_e) method.
- For the mixes considered in this study, the calculation of maturity indexes based on typically assumed values of Activation Energy and Datum Temperature appeared satisfactory.
- The experimental determination of E and T_0 is recommended for "exotic"/special mixes only.

4.3.1.2 How should laboratory calibration be performed?

- It is recommended that calibration be performed at three temperatures spanning the range of potential field temperatures for which the laboratory calibration curve for that mix may be used. The temperatures of 10, 23 and 40ºC spanned the approximate range of temperatures encountered on the three instrumented field projects included in this study. This calibration is necessary to be certain that the maturity assumption is true for the given mix. After sufficient field experience is obtained, it may be possible to reduce the laboratory calibration work to one curing temperature.
- The maturity method assumes that sufficient moisture is available. This should be assumed for a slab. Therefore, laboratory calibration should use specimens cured in 100 percent relative humidity conditions.

4.3.1.3 *How should maturity be measured in the field?*

- In the slab, the maturity meter should be installed close to the shoulder (around 300 mm from the edge), inserted at 50 mm depth.
- The basic requirement of any maturity meter is that it must provide complete temperature history, not just the calculated values of one or more maturity indexes at specific ages. With the complete temperature history, the engineer can verify the calculations, double-check the results, and even alter parameters, guaranteeing a greater control of the process.
- Wireless sensors read with a PDA equipped with an antenna were found by the field researchers to be the most convenient for field use. Sensors that require wires coming from the slab had the wires cut by construction equipment or laborer's tripping over them several times during the study. Several data collection devices left near the slab were damaged by construction equipment or stolen during this study.

4.3.1.4 *Should some beams or cylinders still be tested in the field?*

- Because of the relatively few projects included in this study, and the high cost of failure of pavements or structures if the maturity method were to underestimate concrete strength, it is recommended that a limited number of flexural beams continue to be tested for pavements and compressive cylinders for structures. Once sufficient experience is gained with the maturity method, it is likely that the number of specimens to be tested can be reduced considerably.
- It is recommended that several specimens be cast from the field mix, cured at 23ºC in the laboratory, and tested at several time intervals to confirm that the mix used in the

field has a similar maturity curve to the curve developed from materials submitted by the contractor prior to commencement of construction.

- It is recommended that several specimens be periodically cast and cured in the field. As a check, these specimens should be tested when the critical strength has been estimated to have been achieved in the concrete pavement or structure. Maturity should be measured in these specimens for comparison with the strength predicted from the laboratory curve at same maturity.

4.4 Application of Maturity Method in Field

Based on the experience developed during this work, it is worth highlighting a few important steps that must be considered in the test method for estimating slab strength in the field:

- Beams should be cast and cured in the laboratory at temperatures spanning the range of temperatures expected in the slabs in the field (10, 23 and 40ºC may be a practical range) using materials supplied by the contractor. The results should be combined to develop the laboratory maturity curve. Utilizing a range of temperatures yields a more accurate model for strength prediction.
- Once the plant is operational, beams should be cast and cured in the laboratory at 23ºC, and tested at several time intervals to confirm the laboratory maturity curve.
- The slab should be instrumented in advance, and caution should be taken to avoid misplacement and damage to the temperature meter during concrete placement.
- Several field beams should be cast, field cured, and instrumented for maturity measurement (this requirement may be eliminated later).

- It is recommended that the maturity meter should be installed close to the shoulder, in the upper third of the depth of the slab (“shoulder top” location).
- Recording of temperature history and maturity must be started as soon as the concrete is placed.
- Maturity should be monitored continuously, and the maturity meter must provide the entire temperature history. Time intervals of 30 min. for the initial 48 hours, and 1 hour thereafter, seem appropriate.
- Slab maturity is entered in the laboratory calibrated curve to estimate strength.
- Once the critical strength (typically the opening strength or final strength) is estimated by the maturity method to have been reached, the field cast and cured beams should be tested to confirm the laboratory curve. The field beam maturity must be entered into the laboratory maturity curve, not the slab maturity, for this confirmation.

5.0 FUTURE WORK

In order for the maturity method to become a well established and widely accepted method for flexural strength estimation in concrete pavements, further complementary work could be beneficial. Some important tasks that should be performed include:

1. Validate the Caltrans maturity procedure through monitoring of pilot projects.
2. Develop a database of maturity data for a series of construction projects, and expand the database to include additional mix designs and environmental conditions that were not investigated in this study.
3. Evaluate the effect of moisture in the strength-maturity relationship. The basic assumption of using a laboratory developed maturity curve is that the concrete is properly cured (i.e., moisture is available during hydration). In a field condition, the moisture available depends on location, weather, and curing method and operation. The literature search included in this report indicates that the effect of moisture levels on the strength prediction by the maturity method has not been investigated.
4. Evaluate the effect of maturity on cyclic loading resistance (fatigue). The flexural strength is a static loading parameter. The pavement however, is subjected to a dynamic loading condition and fatigue is one of its potential failure modes. The fatigue life of the early pavement should be considered in relation with the concrete maturity.
5. Develop a new, simpler, and more reasonable procedure to determine the activation energy and datum temperature parameters. The measurement of T_0 and E in the lab is currently based on compressive strength tests only. In addition, measurement of these values is a labor intensive and time consuming process.

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APPENDIX A: LITERATURE REVIEW

Maturity is defined as the extent of cement hydration in a given concrete mixture, as measured by calculating the temperature history of hydration. Cement hydration is an exothermal process in which the temperature development depends on 1) mixture composition, 2) ambient temperatures, 3) moisture, 4) size of structure, and 5) location within structure. The principle of maturity was first laid out 1951, when it was established that "Concrete of the same mix design at the same maturity has approximately the same strength whatever combination of temperature and time go to make up that maturity."(*2*)

The maturity concept originated from the need for a procedure to account for the effects of both time and temperature on strength development, presented in the early works of Nurse (*3*) and Saul (*2*). This concept was developed in a new approach to estimate the in-situ concrete strength development under variable temperatures. The maturity method relies on the measured temperature history of concrete to estimate the strength development during the curing period, when enough moisture is available for cement hydration.(*4*)

Many studies have been performed and good correlation has been obtained between compressive strength and maturity.(*5*) However, the reliability of the maturity method to predict strength has been studied by many researchers and has been controversial, and caution has been recommended for the application of this method.(*4*) Although some researchers have reported good correlation between maturity and compressive strength of concrete, others have questioned the validity of the maturity concept. For example, the maturity concept does not take into consideration the influences of humidity of curing and curing temperature at early ages. Contrary to the assumption made by the maturity concept, these factors have been found to exercise a significant effect on strength development.(*1*)

In summary, one has to be aware of a few important facts:

- Proper selection of a maturity index may be critical for the strength and maturity correlation to be sufficiently unique and independent of the curing temperatures.
- Advances in concrete technology make the materials used today different from those used fifty years ago when the maturity concept was first established. The use of chemical and mineral admixtures in order to achieve the desired workability, high strength, and durability is now routine practice. The exothermal hydration process is further complicated with the chemistry of the material. Thus, the uniqueness of the correlation between maturity and strength needs to be proved for each mix in the laboratory.
- The temperature range in which the correlation between maturity and strength is unique is limited.
- Current understanding of strength development of concrete is now greater than purely empirical observations of age and temperature history. With the help of microscopy technology, new perspectives have been obtained regarding concrete microstructure and its role in strength development. For example, not only the degree of hydration (chemistry) but also the distribution of hydrates (microstructure) plays an important role in strength development.(*6*) This poses the question of whether a concrete will have the same microstructures at a given maturity, but achieved by different curing temperatures.

Use of the Maturity Method to Estimate Flexural Strength

The maturity method has been developed and studied exclusively for determining the compressive strength of concrete, since the tensile strength of the material is usually not a concern for the majority of concrete material applications due to the use of steel reinforcement in structures. For the concrete used in pavements, however, tensile stresses caused by load, thermal deformation and shrinkage determine its performance.

The flexural strength of concrete, usually measured by third point loading tests, is an index for quality control used by Caltrans to determine the acceptable opening time for traffic. To determine an appropriate time to open a pavement to traffic, it is imperative to know the exact time at which concrete has achieved the specified strength. Concrete maturity may be an ideal tool for this purpose due to its simplicity and low cost. For the past decade, the Federal Highway Administration has been encouraging state departments of transportation to evaluate the maturity method and to refine procedures and protocols to fit the individual needs of the states.

Therefore, the primary goal of this research is to study the feasibility of using concrete maturity to estimate the flexural strength development in concrete pavements. Compressive strength has been studied in this research to provide links to previous research on maturity, and to provide information to Caltrans for the implementation of the maturity method for structures.

Procedure

Essentially, the procedure of using the maturity method to predict in-situ strength includes the following steps:

- Selection of a proper method to calculate the maturity index (Nurse-Saul or Arrhenius function).
- Development of the maturity versus strength relationship (curve) under appropriate laboratory conditions.

- Prediction of strength gain in the field based on the relationship developed in the laboratory, assuming the concrete in the field is cured under moisture conditions similar to those used in the laboratory testing.

Calculation of Maturity Indexes

Since the degree of cement hydration depends on both time and temperature, the strength of concrete may be evaluated from the concept of maturity, which is expressed as a function of the time and the temperature of curing. It is assumed that batches of the same concrete mixtures of same maturity will attain the same strength regardless of the time-temperature combinations leading to that maturity.(*1*)

There are basically two accepted methods used to calculate the maturity index: the Nurse-Saul maturity function, used to determine a Time-Temperature Factor (*TTF*), and the Arrhenius equation, used to calculate the Equivalent Age term (t_e). Equation 1 shows the Nurse-Saul maturity function (time-temperature factor):

$$M(t) = \sum (T_a - T_0)\Delta t \qquad \textbf{(1)}$$

Where,
$M(t)$ = temperature-time factor (degree-hours)
Δt = time interval (hours)
T_a = average concrete temperature during interval (ºC)
T_0 = datum temperature (ºC)

This function is simple to use. It assumes that the initial strength gain is a linear function of temperature, but independent of the temperature variation. It applies well only to curing conditions in which the curing temperature does not vary over a wide range. Generally, the datum temperature (T_0) is assumed to be –10ºC (14ºF). The "datum temperature" is the temperature below which there is no strength development in the concrete.

The equivalent age is calculated by the Arrhenius equation (Equation 2):

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

Where,
t_e = equivalent age at specified temperature (hours)
T_a = average temperature of concrete during interval (K)
T_s = specified temperature (K)
Δt = time interval (hours)
Q = activation energy divided by gas constant (E/R)

The Arrhenius equation (Equation 2) overcomes the temperature limitation of Nurse-Saul equation (Equation 1) by using a non-linear relationship between the initial strength gain and curing temperature. Figure A-1 shows a plot of temperature versus age conversion factor (the exponential term in the Arrhenius equation), in order to illustrate the non-linearity of this index as a function of the activation energy value.

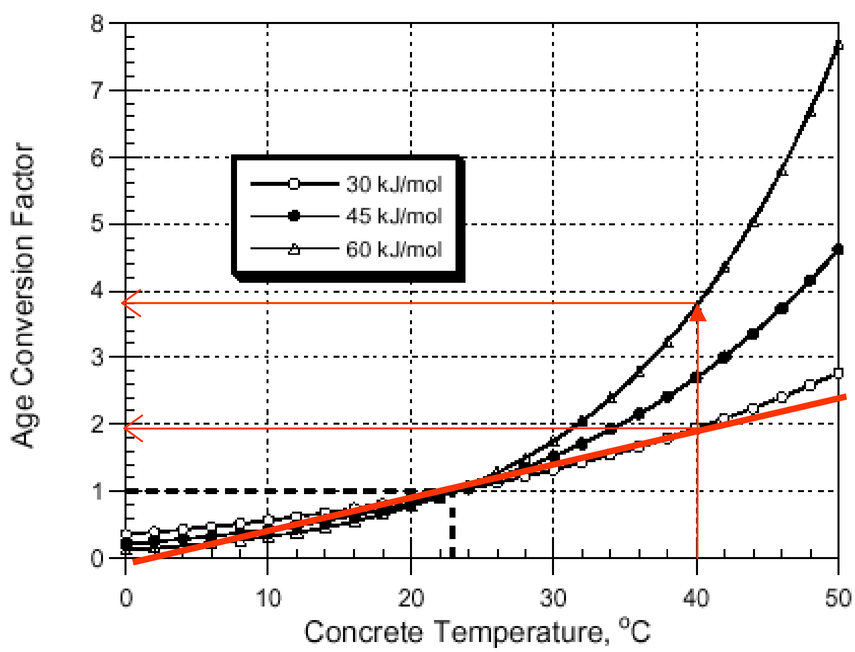

Figure A-1. Concrete temperature versus age conversion factor, for different values of activation energy (*E*).

The key parameter in this equation is the "activation energy" that describes the effect of temperature on the rate of strength development. Typically, in order to determine the maturity index, the Activation Energy (*E*) is assumed to be 48 kJ/mole, however it is important to highlight that this value can vary significantly as a function of concrete mix design parameters, such as water-to-cement ratio, cement type, and chemical and mineral admixtures. For example, activation energies ranging from 30 kJ/mole to 64 kJ/mole have been reported for concretes produced with the same water-to-cement ratios but with different cementitious materials. When necessary, the values of datum temperature and activation energy can be determined experimentally, as discussed in Section.

Experimental Determination of Datum Temperature and Activation Energy

The datum temperature [Nurse-Saul equation (Equation 1)] and activation energy [Arrhenius equation (Equation 2)] can be experimentally determined for a particular concrete mix in order to calculate the maturity indexes.

The idea of "activation energy" was first proposed by Svante Arrhenius in 1888 to explain why chemical reactions do not occur instantaneously when reactants are brought together, even though the reaction products are at a lower energy state than the reactants. Arrhenius proposed that before the lower energy state is achieved, the reactants must have sufficient energy to overcome an energy barrier separating the unreacted and reacted states. A physical analogy is given in Figure A-2. In this "peak and valley" representation, "energy" could be thought of simply as potential energy, with the energy level of each component increasing with height and the chemical reactions proceeding from left to right.

It is simple to visualize the meaning of the Activation Energy term. Even though the products of the reaction are at a lower energy state, the reactants will not react instantaneously:

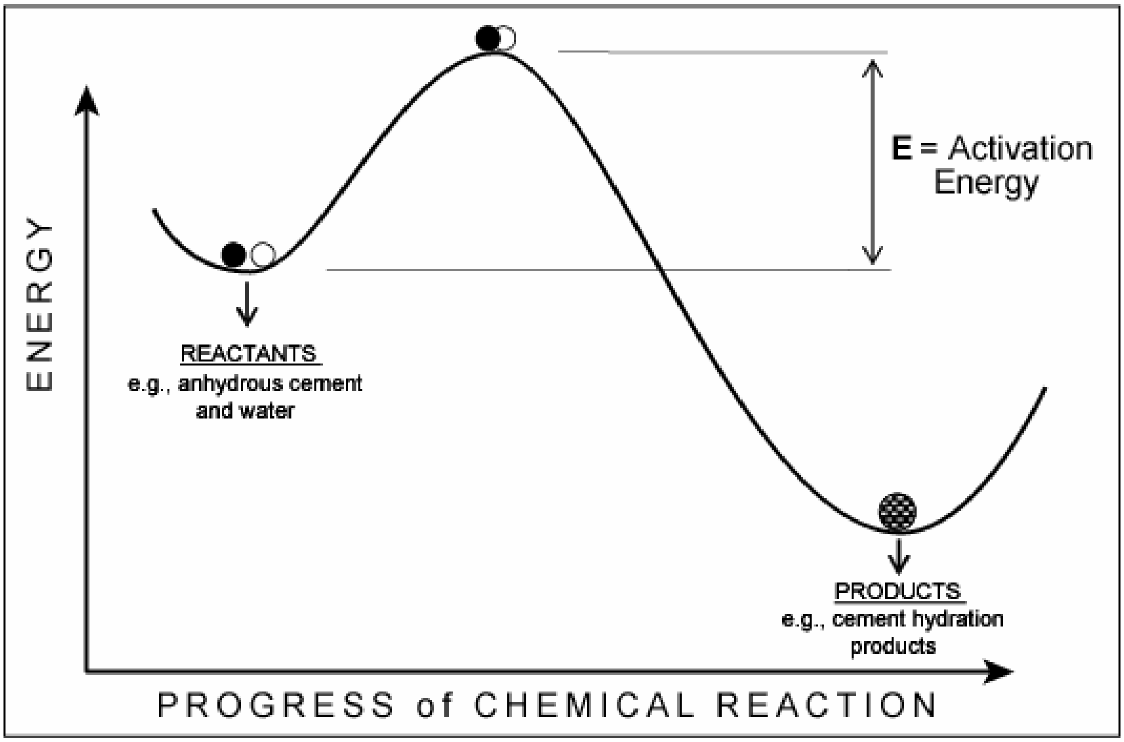

Figure A-2. Peak and valley representation of the concept of Activation Energy.

the activation energy barrier must first be overcome. That is to say that the small balls must be pushed up the hill before they can roll down the slope toward the valley (low energy state) forming the reaction products. Finally, it is important to notice that the height of the activation energy barrier is variable and depends on the particulars of each system.

For molecular systems, for example, the reactant molecules are in constant motion and energy is transferred between them as they collide. A certain number of molecules will acquire sufficient energy to surmount the activation energy barrier and form the lower energy reaction product. As the system is heated by these initial reactions, the kinetic energy of the molecules increases and more molecules will surmount the barrier. Thus the rate of reaction increases with increasing temperature.(*7*)

Carino (*4*) has developed a procedure to obtain the Activation Energy of a given cementitious mixture (this procedure later evolved into ASTM C1074). The procedure is based on determining the effect of curing temperature on the rate constant for strength development. The rate constant is related to the curing time needed to reach a certain fraction of the long-term strength, and can be obtained by fitting an appropriate equation to the strength-versus-age data acquired under constant temperature (isothermal) curing.

Due to the reasons mentioned above, the field work performed by the Partnered Pavement Research Center (detailed in the PPRC Test Plan entitled "Concrete Maturity Method: Implementation and Calibration for Concrete Pavement Application in California") included the experimental determination of activation energies and datum temperatures for each construction site where the maturity method is being evaluated with consideration of mix design (cement type, water-to-cement ratio, and several types and quantities of chemical and mineral admixtures). This work was performed to permit comparison of the maturity indexes calculated from measured and assumed values of E and T_0, and to facilitate an adequate correlation between field and laboratory results.

In summary, the procedure to determine the activation energy in the laboratory includes the following steps:

- Cure mortar specimens at a range of constant temperatures.
- Determine compressive strengths at regular age intervals.
- Determine the value of the "rate constant for strength development" (K) at each temperature by fitting a strength-age relationship to each set of strength-age data.
- Plot the natural logarithms of the rate constants versus the inverse of the curing temperature.

- Determine the best-fit Arrhenius equation to represent the variation of the rate constant with the temperature.

Application of the Maturity Method to Concrete Pavement

The following issues must be considered for the successful application of the maturity method to pavements in California:

1. The strength-maturity correlation must be determined for splitting or flexural tension, instead of, or in conjunction with compressive strength.
2. Mix designs with admixtures must be included.
3. A range of curing temperatures must be included.

The first issue can be considered a requirement because pavements fail by tension, not shear or compression, and there is no relation between tensile and compressive strength that is sufficiently precise when extrapolated across multiple mixes, curing temperatures, or maturities for a given mix.

With regard to the second issue, previous tests have shown good correlation between the strength and maturity for Type I/II Portland cement concrete specimens with minimal or no admixtures. There is very little information available in the literature regarding non-conventional concrete mix designs with large amount of admixtures to achieve special properties in concrete such as high early strength and minimal shrinkage.(*5*) For example, higher content of cementitious materials often develop high temperatures during hydration, and the traditional maturity-strength relationship based on standard cured cylinders does not represent the strength under such accelerated curing conditions.(*8*)

With regard to the third issue, field temperature varies with season and day/night cycles and is far from the constant temperatures at which a maturity curve is developed in the laboratory. Curing temperature may affect early-age temperature development in concrete, and the strength-maturity relationship is no longer unique for one mix.(*4*) Although the strength-maturity relationship is usually assumed to be completely independent of curing temperature, this may not be always the case, as discussed later in this report. While ASTM 1074 does not require multiple curing temperatures (only that the temperature be recorded), the development of a maturity curve calibrated for a range of curing temperatures anticipated in the field may be necessary for some mixes. Data included in this report addresses this issue for the mixes included in the study.

Current Field Application

Because of its simplicity and low cost, the application of the maturity concept has received wide attention as a prospective in-situ testing method for concrete pavements. For example, in a survey reported by Tikalsky et al., 32 states reported conducting research on the use of the maturity method.(*9*) However, at that time, 29 states did not have any protocol, and only four states reported the use of maturity to determine pavement opening times. Although this scenario was rapidly evolving at the time of the survey, it clearly shows that the application of maturity for concrete pavements is indeed very new and a topic of great interest across the country. The application to flexural strength was not identified in the survey, and California may be the first state to consider this extension of the maturity concept.

For the past decade, the Federal Highway Administration has been encouraging state DOTs to evaluate the maturity method and to refine procedures for its application. Among the advantages of the maturity method over the traditional concrete strength tests that justify the growing interest in the method, one could cite 1) the maturity method allows contractors to determine the precise times at which a specified strength is achieved, and 2) the maturity method provides results that could represent the in-situ strength.

Indeed, maturity is a very well established and standardized method, being described by both ASTM 1074-98 (Standard Practice for Estimating Concrete Strength by the Maturity Method) and AASHTO TP 52-95 (Estimating the Strength of Concrete in Transportation Construction by Maturity Tests) standards. However, as discussed previously, the maturity concept was developed based on the determination of compressive strength of conventional concretes made with Type I/II cements with no chemical or mineral admixtures. Recent advances in concrete technology make the material today different from that of fifty years ago.

The strength-maturity correlation has been generally developed for concrete cylinders tested under uniaxial compressive strength, because this is usually the most important strength index for conventional structures. In pavements, where concrete is submitted to bending stresses, flexural strength is the preferred measure for quality control.

The indirect correlation between the concrete maturity and flexural strength has been seen practiced in the field. In some cases, the laboratory established compressive strength versus maturity curve has been used to predict the compressive strength, from which the flexural strength in the field is derived by correlating the compressive (F'_c) and flexural (MR) strength in the lab. However, this relation (F'_c to MR) may have large variability, and changes significantly depending on the mix, age, and other variables.(*10*)

APPENDIX B: MIX PROPORTIONS

Mix #1 – Ludlow

	Content (kg/m3)		Unit proportions	
Cement (Type II/V)	292	390	1.00	0.75
Fly Ash (F)	98			0.25
Sand	648			1.66
Coarse 1 (25 to 4.75mm)	612	1695	4.35	1.57
Coarse 2 (37.5 to 25mm)	435			1.12
Water	161	161	0.41	0.41
Plastocrete 161 (ml) =	920			
AEA 15 (ml) =	447			

Mix #2 – Riverside I

	Content (kg/m3)		Unit proportions	
Cement (Type III)	420	420	1.00	1.00
Fly Ash (F)	0			0.00
Sand	691			1.65
Coarse 1 (25 to 4.75mm)	648	1837	4.37	1.54
Coarse 2 (37.5 to 25mm)	498			1.19
Water	157.8	157.8	0.38	0.38
Recover (ml/m3) =	273			
ADVA (ml/m3)	2184			
Polarset (ml) =	16			

Mix #3 – Riverside II

	Content (kg/m3)		Unit proportions	
Cement (Type II/V)	267	356	1.00	0.75
Fly Ash (F)	89			0.25
Sand	719			2.02
Coarse 1 (25 to 4.75mm)	485	1797	5.05	1.36
Coarse 2 (37.5 to 25mm)	593			1.67
Water	170	170	0.48	0.48
AEA 15 (ml) =	273			

Mix #4 – Victorville

	Content (kg/m3)		Unit proportions	
Cement (Type II/V)	252	336	1.00	0.75
Fly Ash (F)	84			0.25
Sand	726			2.16
Coarse 1 (25 to 4.75mm)	1057	1783	5.31	3.15
Coarse 2 (37.5 to 19mm)	0			0.00
Water	158	158	0.47	0.47
Pave Air (oz./cu. yd.)	8			
Masterpave (oz./cu. yd.)	22			

UC Berkeley Mixing Data Sheet										
Project Name:	Date	Time	Temperature (^{o}C)				Relative Humidity (%)	Slump (mm)	Unit Weight (kg/m^3)	Air Content (%)
			Air	Aggregate	Water	Mix				
Ludlow (I-40)	9/27/2002	4:25 p.m	25	25	15	20	--	50.8	2246	5.5
Riverside (SR-91)_FCI	1/13/2003	4:00 p.m	14.5	14.6	14	19	--	101.6	2415	
Riverside (SR-91)_Brutoco	11/12/2002	3:30 p.m	18	18	15	19	--	50.8	2323	2
Victorville (I-15)	9/25/2003	12:30 p.m	19	19	16	19	--	50.8	2277	
Baker (I-15)							--			
Mixing Superviser:										
Comments:										

APPENDIX C: TEST DATA AND ANALYSES

Contents

Appendix C1: Activation Energy (E) and Datum Temperature (T_0) Determination

Table C1-1 Activation Energy and Datum Temperature Determination, Mix #1 – Ludlow

COLD Curing					
Su =	38.91		**T (ºC) =**	8.5	
k =	0.298		**T (K) =**	281.5	
ln k =	-1.210661792		**1/T(K) =**	0.0036	
Age (h)	**Age (days)**	1/age	**fc (MPa)**	1/fc	A
24	**1.0**	1.000	**3.79**	0.264	0.108
48	**2.0**	0.500	**11.84**	0.084	0.438
96	**4.0**	0.250	**19.57**	0.051	1.012
192	**8.0**	0.125	**26.89**	0.037	2.237
384	**16.0**	0.063	**29.11**	0.034	-
768	**32.0**	0.031	**36.09**	0.028	-
STANDARD Curing					
Su =	33.00		**T (ºC) =**	23	
k =	0.5259		**T (K) =**	296	
ln k =	-0.642644198		**1/T(K) =**	0.0034	
Age (h)	**Age (h)**	1/age	**fc (MPa)**	1/fc	A
13	**0.5**	1.920	**4.13**	0.242	0.143
25	**1.0**	0.960	**11.90**	0.084	0.564
50	**2.1**	0.480	**18.05**	0.055	1.208
100	**4.2**	0.240	**22.38**	0.045	2.106
200	**8.3**	0.120	**27.71**	0.036	-
400	**16.7**	0.060	**30.20**	0.033	-
HOT Curing					
Su =	30.03		**T (ºC) =**	40	
k =	1.0565		**T (K) =**	313	
ln k =	0.054961558		**1/T(K) =**	0.0032	
Age (h)	**Age (h)**	1/age	**fc (MPa)**	1/fc	A
7	**0.3**	3.692	**4.02**	0.249	0.154
13	**0.5**	1.846	**9.18**	0.109	0.440
26	**1.1**	0.923	**7.93**	0.126	0.359
52	**2.2**	0.462	**17.13**	0.058	1.327
104	**4.3**	0.231	**24.40**	0.041	-
220	**9.2**	0.109	**27.08**	0.037	-

Table C1-2 Activation Energy and Datum Temperature Determination, Mix #2 – Riverside I

STANDARD Curing					
Su =	64.10		**T (ºC) =**	8.5	
k =	0.9184		**T (K) =**	281.5	
ln k =	-0.085122253		**1/T(K) =**	0.0036	
Age (h)	**Age (days)**	1/age	**fc (MPa)**	1/fc	A
8.58	**0.36**	2.796	**3.93**	0.254	0.065
17.17	**0.72**	1.398	**20.63**	0.048	0.474
34.33	**1.43**	0.699	**33.67**	0.030	1.106
68.67	**2.86**	0.350	**45.22**	0.022	2.394
137.33	**5.72**	0.175	**52.14**	0.019	-
274.67	**11.44**	0.087	**57.20**	0.017	-

HOT Curing					
Su =	69.93		**T (ºC) =**	23	
k =	1.0378		**T (K) =**	296	
ln k =	0.037103088		**1/T(K) =**	0.0034	
Age (h)	**Age (d)**	1/age	**fc (MPa)**	1/fc	A
6.50	**0.27**	3.692	**4.33**	0.231	0.066
13.00	**0.54**	1.846	**24.30**	0.041	0.533
26.00	**1.08**	0.923	**29.69**	0.034	0.738
52.00	**2.17**	0.462	**47.52**	0.021	2.120
104.00	**4.33**	0.231	**54.07**	0.018	-
208.00	**8.67**	0.115	**54.64**	0.018	-

COLD Curing					
Su =	52.91		**T (ºC) =**	40	
k =	1.1836		**T (K) =**	313	
ln k =	0.168560642		**1/T(K) =**	0.0032	
Age (h)	**Age (d)**	1/age	**fc (MPa)**	1/fc	A
14.50	**0.60**	1.655	**3.98**	0.251	0.081
29.00	**1.21**	0.828	**21.80**	0.046	0.701
58.00	**2.42**	0.414	**36.41**	0.027	2.207
116.00	**4.83**	0.207	**47.27**	0.021	8.380
232.00	**9.67**	0.103	**48.80**	0.020	-
464.00	**19.33**	0.052	**47.45**	0.021	-

Table C1-3 Activation Energy and Datum Temperature Determination, Mix #3 – Riverside II and Mix #4 – Victorville

STANDARD Curing					
Su =	58.82		**T (ºC) =**	23	
k =	0.6924		**T (K) =**	296	
ln k =	-0.367591456		**1/T(K) =**	0.0034	
Age (h)	**Age (d)**	1/age	**fc (MPa)**	1/fc	A
11.25	**0.47**	2.133	**4.24**	0.236	0.078
22.5	**0.94**	1.067	**13.10**	0.076	0.287
45.0	**1.88**	0.533	**24.48**	0.041	0.713
90.0	**3.75**	0.267	**34.26**	0.029	1.395
180.0	**7.50**	0.133	**43.78**	0.023	-
360.0	**15.00**	0.067	**54.04**	0.019	-
HOT Curing					
Su =	59.17		**T (ºC) =**	40	
k =	0.7090		**T (K) =**	313	
ln k =	-0.343899752		**1/T(K) =**	0.0032	
Age (h)	**Age (d)**	1/age	**fc (MPa)**	1/fc	A
6.75	**0.28**	3.556	**5.48**	0.182	0.102
13.5	**0.56**	1.778	**15.94**	0.063	0.369
27.0	**1.13**	0.889	**25.08**	0.040	0.736
54.0	**2.25**	0.444	**35.72**	0.028	1.524
108.0	**4.50**	0.222	**44.82**	0.022	-
216.0	**9.00**	0.111	**49.44**	0.020	-
COLD Curing					
Su =	36.90		**T (ºC) =**	8.5	
k =	0.4		**T (K) =**	281.5	
ln k =	-0.916290732		**1/T(K) =**	0.0036	
Age (h)	**Age (d)**	1/age	**fc (MPa)**	1/fc	A
20.5	**0.85**	1.171	**5.02**	0.199	0.157
41.0	**1.71**	0.585	**13.99**	0.071	0.611
82.0	**3.42**	0.293	**24.19**	0.041	1.904
164.0	**6.83**	0.146	**22.33**	0.045	1.533
328.0	**13.67**	0.073	**23.70**	0.042	-
656.0	**27.33**	0.037	**34.64**	0.029	-

Data Used to Prepare Tables C1-1 through C1-3.

Mix #1 – Ludlow

COLD Curing									
Cast on:	***Mon***	***7/1/02 4:00 PM***							
Tested Date	**Time**	**Age (hours)**	**Age (days)**		**A**	**B**	**C**	**Average**	**Std. Dev.**
Tue	**7/2/02 4:00 PM**	**24**	**1**	Load (kN)	10.12	10.23	9.03	9.79	0.66
				fc (psi)	568.57	574.75	507.33	**550.21**	37.27
				fc (MPa)	3.92	3.96	3.50	**3.79**	0.26
Wed	**7/3/02 4:00 PM**	**48**	**2**	Load (kN)	30.14	32.18	29.41	30.58	1.44
				fc (psi)	1693.34	1807.95	1652.33	**1717.87**	80.66
				fc (MPa)	11.67	12.47	11.39	**11.84**	0.56
Fri	**7/5/02 4:00 PM**	**96**	**4**	Load (kN)	50.67	50.37	50.52	50.52	0.15
				fc (psi)	2846.77	2829.91	2838.34	**2838.34**	8.43
				fc (MPa)	19.63	19.51	19.57	**19.57**	0.06
Tue	**7/9/02 4:00 PM**	**192**	**8**	Load (kN)	62.13	77.15	68.97	69.42	7.52
				fc (psi)	3490.62	4334.48	3874.90	**3900.00**	422.49
				fc (MPa)	24.07	29.88	26.72	**26.89**	2.91
Wed	**7/17/02 4:00 PM**	**384**	**16**	Load (kN)	73.68	71.95	79.85	75.16	4.15
				fc (psi)	4139.52	4042.33	4486.17	**4222.67**	233.31
				fc (MPa)	28.54	27.87	30.93	**29.11**	1.61
Fri	**8/2/02 4:00 PM**	**768**	**32**	Load (kN)	95.21	95.43	88.86	93.17	3.73
				fc (psi)	5349.13	5361.49	4992.37	**5234.33**	209.63
				fc (MPa)	36.88	36.97	34.42	**36.09**	1.45

STANDARD Curing									
Cast on:	***Tue***	***7/9/02 8:30 AM***							
Tested Date	**Time**	**Age (hours)**	**Age (days)**		**A**	**B**	**C**	**Average**	**Std. Dev.**
Tue	**7/9/02 9:00 PM**	**12.5**	**0.5**	Load (kN)	10.91	10.73	10.31	10.65	0.31
				fc (psi)	612.95	602.84	579.24	**598.34**	17.30
				fc (MPa)	4.23	4.16	3.99	**4.13**	0.12
Tue	**7/10/02 9:30 AM**	**25.0**	**1.0**	Load (kN)	28.31	34.61	29.26	30.73	3.40
				fc (psi)	1590.53	1944.48	1643.90	**1726.30**	190.82
				fc (MPa)	10.97	13.41	11.33	**11.90**	1.32
Thu	**7/11/02 10:30 AM**	**50.0**	**2.1**	Load (kN)	48.29	44.44	47.09	46.61	1.97
				fc (psi)	2713.05	2496.75	2645.63	**2618.48**	110.68
				fc (MPa)	18.71	17.21	18.24	**18.05**	0.76
Sat	**7/13/02 12:30 PM**	**100.0**	**4.2**	Load (kN)	61.96	57.33	54.03	57.77	3.98
				fc (psi)	3481.07	3220.94	3035.54	**3245.85**	223.81
				fc (MPa)	24.00	22.21	20.93	**22.38**	1.54
Wed	**7/17/02 4:30 PM**	**200.0**	**8.3**	Load (kN)	74.11	65.25	75.25	71.54	5.47
				fc (psi)	4163.68	3665.91	4227.73	**4019.11**	307.55
				fc (MPa)	28.71	25.28	29.15	**27.71**	2.12
Fri	**7/26/02 12:30 AM**	**400.0**	**16.7**	Load (kN)	78.40	80.53	74.95	77.96	2.82
				fc (psi)	4404.71	4524.37	4210.88	**4379.99**	158.20
				fc (MPa)	30.37	31.19	29.03	**30.20**	1.09

HOT Curing									
Cast on:	***Tue 8/20/02 8:30 AM***								
Tested		**Age**	**Age**		**A**	**B**	**C**	**Average**	**Std. Dev.**
Date	**Time**	**(hours)**	**(days)**						
Tue	**8/20/02 3:00 PM**	**6.50**	**0.3**	Load (kN)	10.39	10.11	10.61	10.37	0.25
				fc (psi)	583.45	567.72	596.10	**582.42**	14.21
				fc (MPa)	4.02	3.91	4.11	**4.02**	0.10
Tue	**8/20/02 9:30 PM**	**13.00**	**0.5**	Load (kN)	22.67	23.43	25.02	23.71	1.20
				fc (psi)	1273.66	1316.36	1405.69	**1331.90**	67.37
				fc (MPa)	8.78	9.08	9.69	**9.18**	0.46
Wed	**8/21/02 10:30 AM**	**26.00**	**1.1**	Load (kN)	20.05	21.30	20.05	20.47	0.72
				fc (psi)	1126.46	1196.69	1126.46	**1149.87**	40.55
				fc (MPa)	7.77	8.25	7.77	**7.93**	0.28
Thu	**8/22/02 12:30 PM**	**52.00**	**2.2**	Load (kN)	39.07	41.84	51.74	44.22	6.66
				fc (psi)	2195.05	2350.67	2906.88	**2484.20**	374.23
				fc (MPa)	15.13	16.21	20.04	**17.13**	2.58
Sat	**8/24/02 4:30 PM**	**104.00**	**4.3**	Load (kN)	63.69	63.44	61.85	62.99	1.00
				fc (psi)	3578.26	3564.22	3474.89	**3539.12**	56.07
				fc (MPa)	24.67	24.57	23.96	**24.40**	0.39
Wed	**8/29/02 12:30 PM**	**220.00**	**9.2**	Load (kN)	71.68	68.80	69.22	69.90	1.56
				fc (psi)	4027.16	3865.35	3888.95	**3927.15**	87.41
				fc (MPa)	27.77	26.65	26.81	**27.08**	0.60

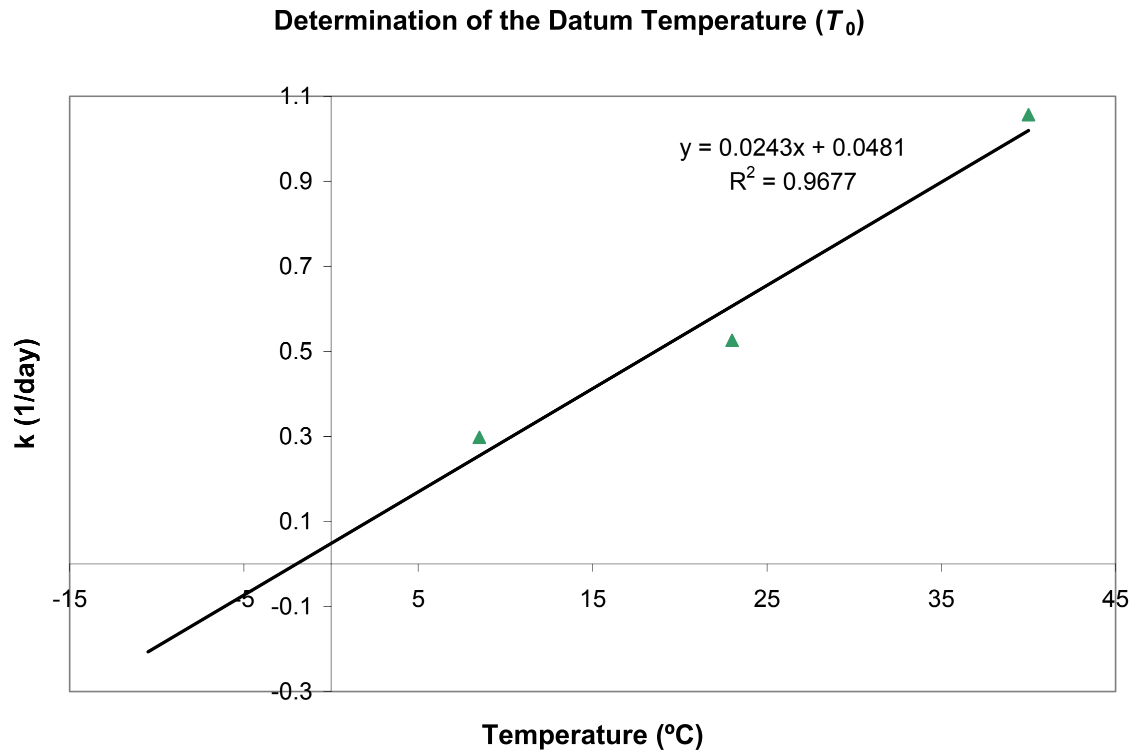

Figure C1-1. Determination of datum temperature (T_0) for Mix #1, Ludlow.

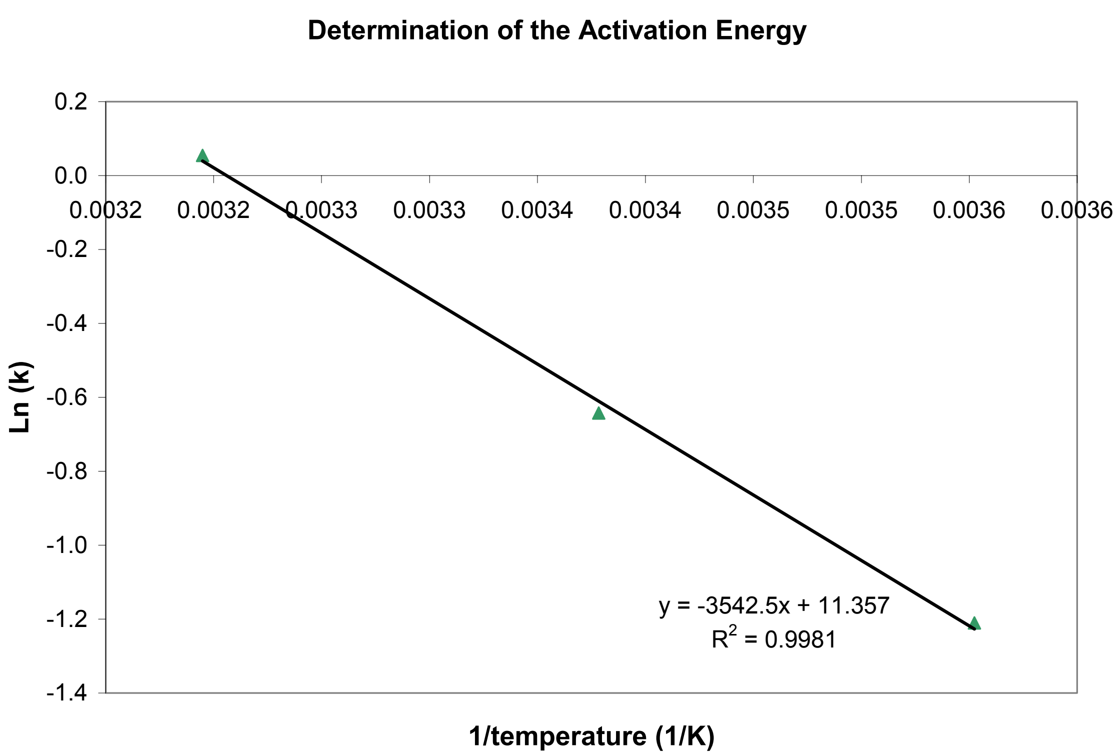

Figure C1-2. Determination of activation energy (E) for Mix #1, Ludlow.

Mix # 2 – Riverside I

STANDARD TEMPERATURE

Time to reach 4 MPa (h): **8:35**

Test #	Age (hours)	Test Date and Time:	Strength		
MIX	0	12:00 PM	lbs	psi	MPa
1st	8h35min	8:35 PM	2160	540	3.72
			2400	600	4.14
			2280	**570**	**3.93**
2nd	17h10min	5:10 AM	12200	3050	21.03
			12100	3025	20.86
			11600	2900	19.99
			11967	**2992**	**20.63**
3rd	34h20min	10:20 PM	20350	5088	35.08
			19000	4750	32.75
			19250	4813	33.18
			19533	**4883**	**33.67**
4th	68h40min	8:40 AM	27200	6800	46.88
			25000	6250	43.09
			26500	6625	45.68
			26233	**6558**	**45.22**
5th	137h20min	5:20 AM	30050	7513	51.80
			31600	7900	54.47
			29100	7275	50.16
			30250	**7563**	**52.14**
6th	274h40min	10:40 PM	34450	8613	59.38
			31600	7900	54.47
			33500	8375	57.74
			33183	**8296**	**57.20**

HOT TEMPERATURE

Time to reach 4 MPa (h): **6:30**

	Age (hours)	Test Date and Time:	Strength		
MIX	0	10:30 AM	lbs	psi	MPa
1st	6h30min	5:00 PM	2460	615	4.24
			2560	640	4.41
			2510	**627.5**	**4.33**
2nd	13h00min	11:30 PM	14000	3500	24.13
			13900	3475	23.96
			14400	3600	24.82
			14100	**3525**	**24.30**
3rd	26h00min	12:30 PM	21000	4957	34.18
			22000	5193	35.81
			13500	3375	23.27
			14800	3700	25.51
			17825	**4306.389**	**29.69**
4th	52h00min	2:30 PM	26800	6700	46.19
			28800	7200	49.64
			27100	6775	46.71
			27567	**6892**	**47.52**
5th	208h00min	6:30 PM	32450	8113	55.93
			31150	7788	53.69
			30500	7625	52.57
			31367	**7842**	**54.07**
6th	416h00min	2:30 AM	31800	7950	54.81
			31600	7900	54.47
			31700	**7925**	**54.64**

COLD TEMPERATURE

Time to reach 4 MPa (h): **14:30**

	Age (hours)	Test Date and Time:	Test Date and Time:	Strength		
MIX	**0**	**11/13/03 18:00**	**12/9/03 8:30**	**lbs**	**psi**	**MPa**
1st	**14h30min**	**11/14/03 8:30**	**12/9/03 23:00**	2338.01	584.50	4.03
				2343.81	585.95	4.04
				2239.38	559.85	3.86
				2307.07	**576.77**	**3.98**
2nd	**29h00min**	**11/14/03 23:00**	**12/10/03 13:30**	12130.95	3032.74	20.91
				12502.25	3125.56	21.55
				13302.86	3325.71	22.93
				12645.35	**3161.34**	**21.80**
3rd	**58h00min**	**11/16/03 4:00**	**12/11/03 18:30**	21390.16	5347.54	36.87
				21343.75	5335.94	36.79
				20641.77	5160.44	35.58
				21125.22	**5281.31**	**36.41**
4th	**116h00min**	**11/18/03 14:00**	**12/14/03 4:30**	19218.34	4804.58	33.13
				27272.55	6818.14	47.01
				27573.96	6893.49	47.53
				27423.25	**6855.81**	**47.27**
5th	**232h00min**	**11/23/03 10:00**	**12/19/03 0:30**	25414.14	6353.54	43.81
				30413.72	7603.43	52.42
				29107.35	7276.84	50.17
				28311.74	**7077.93**	**48.80**
6th	**464h00min**	**12/3/03 2:00**	**12/28/03 16:30**	28438.99	7109.75	49.02
				26971.21	6742.80	46.49
				27174.26	6793.57	46.84
				27528.16	**6882.04**	**47.45**

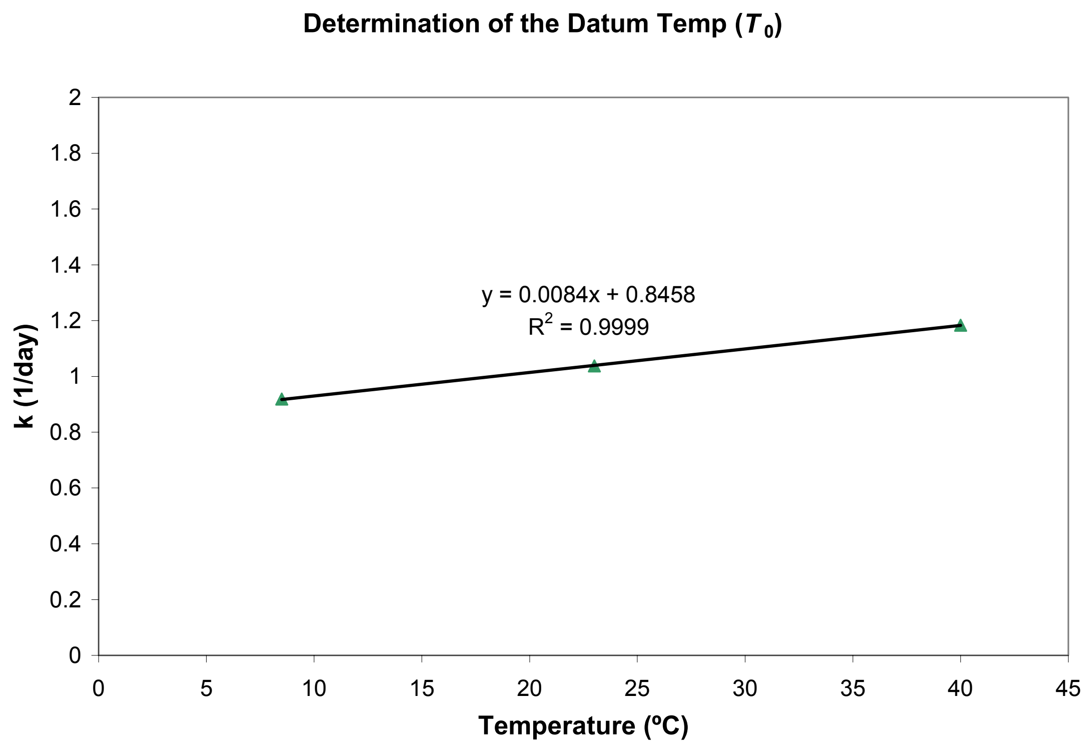

Figure C1-3. Determination of datum temperature (T_0) for Mix #2, Riverside.

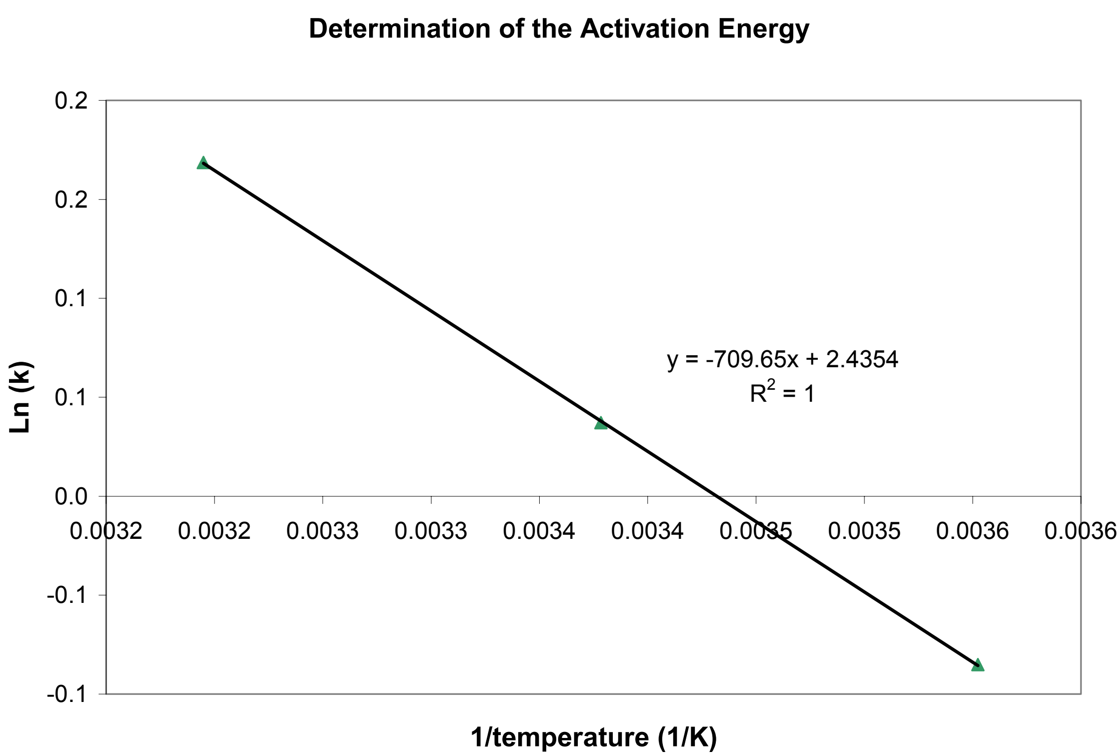

Figure C1-4. Determination of activation energy (E) for Mix #2, Riverside.

Mix # 3 and #4 – Victorville

STANDARD TEMPERATURE

Time to reach 4 MPa (h): **11:15**

Test #	Age (hours)	Test Date and Time:	Strength		
MIX	**0**	**11:00 AM**	**lbs**	**psi**	**MPa**
1st	**11h15min**	**10:15 PM**	2460	615	4.24
			2460	**615**	**4.24**
2nd	**22h30min**	**9:30 AM**	7200	1800	12.41
			8000	2000	13.79
			7600	**1900**	**13.10**
3rd	**45h00min**	**8:00 AM**	14500	3625	24.99
			13900	3475	23.96
			14200	**3550**	**24.48**
4th	**90h00min**	**5:00 AM**	19850	4962.5	34.22
			19900	4975	34.30
			19875	**4968.75**	**34.26**
5th	**180h00min**	**11:00 PM**	25400	6350	43.78
			25400	**6350**	**43.78**

HOT TEMPERATURE

Time to reach 4 MPa (h): **6:45**

	Age (hours)	Test Date and Time:	Strength		
MIX	**0**	**11:15 AM**	**lbs**	**psi**	**MPa**
1st	**6h45min**	**6:00 PM**	3080	770	5.31
			3280	820	5.65
			3180	**795**	**5.48**
2nd	**13h30min**	**12:45 AM**	9250	2312.5	15.94
			9250	2312.5	15.94
			9250	**2312.5**	**15.94**
3rd	**27h00min**	**2:15 PM**	14000	3500	24.13
			15100	3775	26.03
			14550	**3637.5**	**25.08**
4th	**54h00min**	**5:15 PM**	20850	5212.5	35.94
			20600	5150	35.51
			20725	**5181.25**	**35.72**
5th	**108h00min**	**11:15 PM**	25850	6462.5	44.56
			26150	6537.5	45.07
			26000	**6500**	**44.82**
6th	**216h00min**	**11:15 AM**	29100	7275	50.16
			27200	6800	46.88
			29750	7438	51.28
			28683	**7171**	**49.44**

COLD TEMPERATURE

Time to reach 4 MPa (h): **21:00**

	Age (hours)	Test Date and Time:	Test Date and Time:	Strength		
MIX	**0**	**11/13/03 17:30**	**12/8/03 17:15**	**lbs**	**psi**	**MPa**
1st	**21h00min**	**11/14/03 14:30**	**12/9/03 14:15**	2860.14	715.04	4.93
				2894.95	723.74	4.99
				2976.17	744.04	5.13
				2910.42	**727.61**	**5.02**
2nd	**42h00min**	**11/15/03 11:30**	**12/10/03 11:15**	7878.45	1969.61	13.58
				8464.40	2116.10	14.59
				8011.88	2002.97	13.81
				8118.24	**2029.56**	**13.99**
3rd	**84h00min**	**11/17/03 5:30**	**12/12/03 5:15**	14463.16	3615.79	24.93
				13616.14	3404.03	23.47
				14028.05	3507.01	24.18
				14035.78	**3508.95**	**24.19**
4th	**168h00min**	**11/20/03 17:30**	**12/15/03 17:15**	12297.20	3074.30	21.20
				14527.38	3631.84	25.04
				12046.13	3011.53	20.76
				12956.90	**3239.23**	**22.33**
5th	**336h00min**	**11/27/03 17:30**	**12/22/03 17:15**	7077.35	1769.34	12.20
				13330.25	3332.56	22.98
				14170.89	3542.72	24.43
				13750.57	**3437.64**	**23.70**
6th	**672h00min**	**12/11/03 17:30**	**1/5/04 17:15**	22022.52	5505.63	37.96
				19585.89	4896.47	33.76
				18686.66	4671.66	32.21
				20098.36	**5024.59**	**34.64**

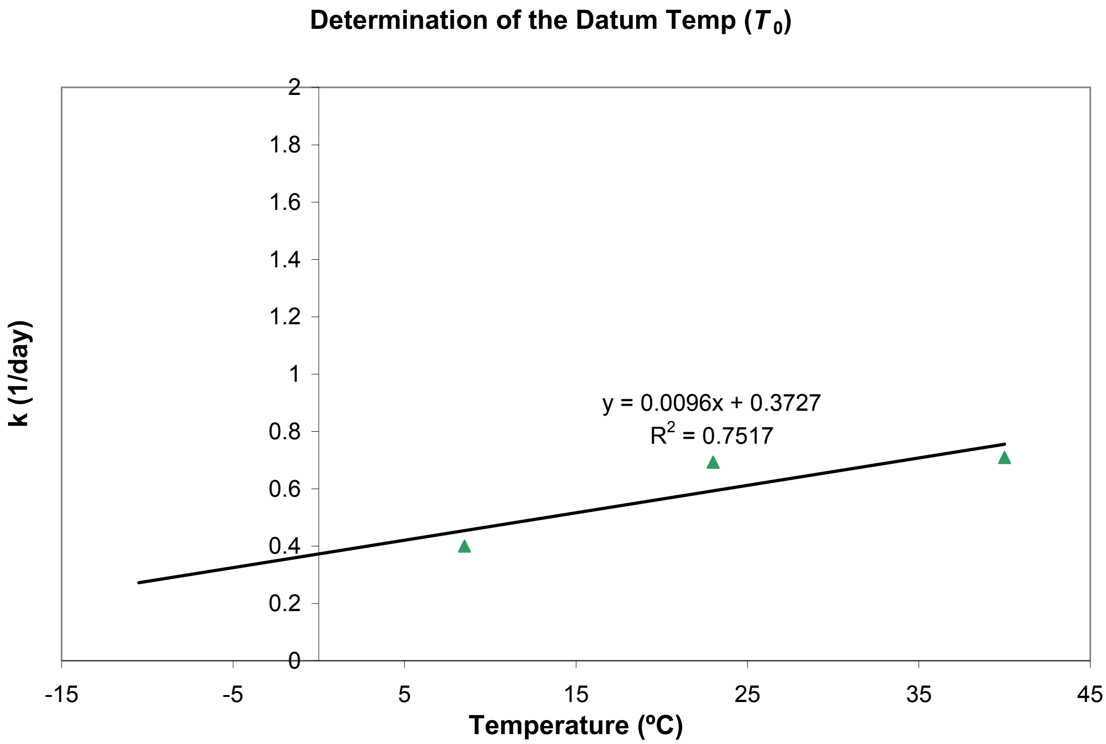

Figure C1-5. Determination of datum temperature (T_0) for Mix #3, Riverside, and Mix #4, Victorville.

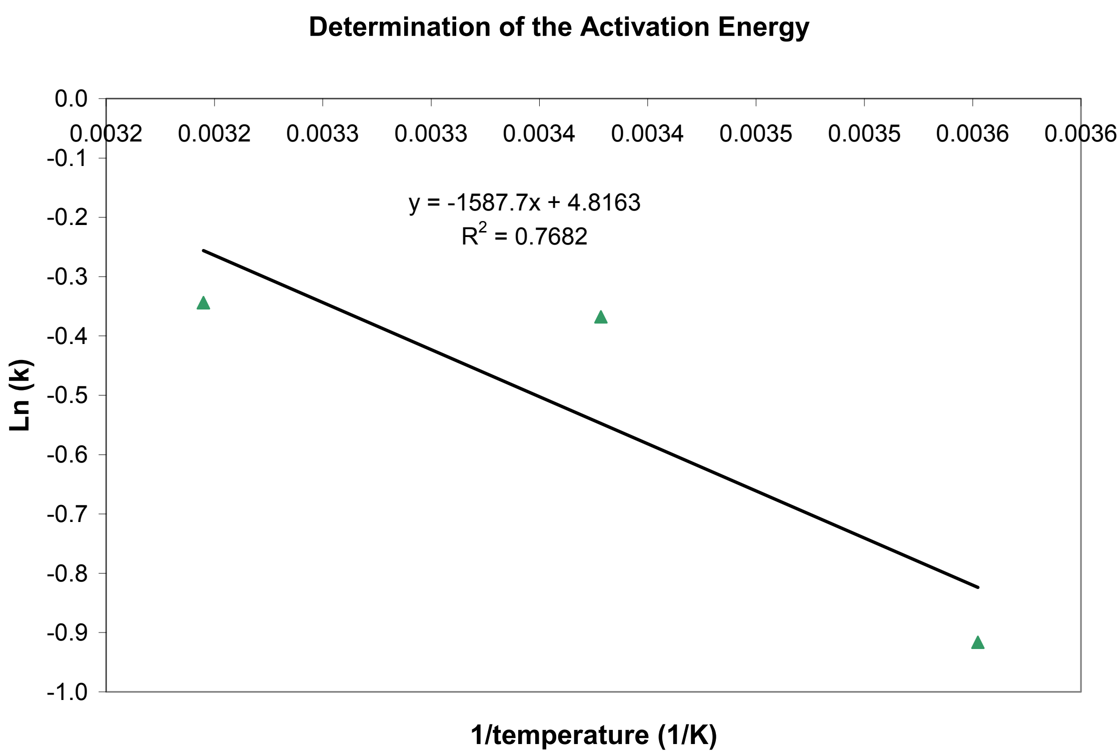

Figure C1-6. Determination of activation energy (*E*) for Mix #3, Riverside, and Mix #4, Victorville.

Appendix C2: Correlations between Compressive and Flexural Strengths and Different Measures of Maturity

Figure C2-1 shows the organization of the work performed to develop strength versus maturity relationships for each of the four mixes. Figure C2-1 also serves as a key to the figures presented in the rest of this appendix—each figure number has an extension letter (a-h) which corresponds to the figure letter in the right side of Figure C2-1.

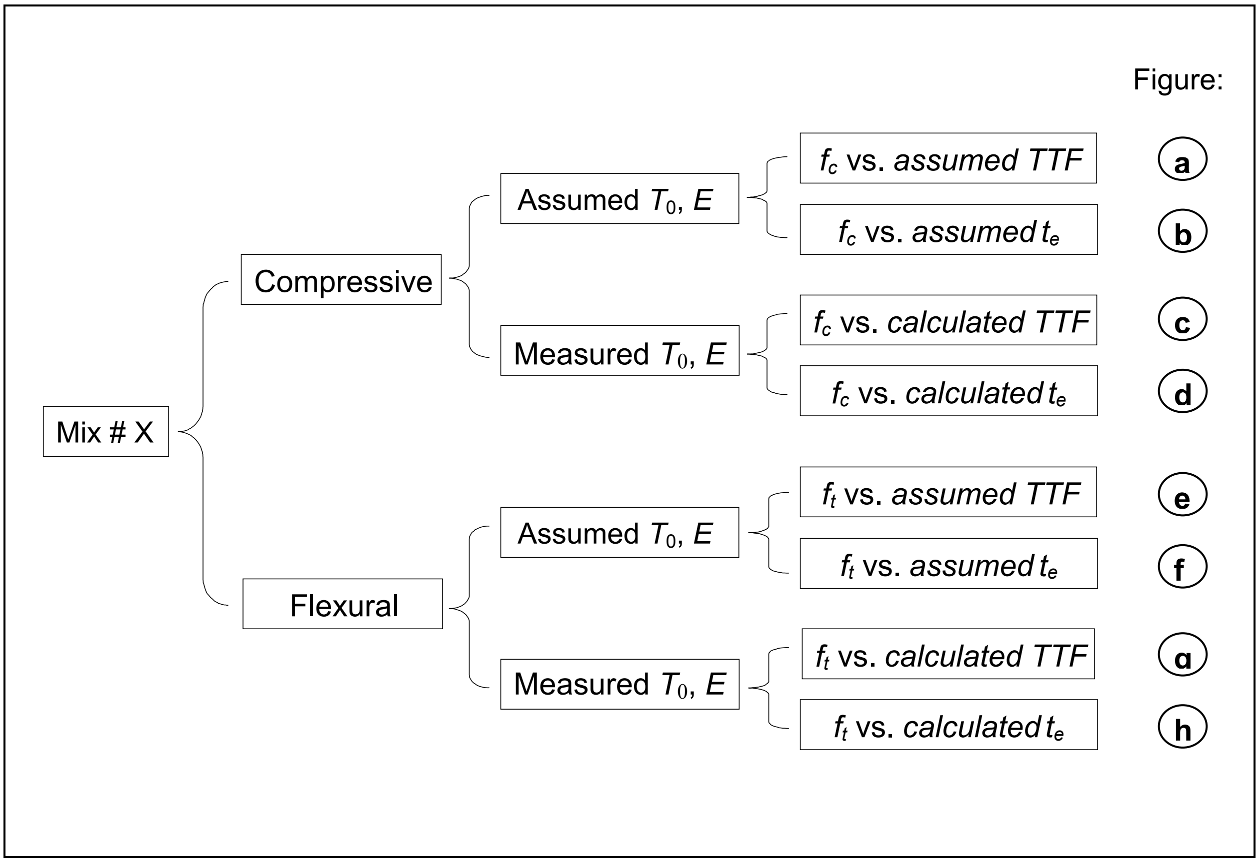

Figure C2-1. Schematic of work performed and resulting relationships.

This section contains strength versus maturity relationships based on: 1) combining data from all curing temperatures; and 2) data based on individual curing temperatures.

<u>Strength-Maturity Relationships – Data Combined from All Curing Temperatures.</u>

Mix #1 – Ludlow Compressive Strength versus Maturity

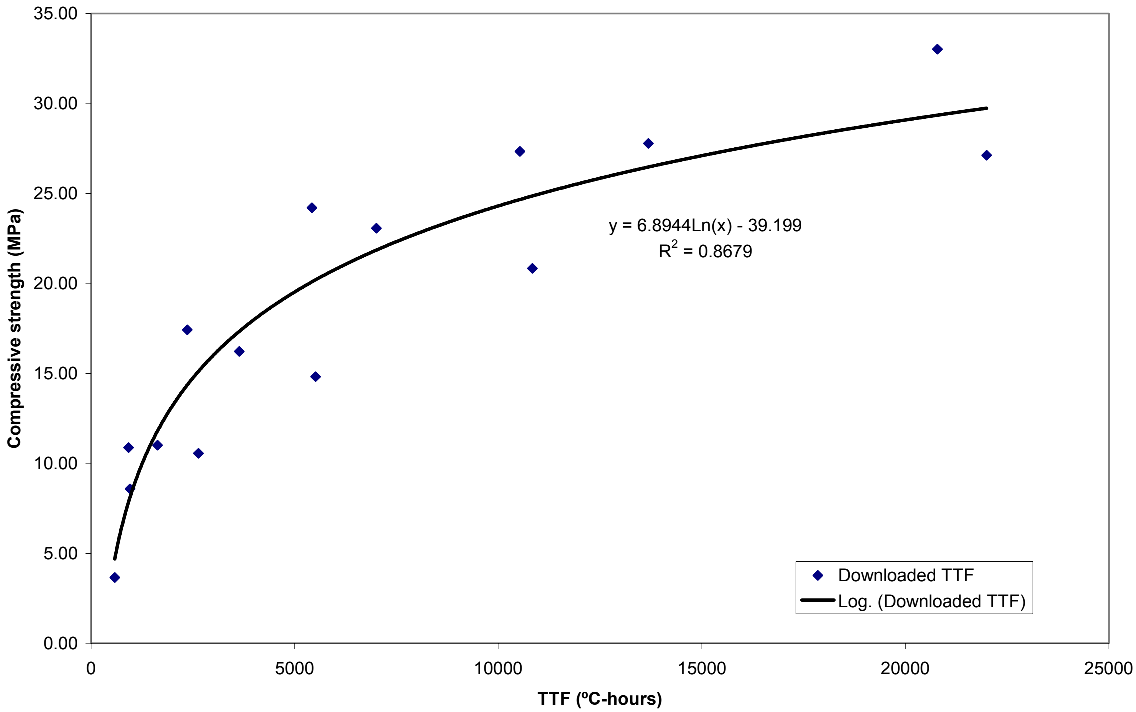

Figure C2-2a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #1, laboratory cylinders).

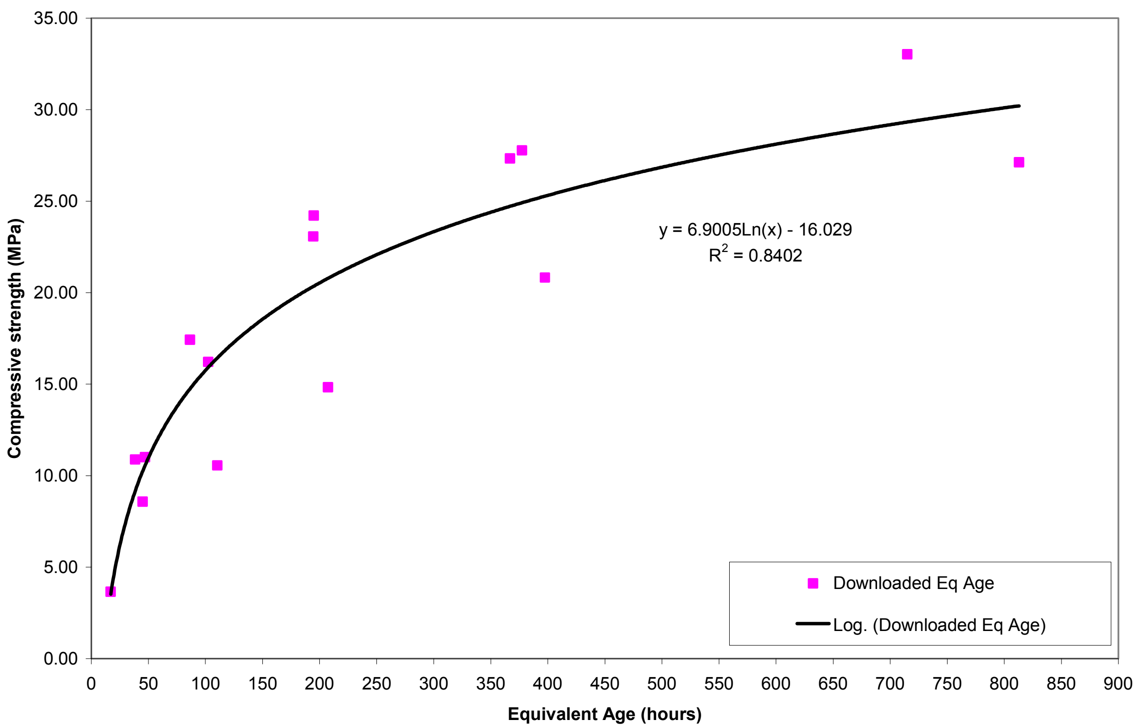

Figure C2-2b. Correlation between compressive strength and t_e, assumed *E* (Mix #1, laboratory cylinders).

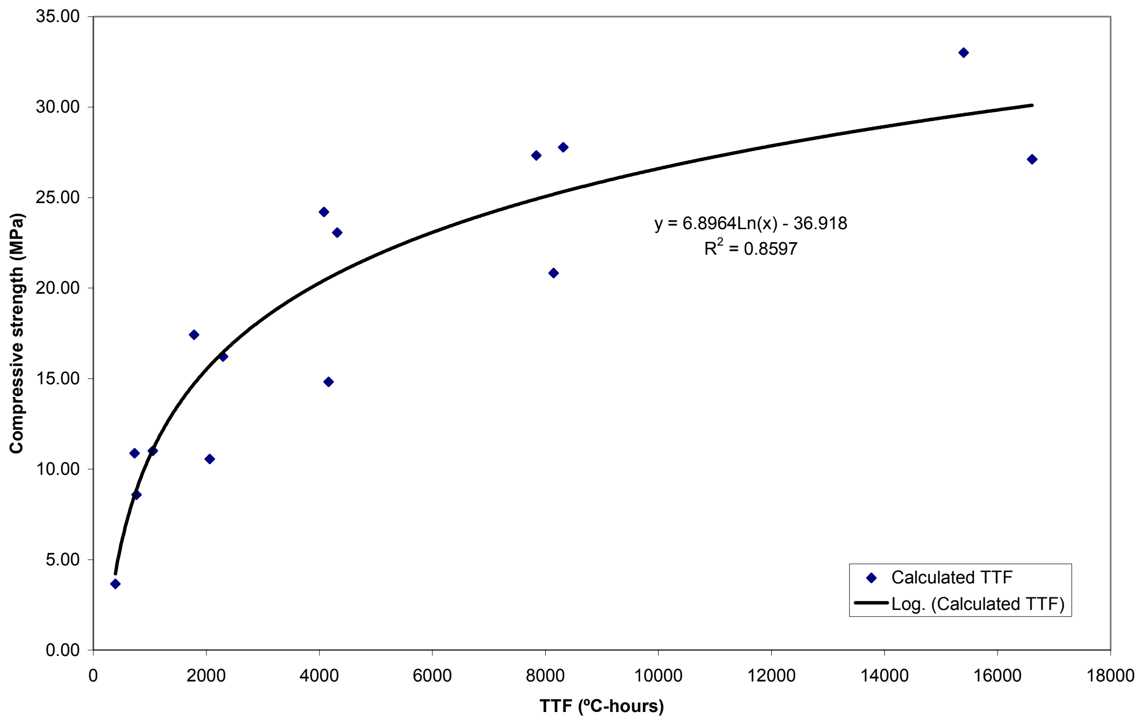

Figure C2-2c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 1, laboratory cylinders).

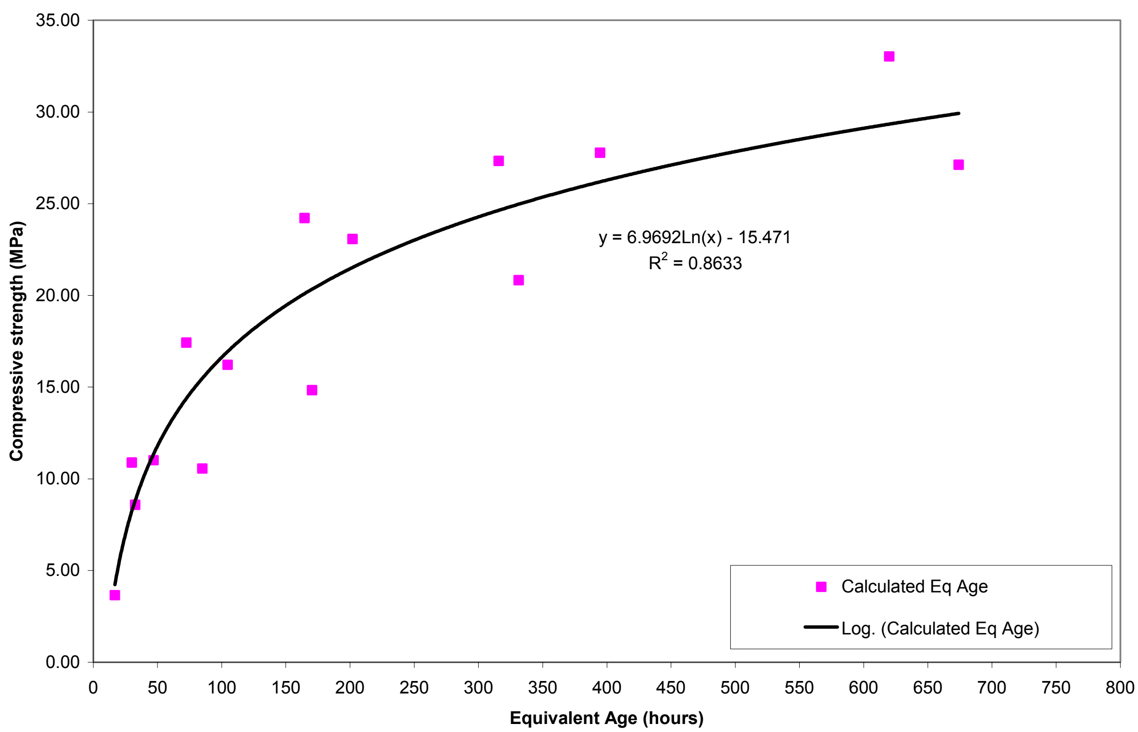

Figure C2-2d. Correlation between compressive strength and t_e, measured *E*, (Mix # 1, laboratory cylinders).

Mix #1 – Ludlow Flexural Strength versus Maturity

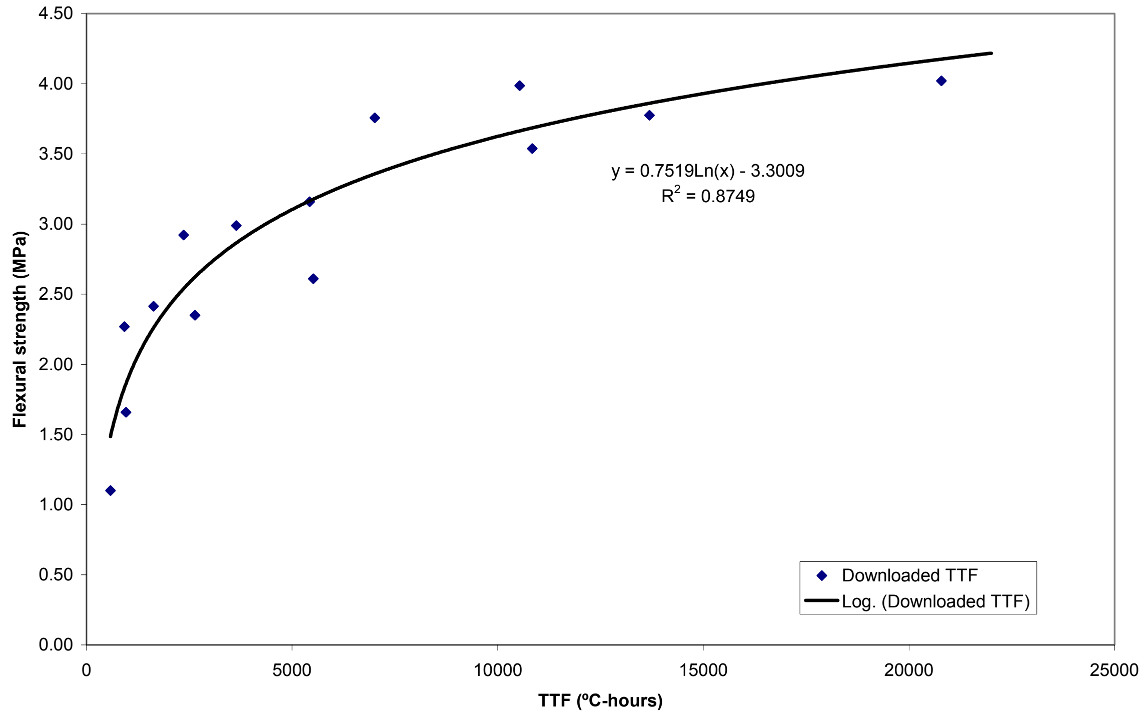

Figure C2-2e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 1, laboratory beams).

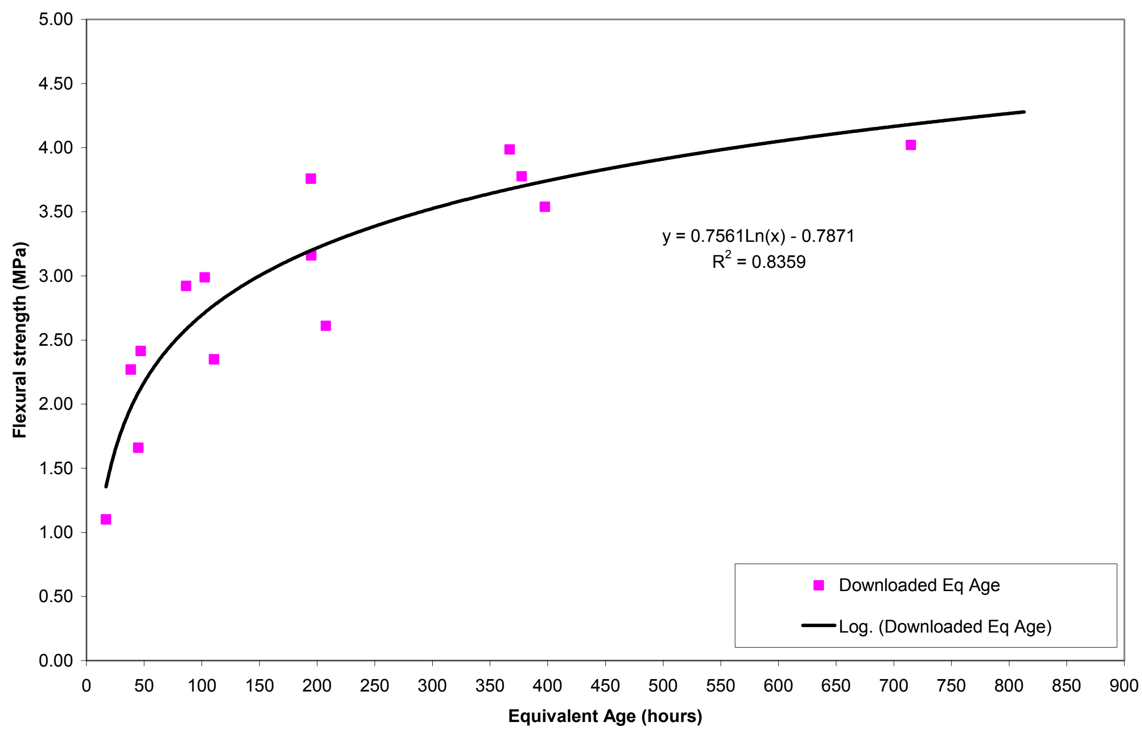

Figure C2-2f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 1, laboratory beams).

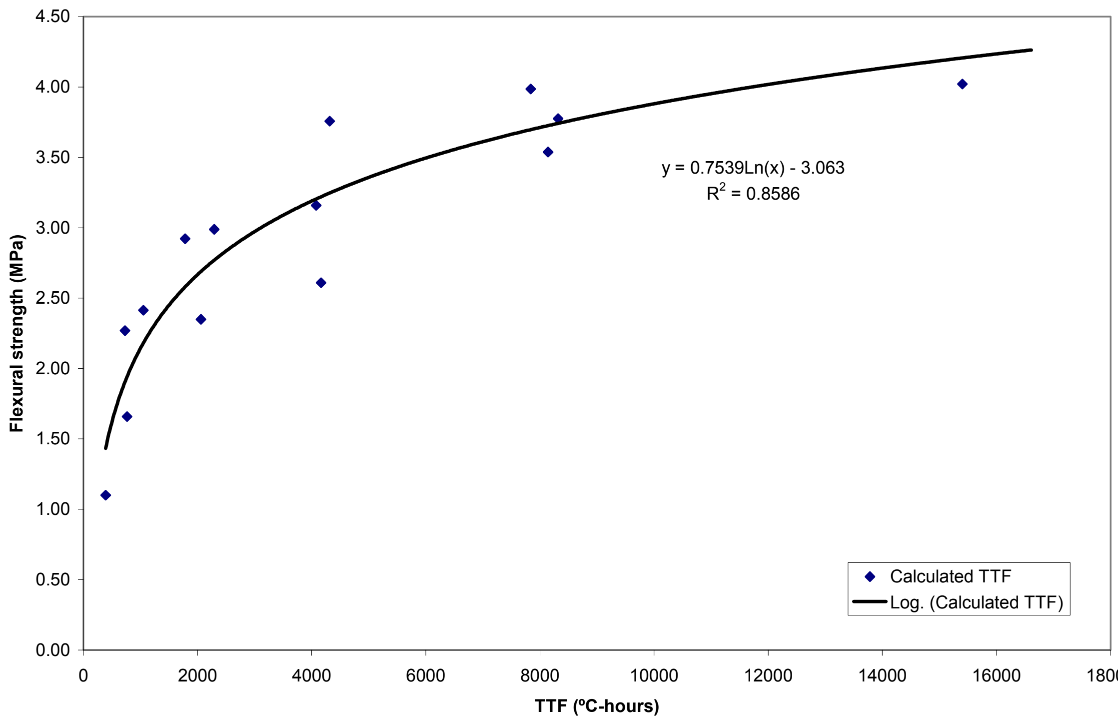

Figure C2-2g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 1, laboratory beams).

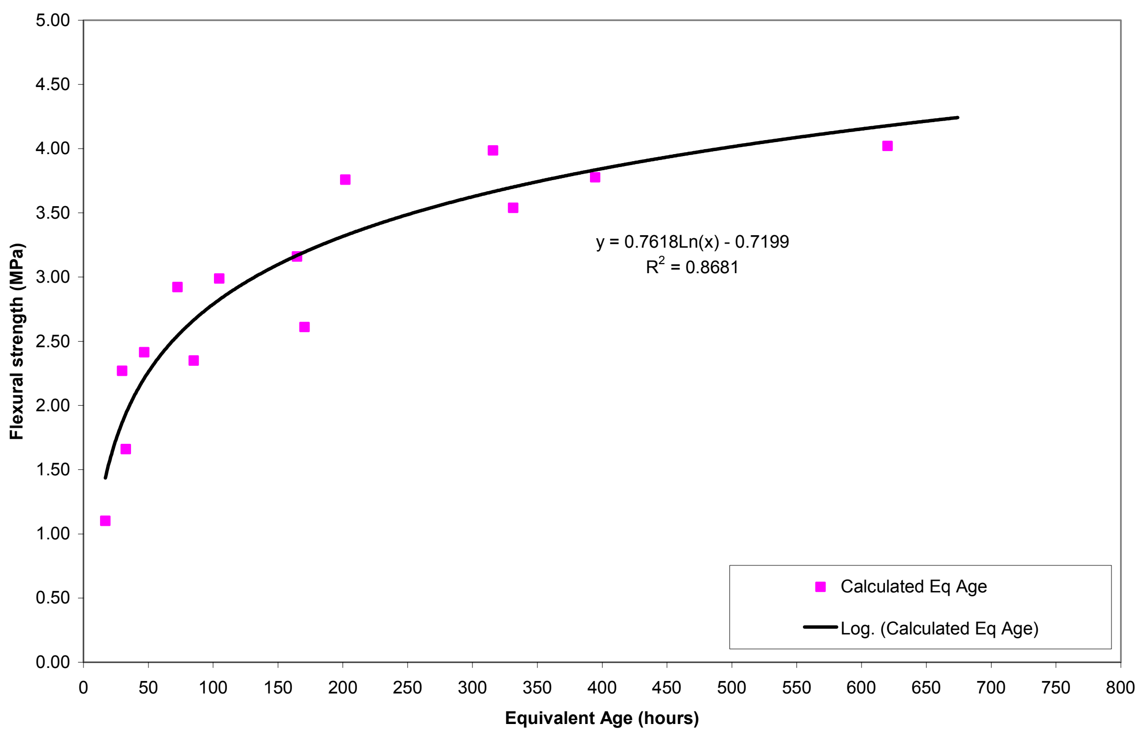

Figure C2-2h. Correlation between flexural strength and t_e, measured *E*, (Mix # 1, laboratory beams).

Mix #2 – Riverside I Compressive Strength versus Maturity

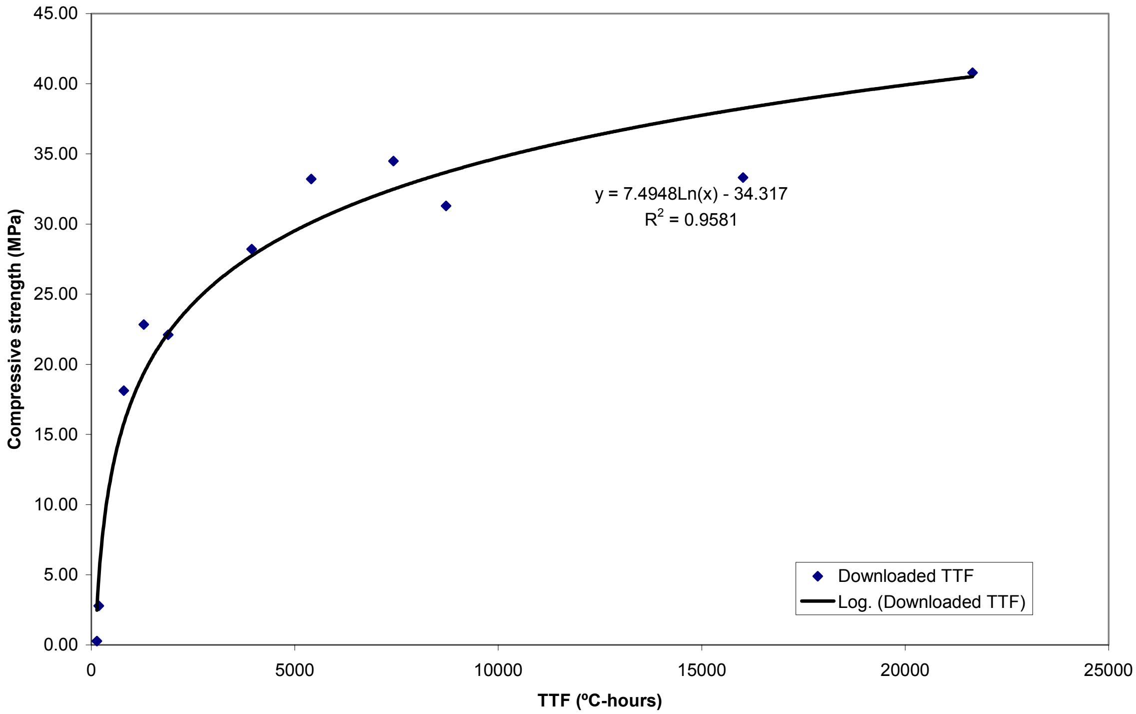

Figure C2-3a. Correlation between compressive strength and *TTF*, assumed T_0, (Mix # 2, laboratory cylinders).

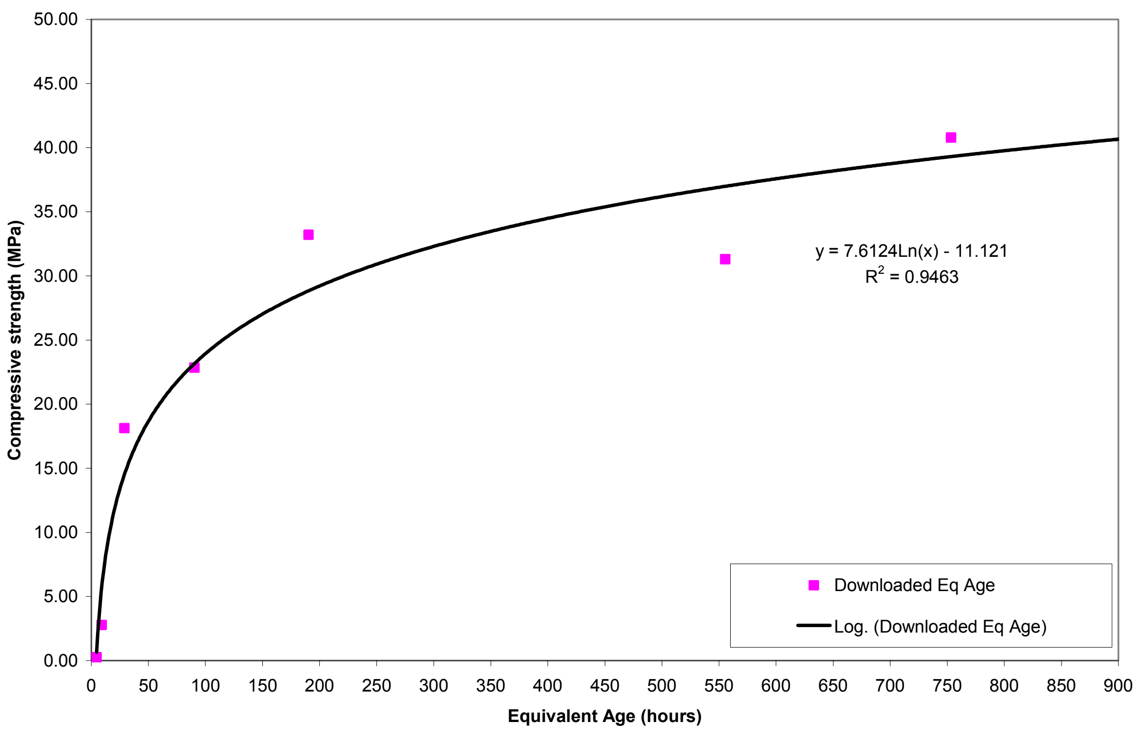

Figure C2-3b. Correlation between compressive strength and t_e, assumed *E*, (Mix # 2, laboratory cylinders).

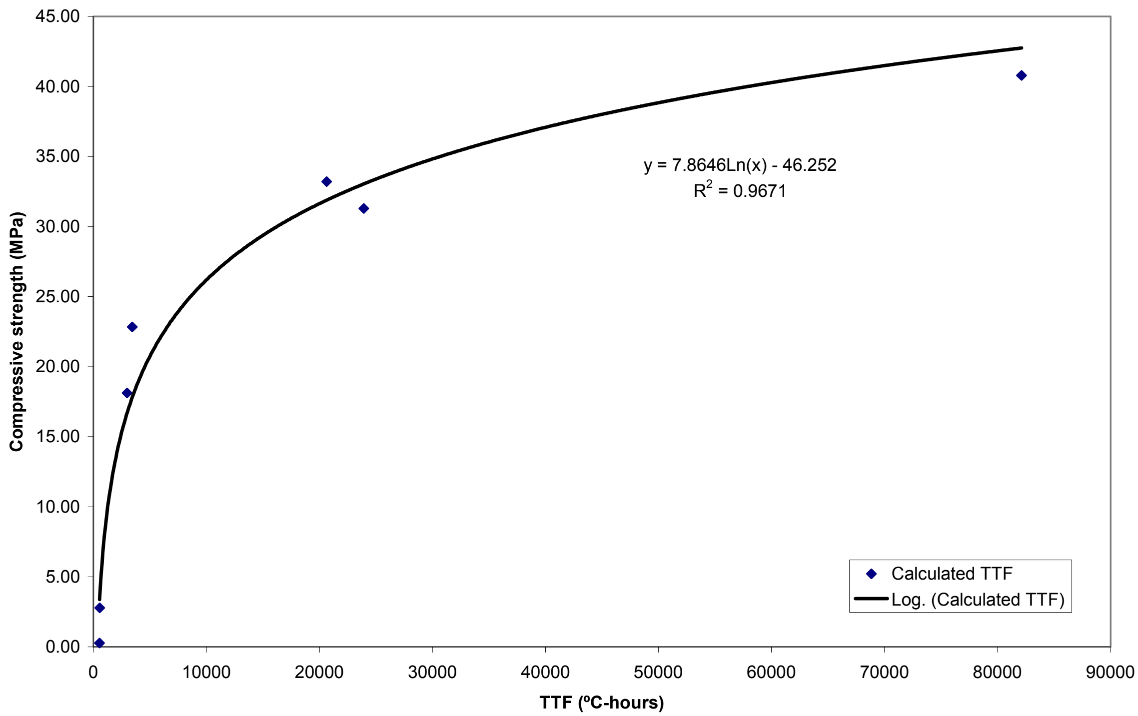

Figure C2-3c. Correlation between compressive strength and *TTF*, measured T_0, (Mix # 2, laboratory cylinders).

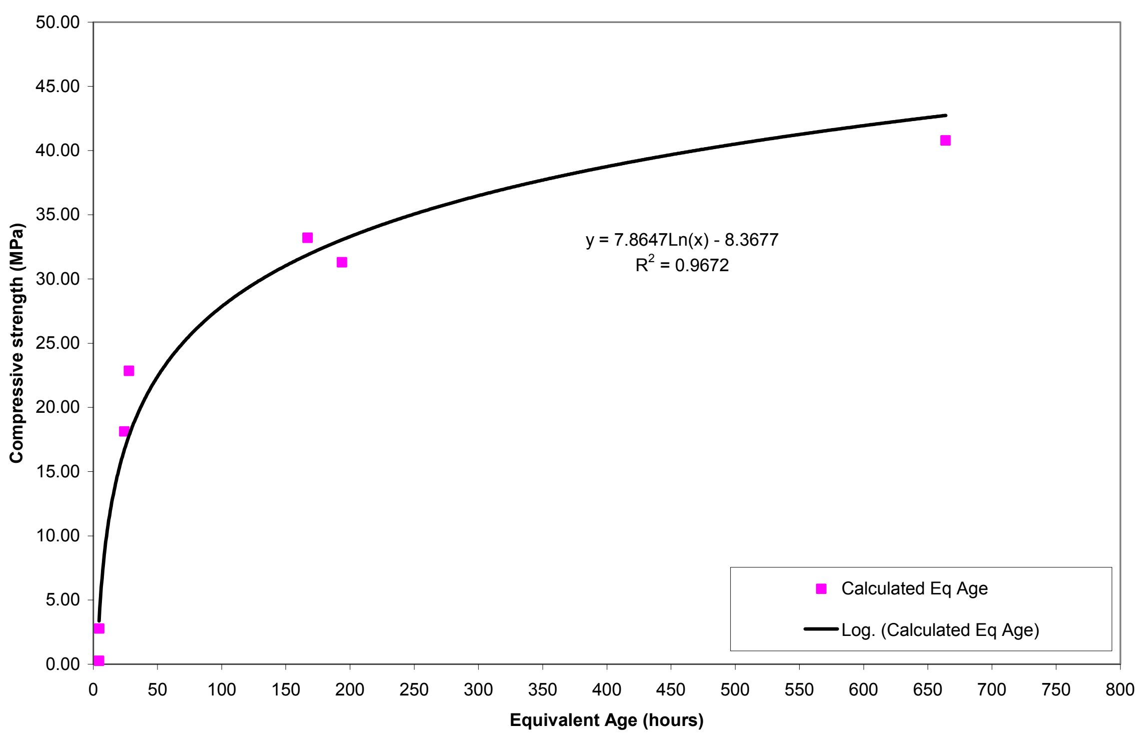

Figure C2-3d. Correlation between compressive strength and t_e, measured *E*, (Mix # 2, laboratory cylinders).

Mix #2 – Riverside I Flexural Strength versus Maturity

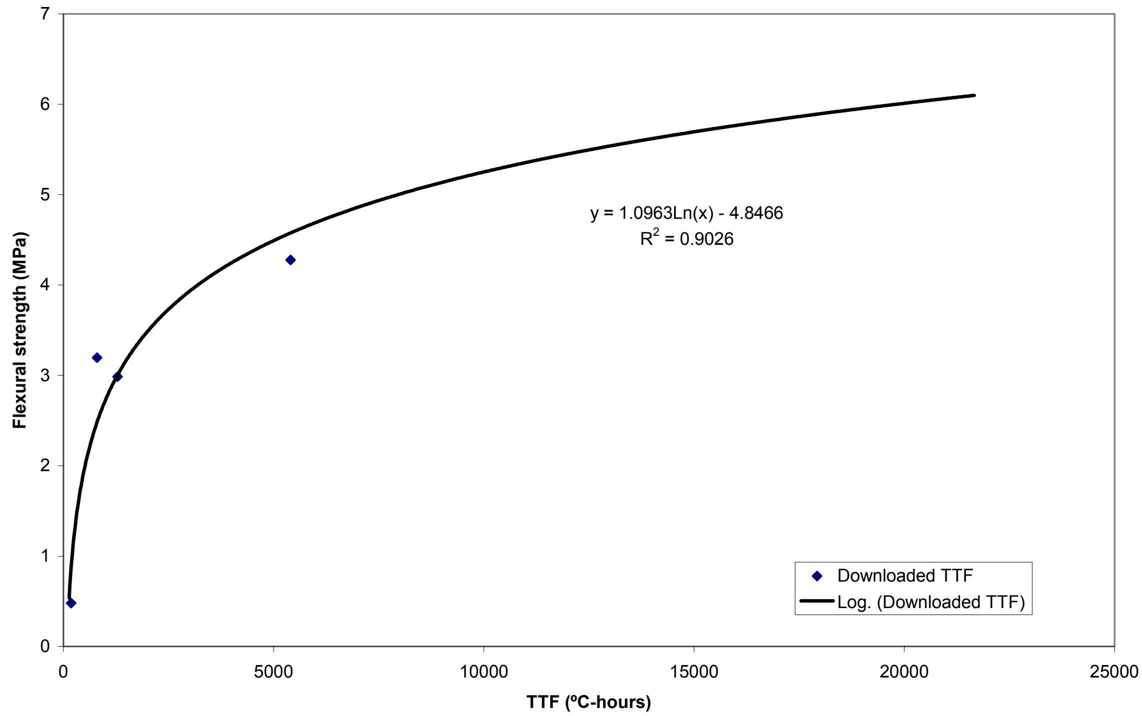

Figure C2-3e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 2, laboratory beams).

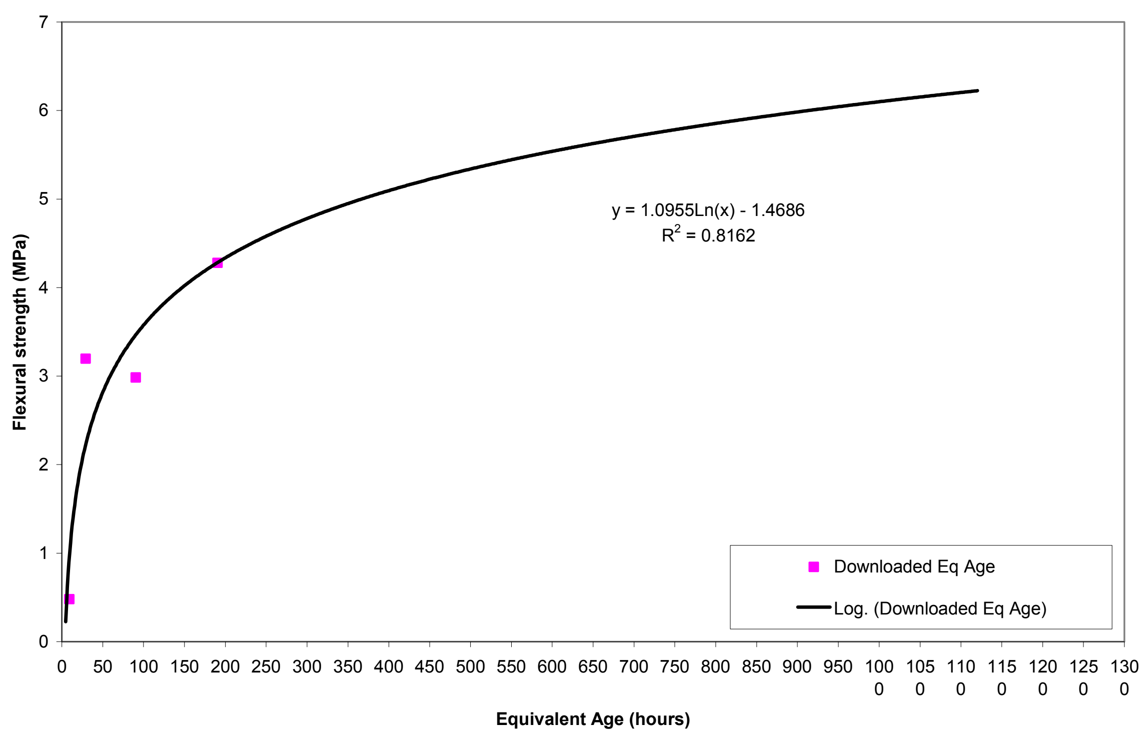

Figure C2-3f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 2, laboratory beams).

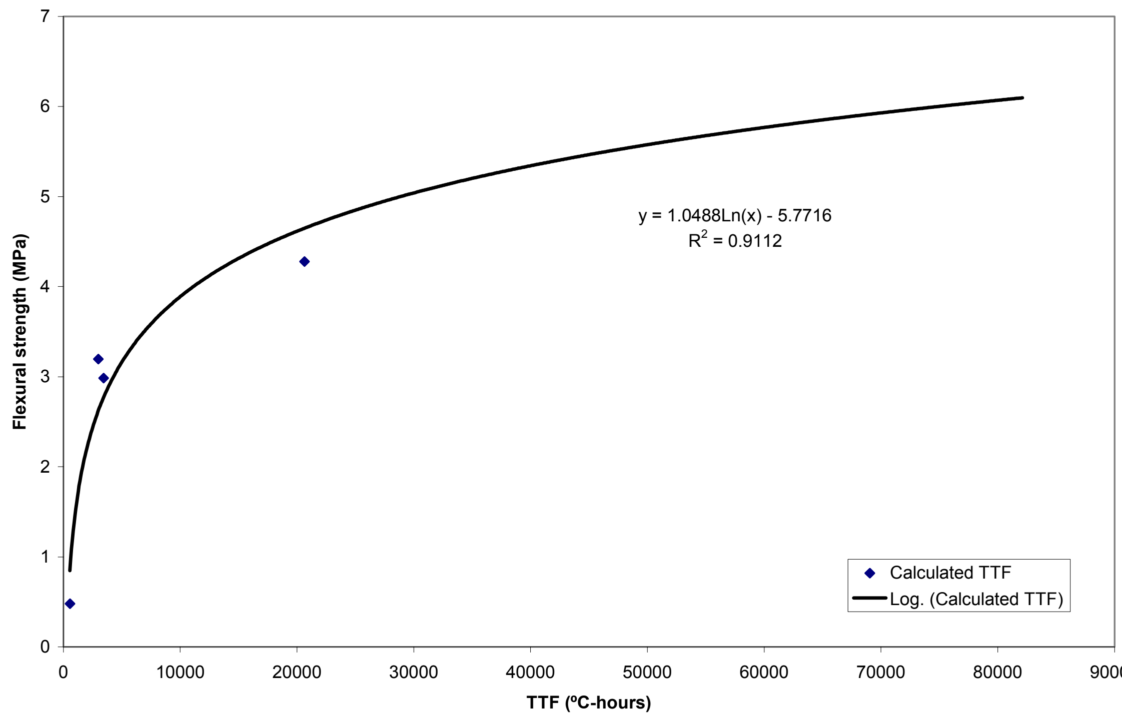

Figure C2-3g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 2, laboratory beams).

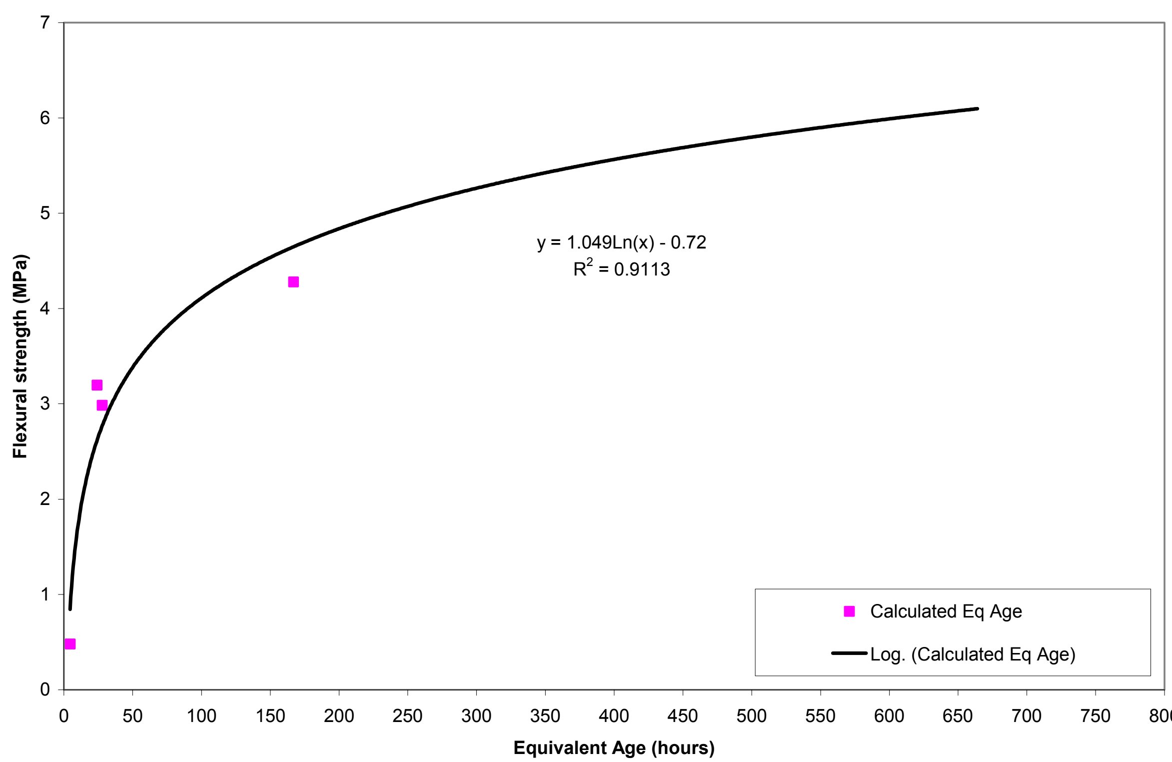

Figure C2-3h. Correlation between flexural strength and t_e, measured *E*, (Mix # 2, laboratory beams).

Mix #3 – Riverside II Compressive Strength versus Maturity

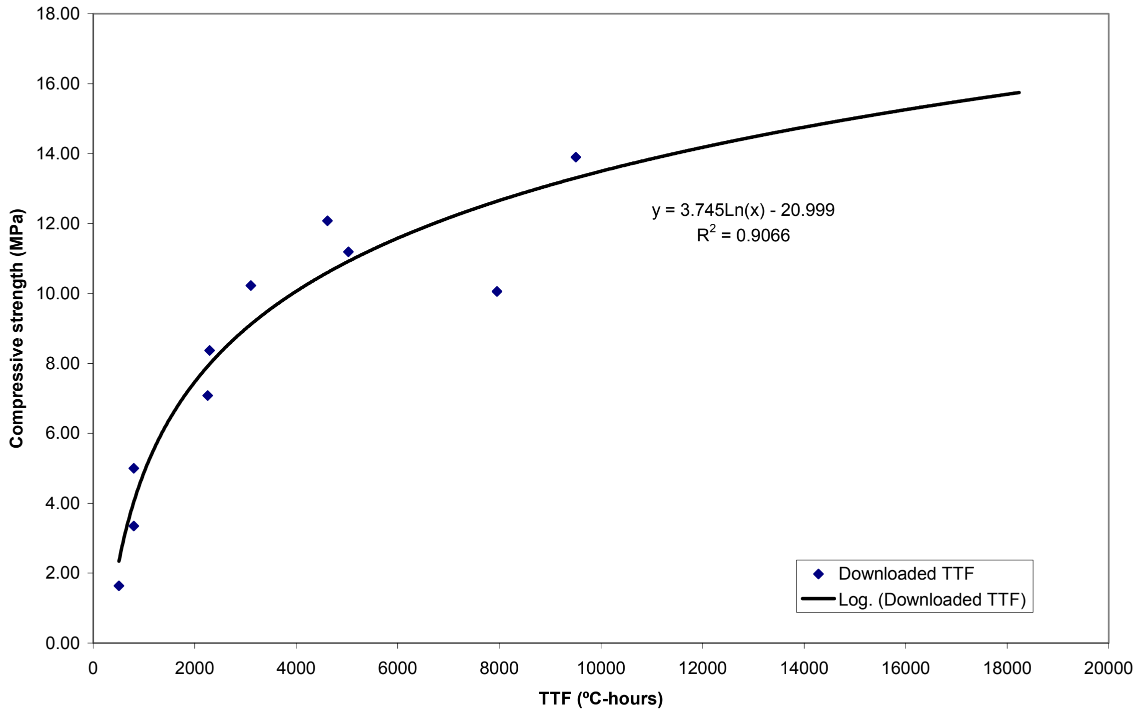

Figure C2-4a. Correlation between compressive strength and *TTF*, assumed T_0, (Mix # 3, laboratory cylinders).

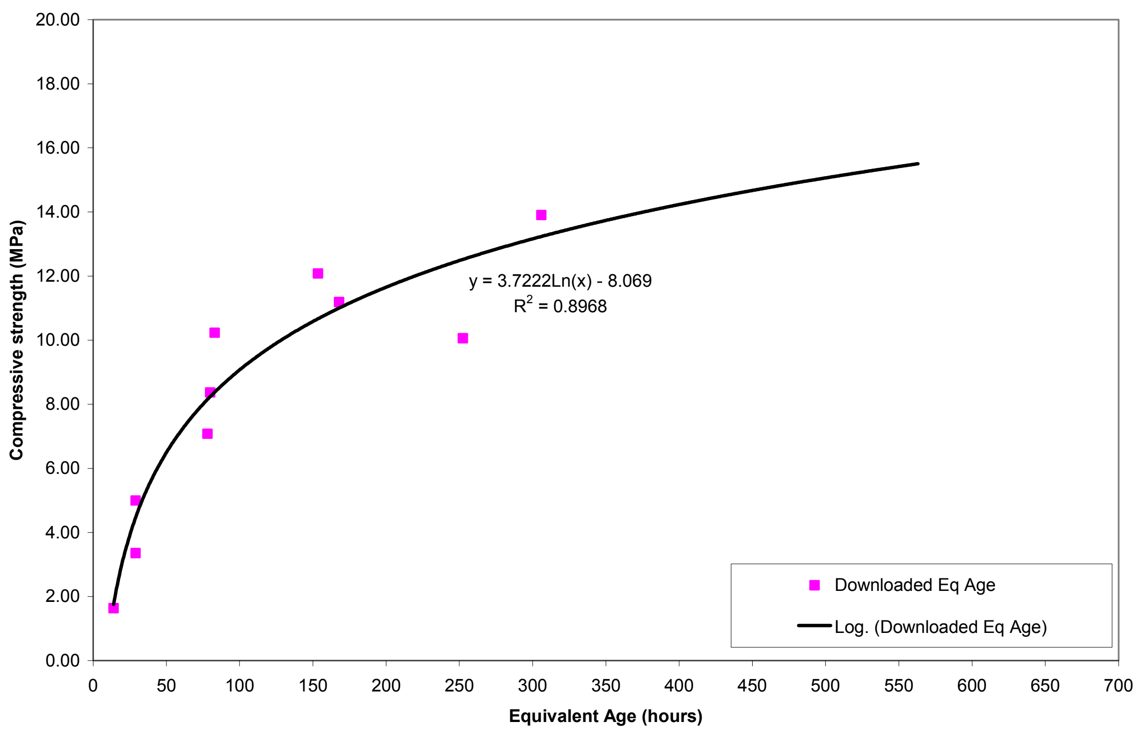

Figure C2-4b. Correlation between compressive strength and t_e, assumed *E*, (Mix # 3, laboratory cylinders).

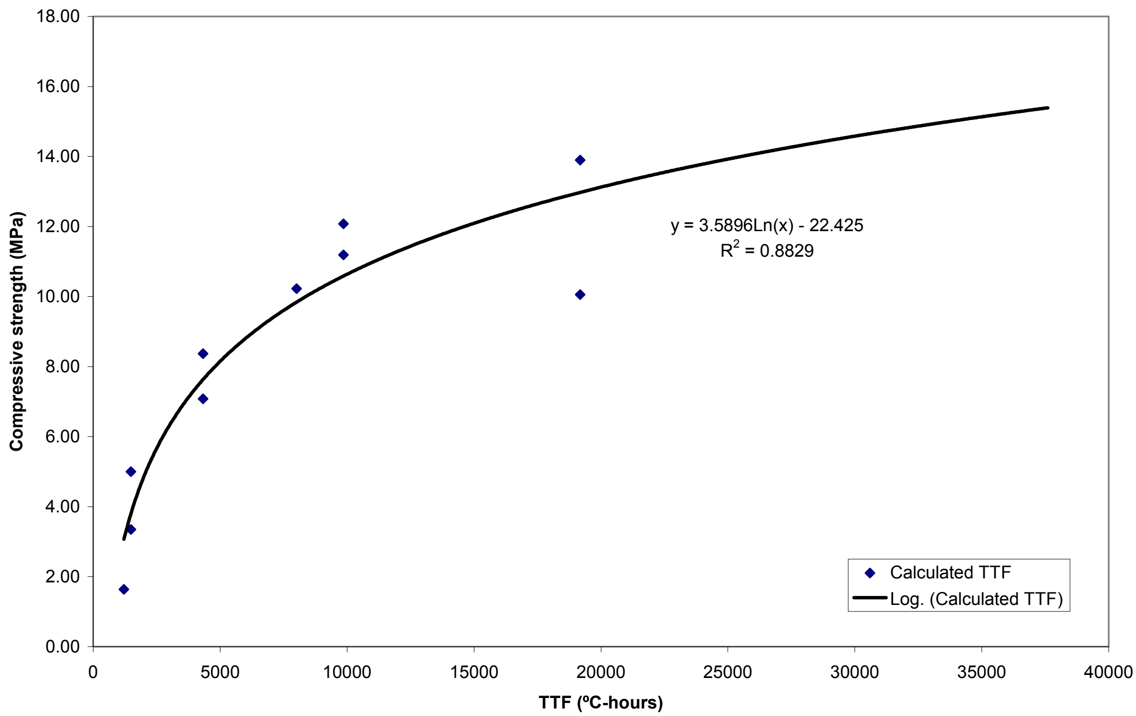

Figure C2-4c. Correlation between compressive strength and *TTF*, measured T_0, (Mix # 3, laboratory cylinders).

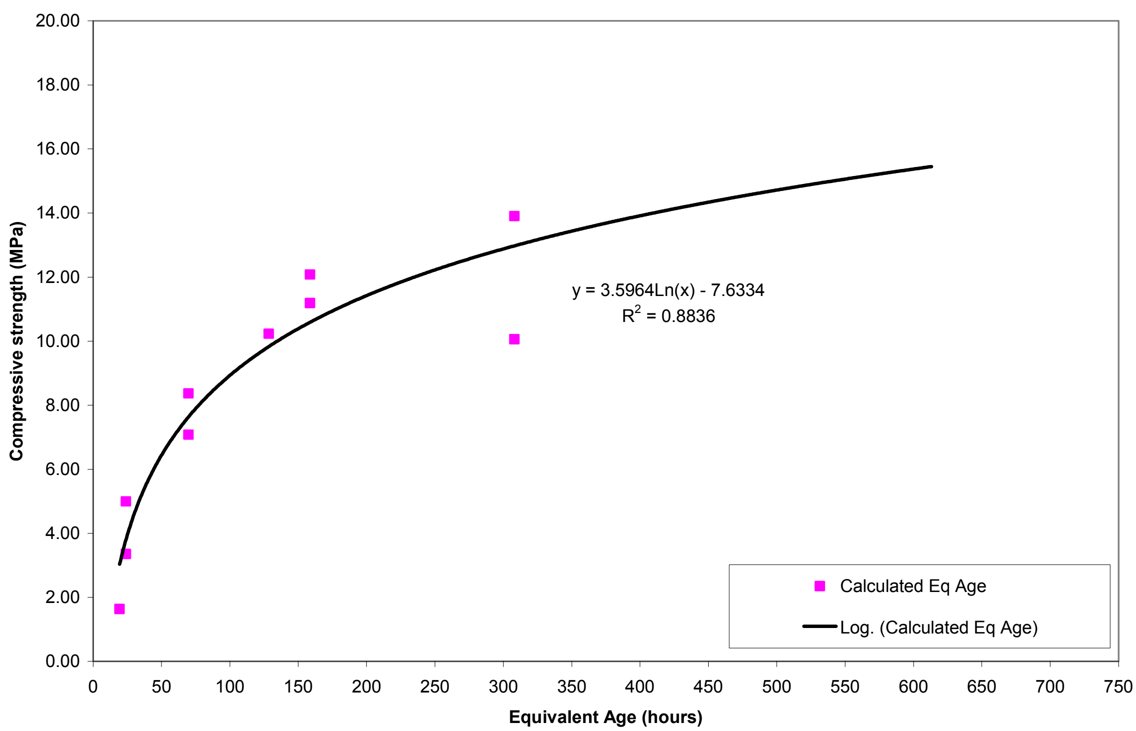

Figure C2-4d. Correlation between compressive strength and t_e, measured *E*, (Mix # 3, laboratory cylinders).

Mix #3 – Riverside II Flexural Strength versus Maturity

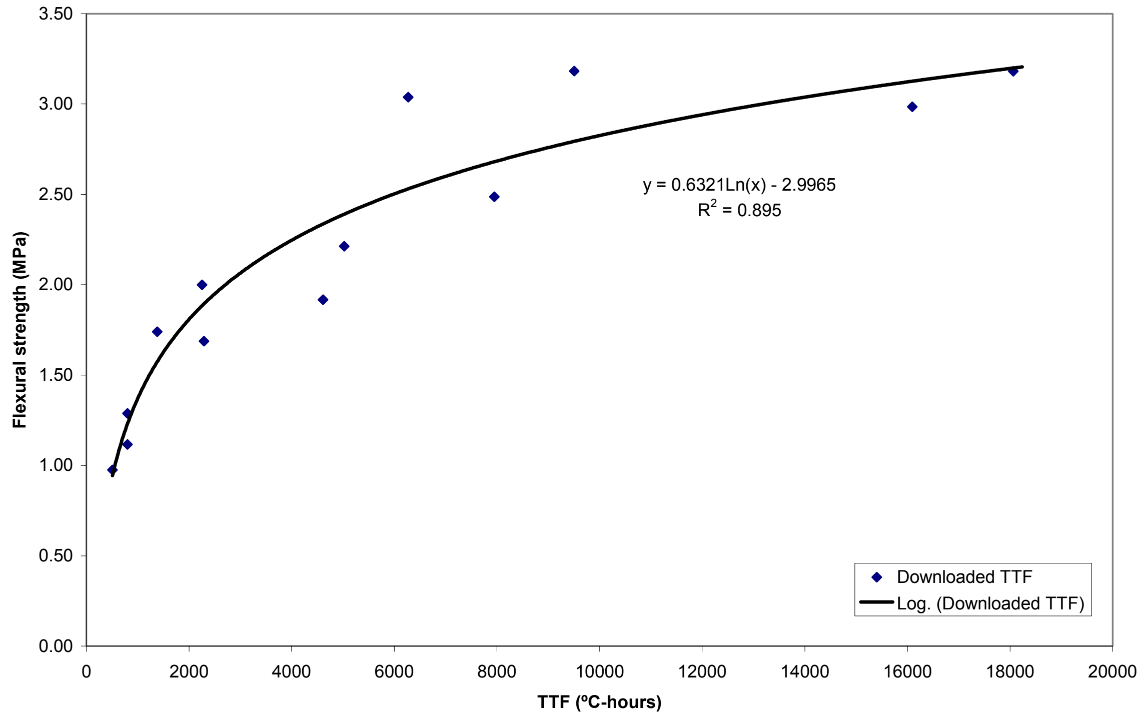

Figure C2-4e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 3, laboratory beams).

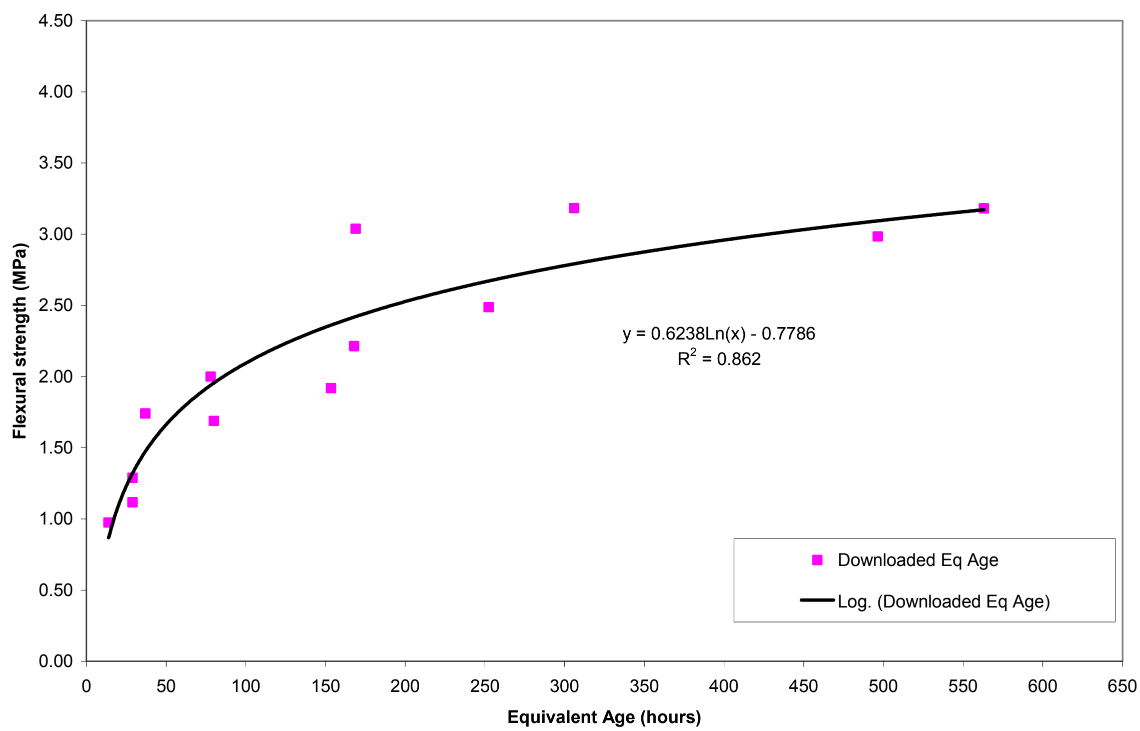

Figure C2-4f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 3, laboratory beams).

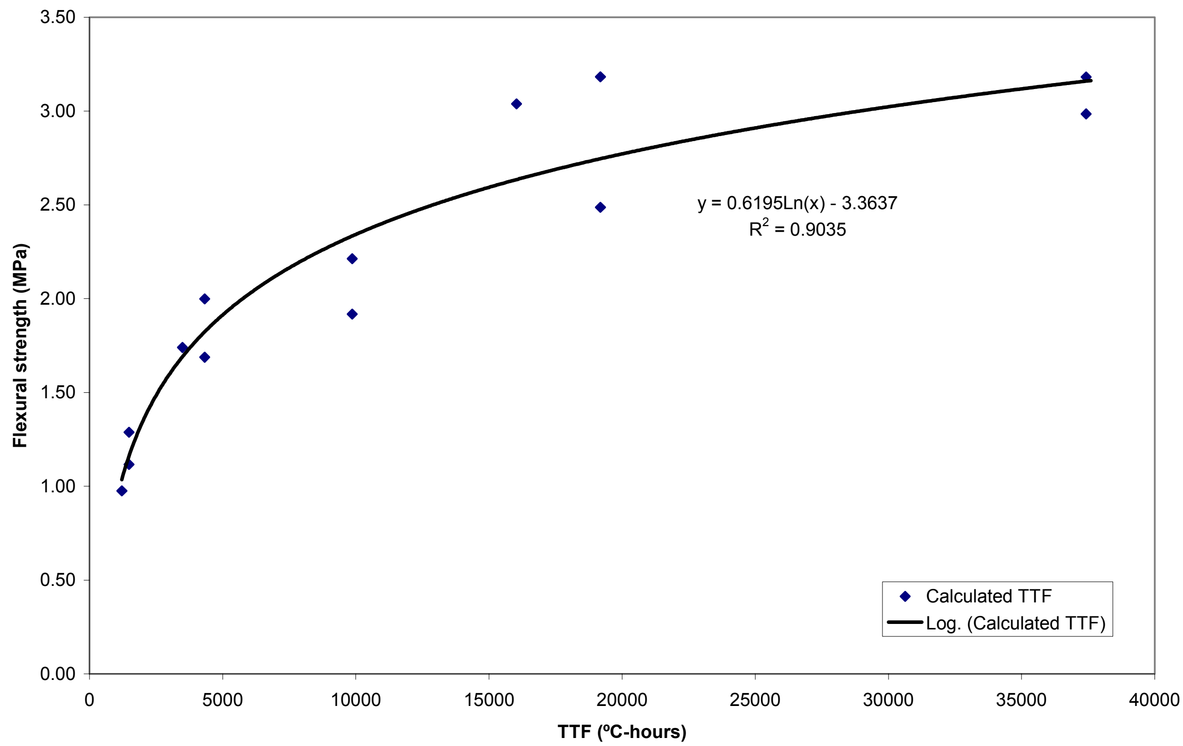

Figure C2-4g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 3, laboratory beams).

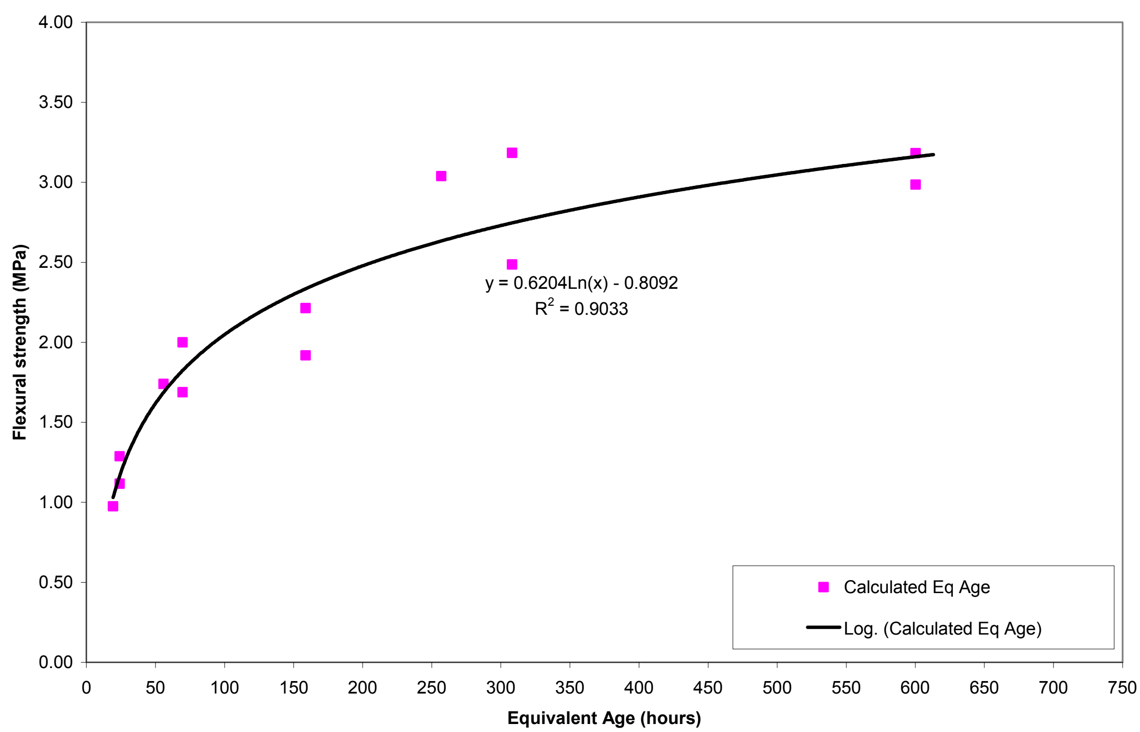

Figure C2-4h. Correlation between flexural strength and t_e, measured *E*, (Mix # 3, laboratory beams).

Mix #4 – Victorville Compressive Strength versus Maturity

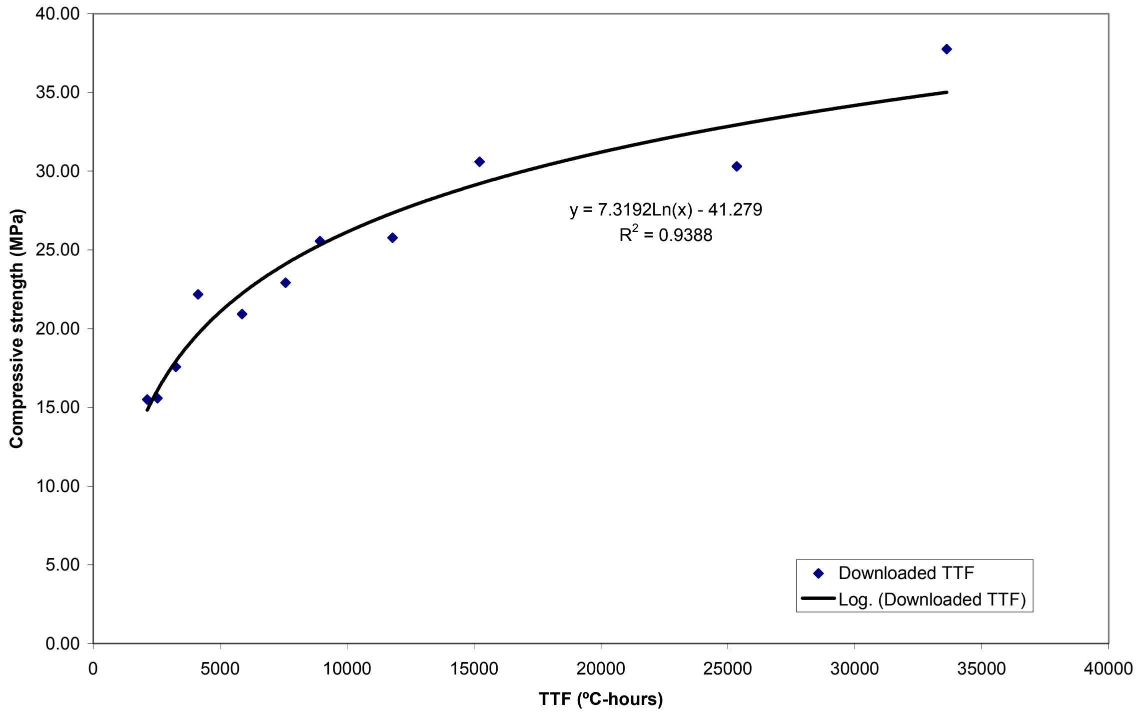

Figure C2-5a. Correlation between compressive strength and *TTF*, assumed T_0, (Mix # 4, laboratory cylinders).

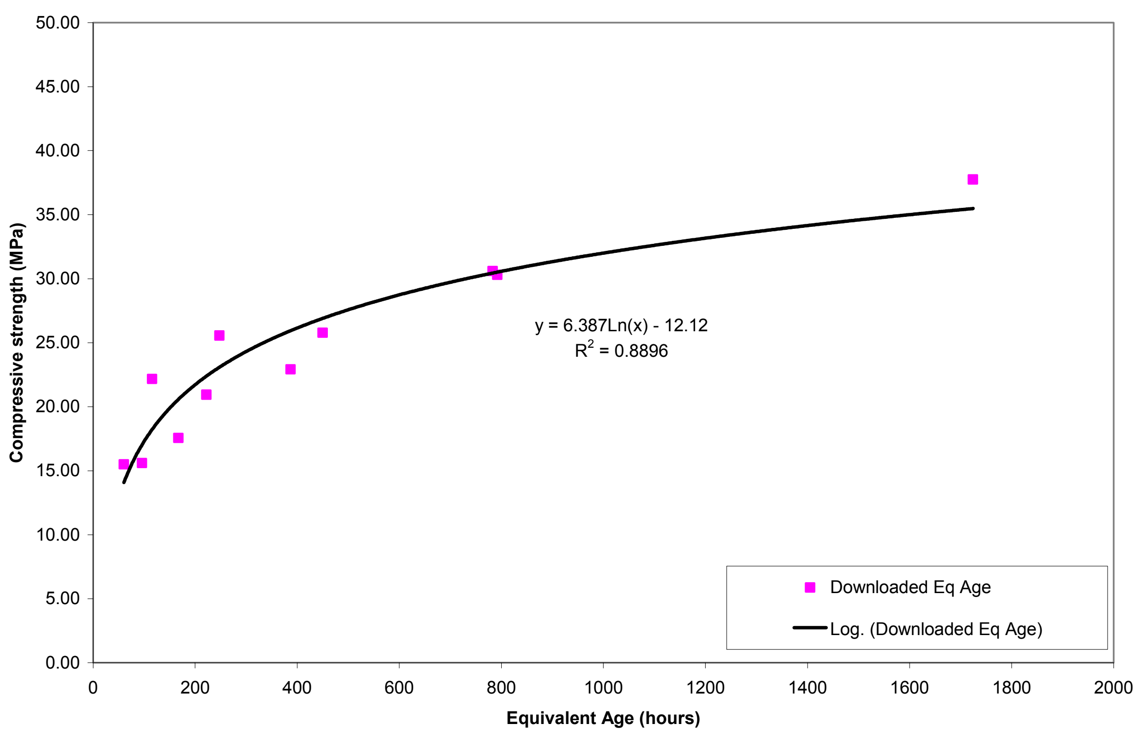

Figure C2-5b. Correlation between compressive strength and t_e, assumed *E*, (Mix # 4, laboratory cylinders).

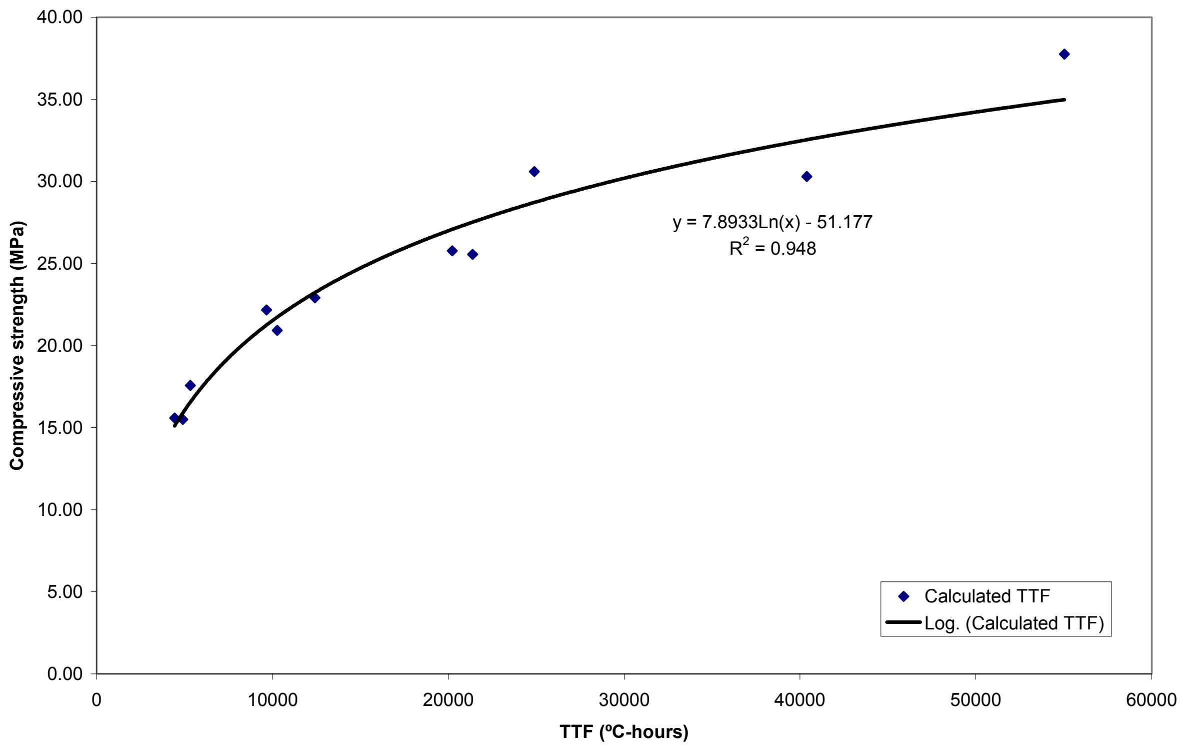

Figure C2-5c. Correlation between compressive strength and *TTF*, measured T_0, (Mix # 4, laboratory cylinders).

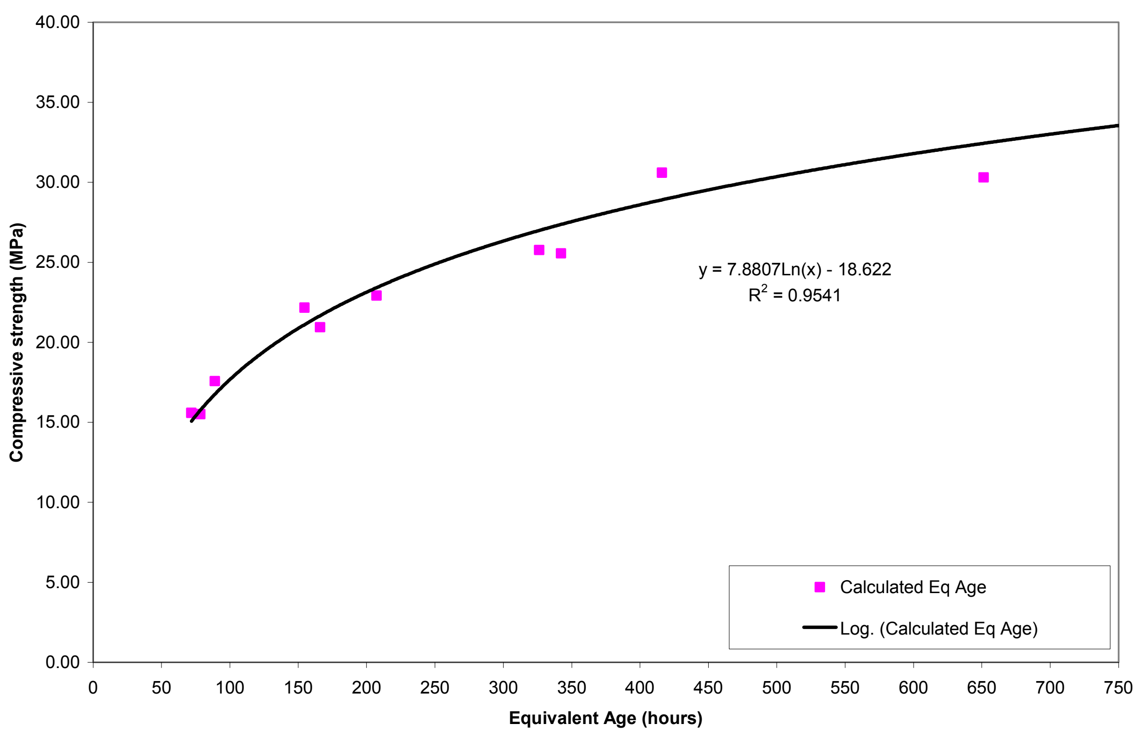

Figure C2-5d. Correlation between compressive strength and t_e, measured *E*, (Mix # 4, laboratory cylinders).

Mix #4 – Victorville Flexural Strength versus Maturity

In this case, as can be observed in Figures 37–40, the correlation between flexural strength and maturity was noticeably influenced by the later ages, leading to a poorer correlation. Note that such correlation is better at earlier ages. This fact is illustrated in Tables C5-6 and C5-7 in Appendix C5 and in comparing Figures C2-5h and C2-6 in this appendix. Further, as illustrated by Figure C2-6, at a fixed, lab-controlled temperature, the correlations tend to be even better.

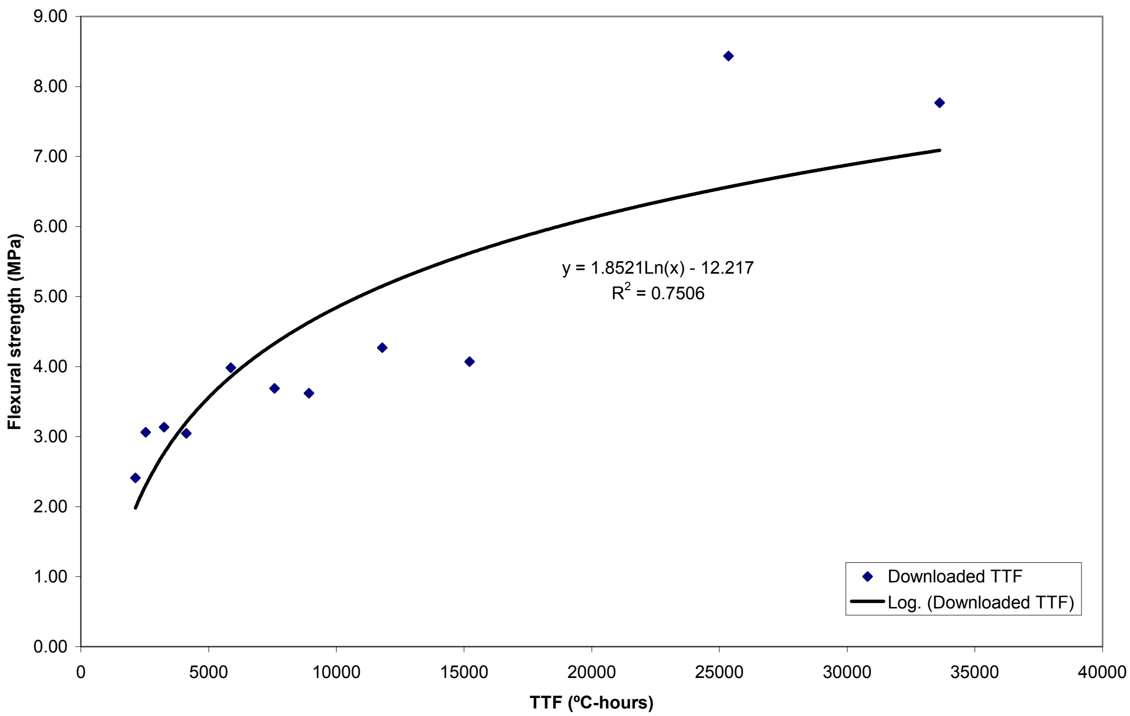

Figure C2-5e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 4, laboratory beams).

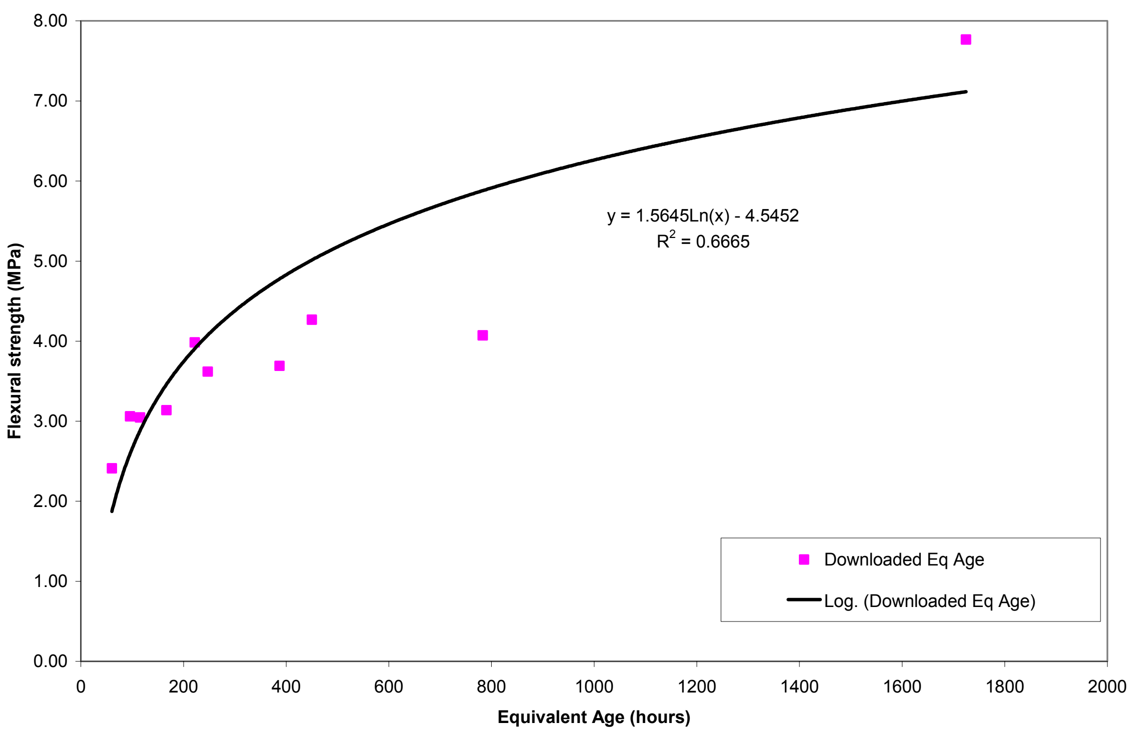

Figure C2-5f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 4, laboratory beams).

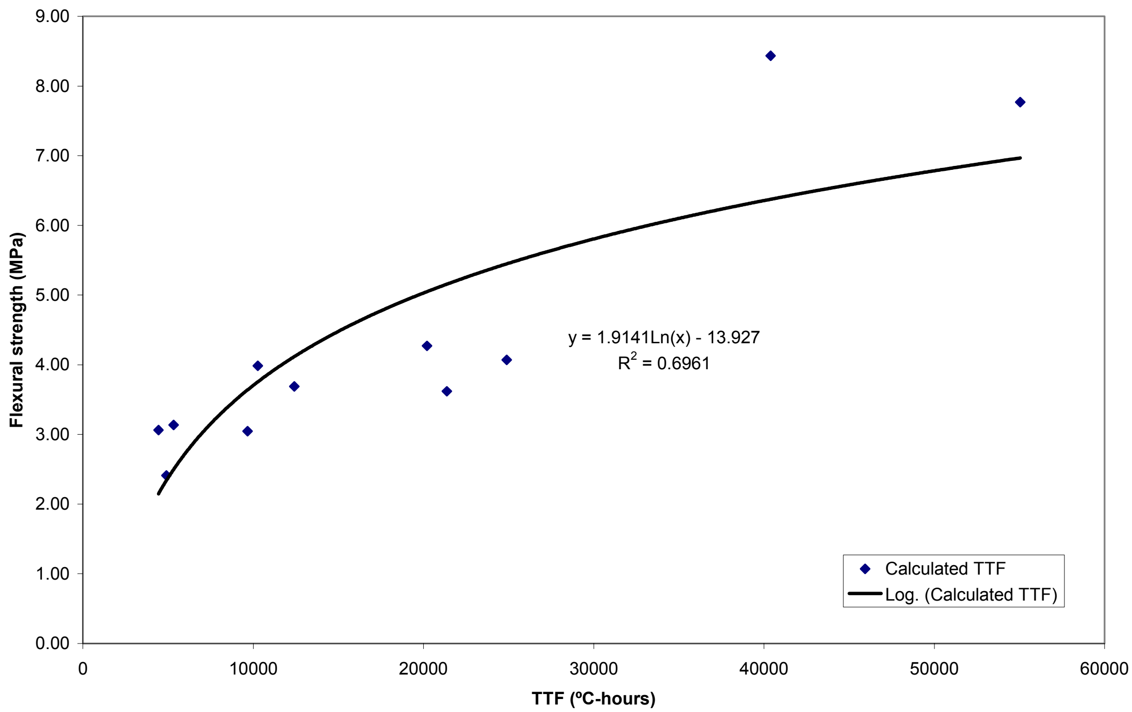

Figure C2-5g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 4, laboratory beams).

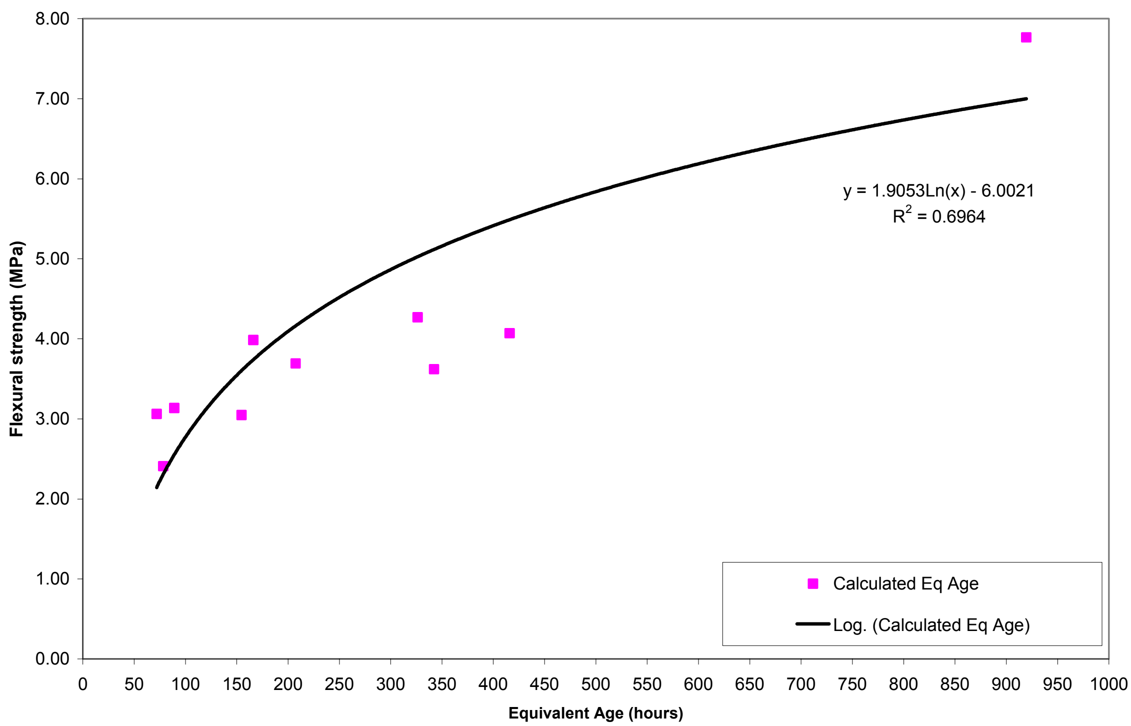

Figure C2-5h. Correlation between flexural strength and t_e, measured *E*, (Mix # 4, laboratory beams).

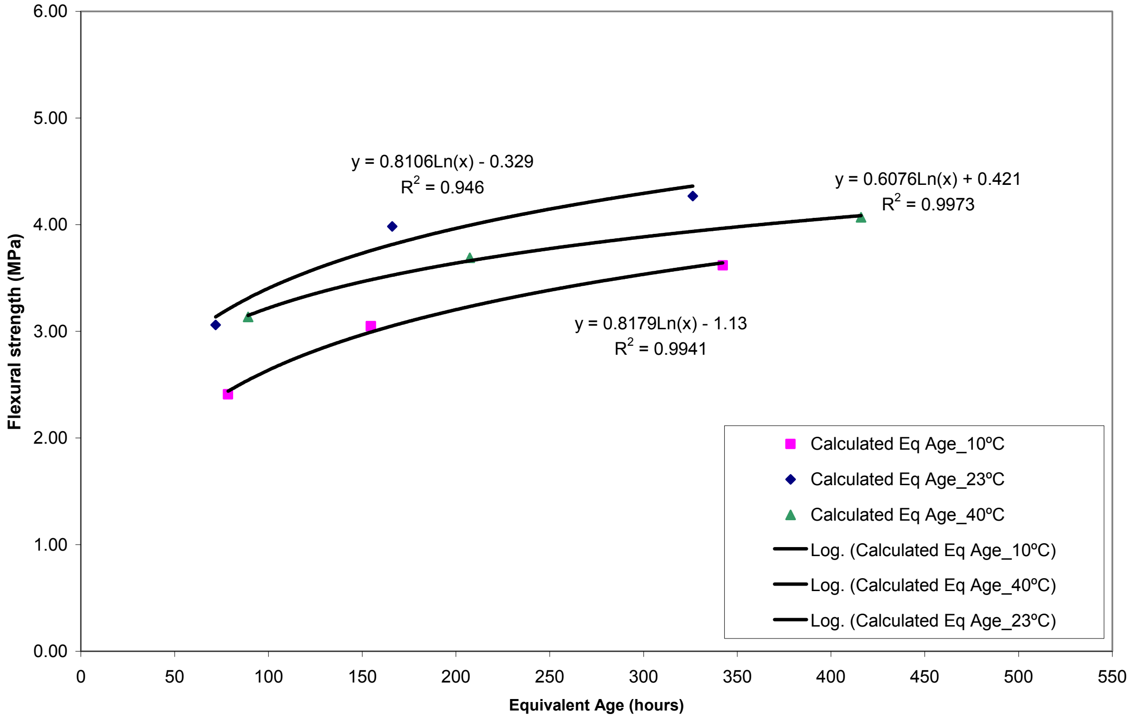

Figure C2-6. Correlation between flexural strength and t_e at earlier ages, measured *E*, (Mix # 4, laboratory beams).

Strength-Maturity Relationships – Individual Curing Temperatures

Mix #1 – Ludlow Compressive Strength versus Maturity

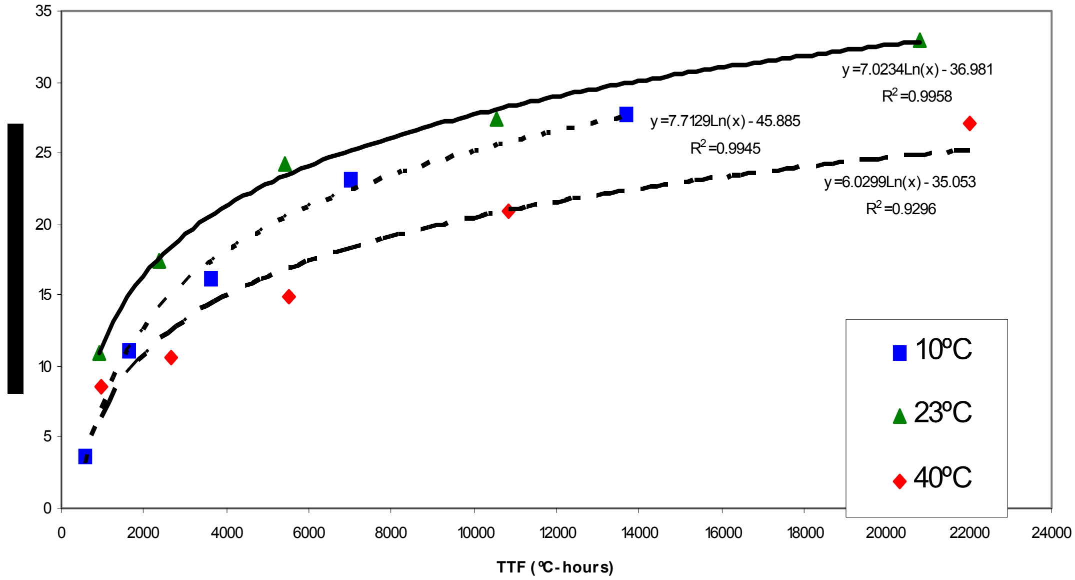

Figure C2-7a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #1, laboratory cylinders).

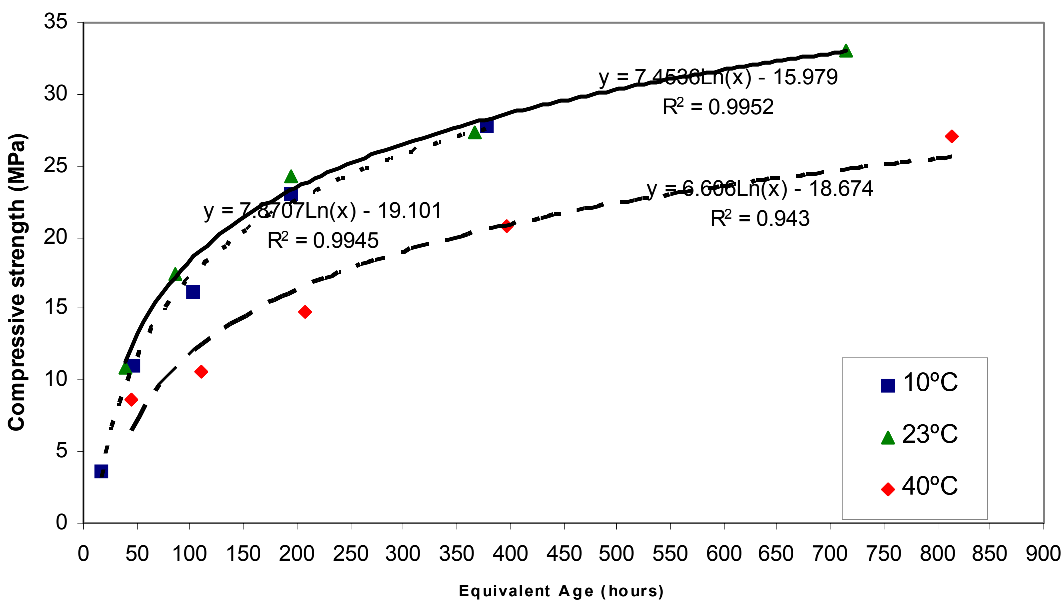

Figure C2-7b. Correlation between compressive strength and t_e, assumed *E* (Mix #1, laboratory cylinders).

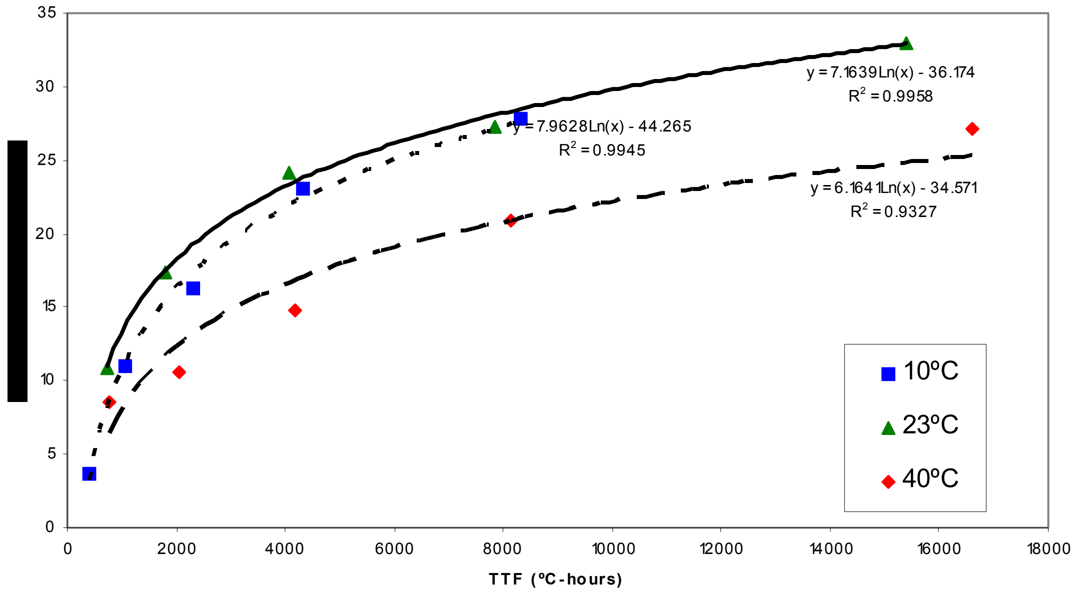

Figure C2-7c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 1, laboratory cylinders).

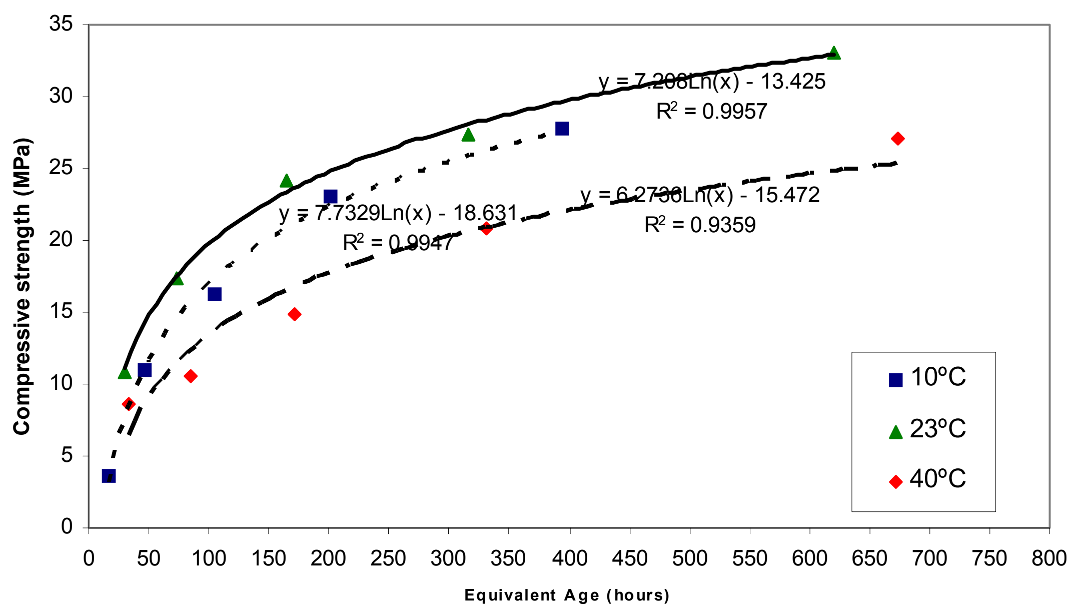

Figure C2-7d. Correlation between compressive strength and t_e, measured *E*, (Mix # 1, laboratory cylinders).

Mix #1 – Ludlow Flexural Strength versus Maturity

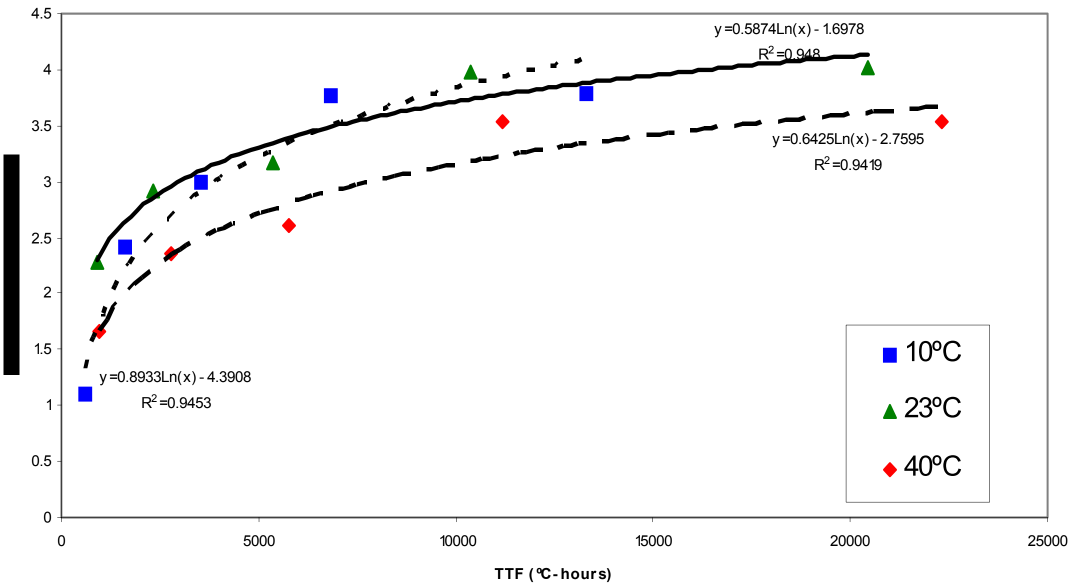

Figure C2-7e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 1, laboratory beams).

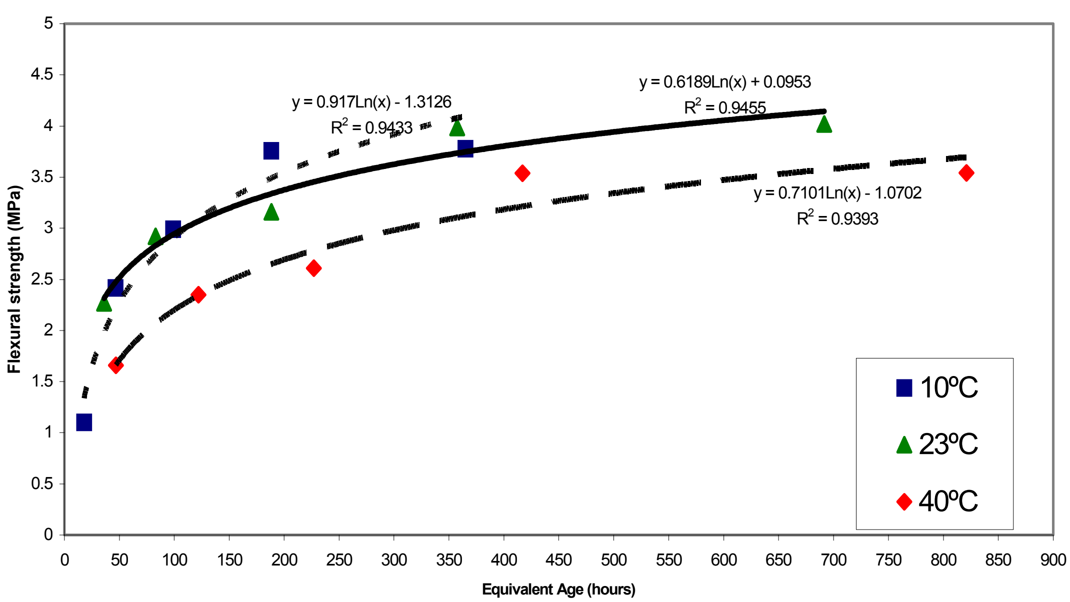

Figure C2-7f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 1, laboratory beams).

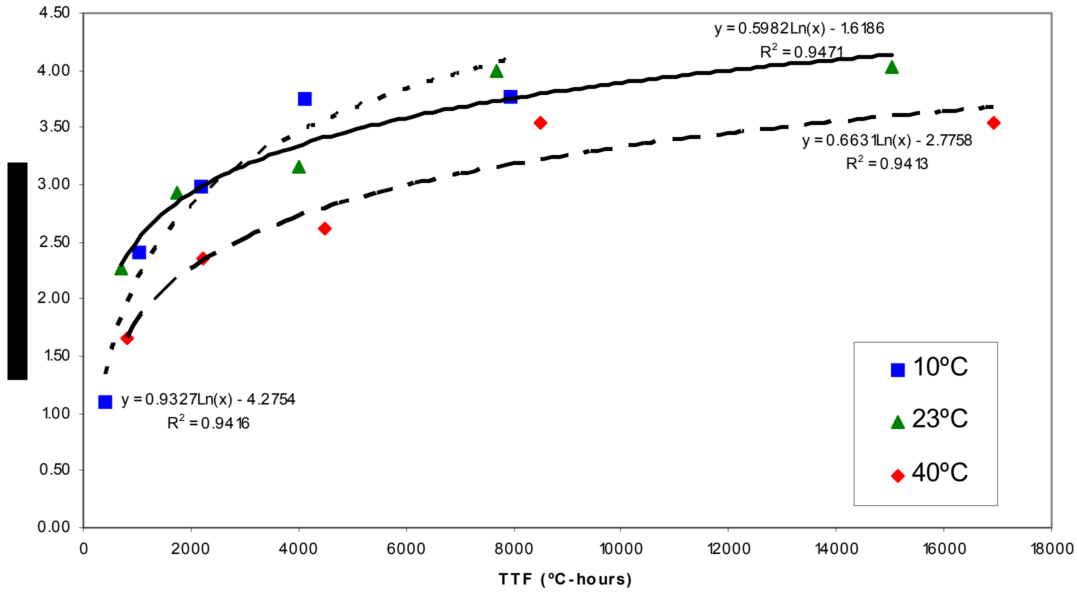

Figure C2-7g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 1, laboratory beams).

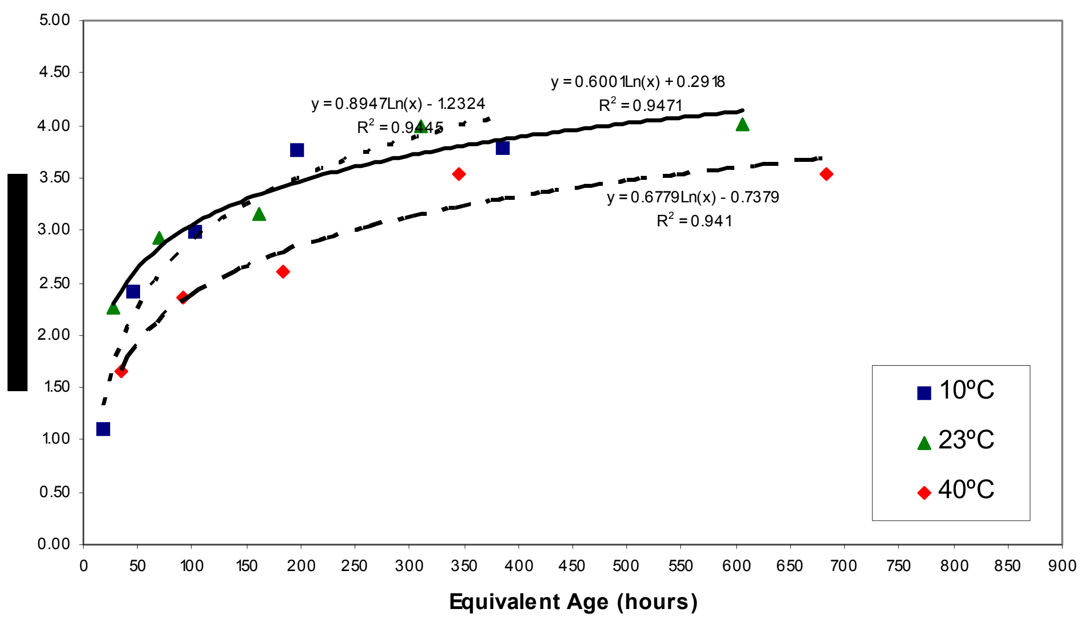

Figure C2-7h. Correlation between flexural strength and t_e, measured *E*, (Mix # 1, laboratory beams).

Mix #2 –Riverside I Compressive Strength versus Maturity

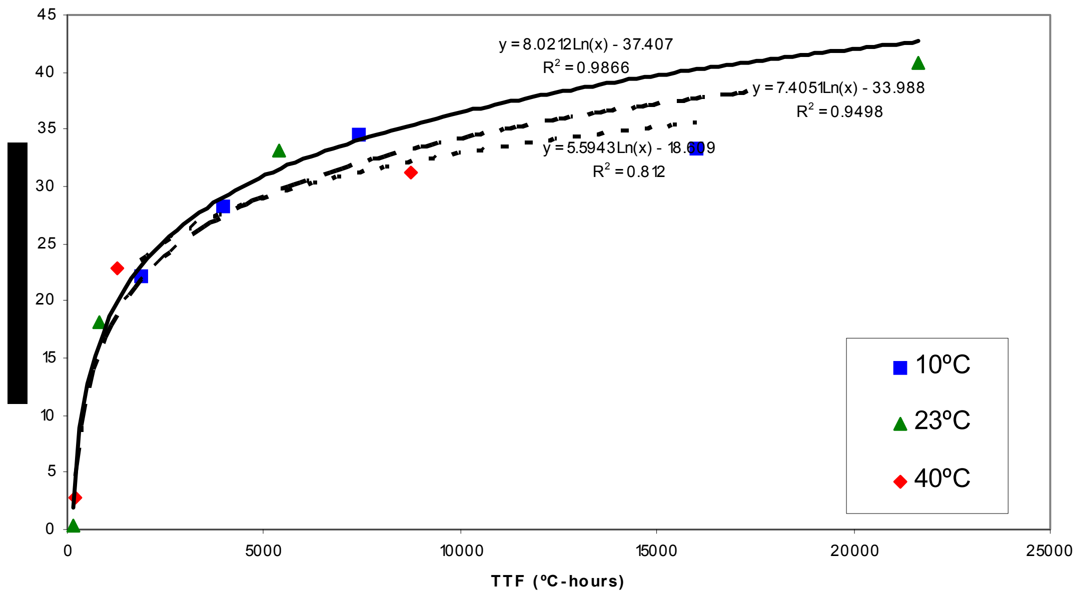

Figure C2-8a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #2, laboratory cylinders).

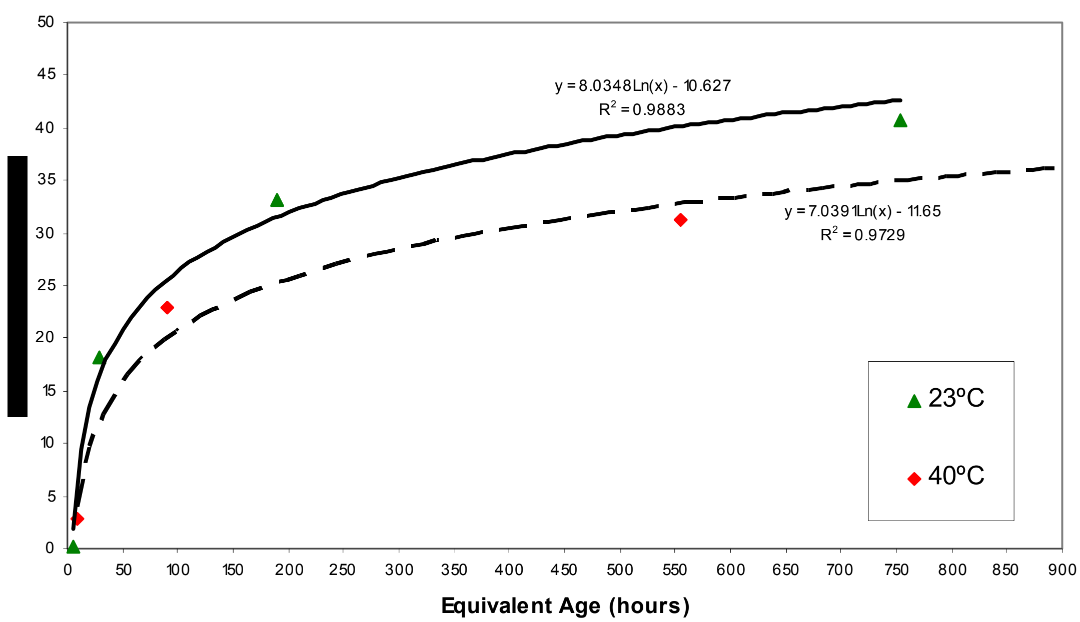

Figure C2-8b. Correlation between compressive strength and t_e, assumed *E* (Mix #2, laboratory cylinders).

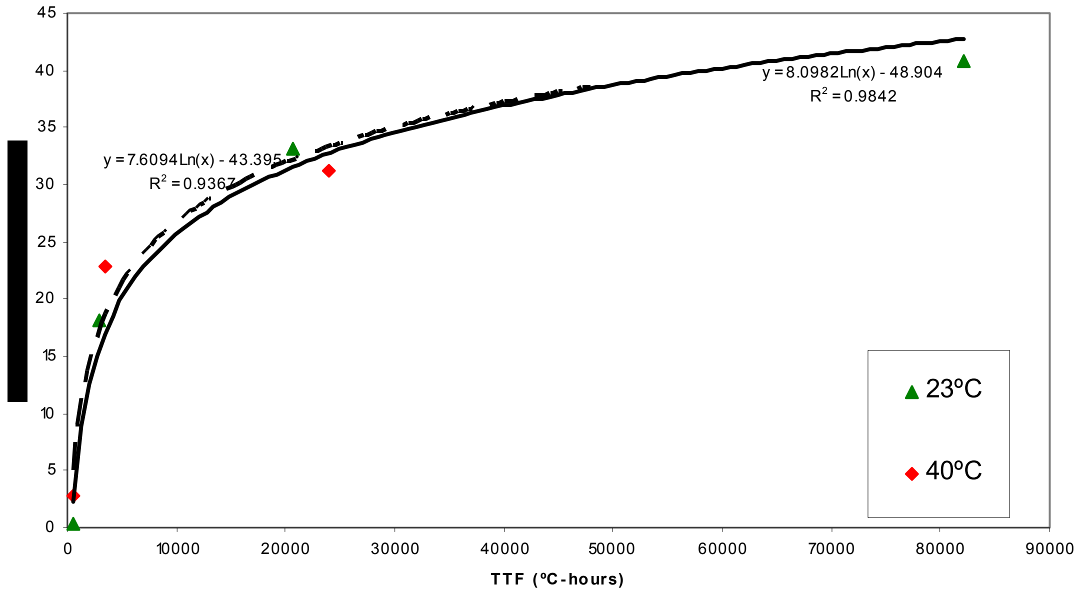

Figure C2-8c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 2, laboratory cylinders).

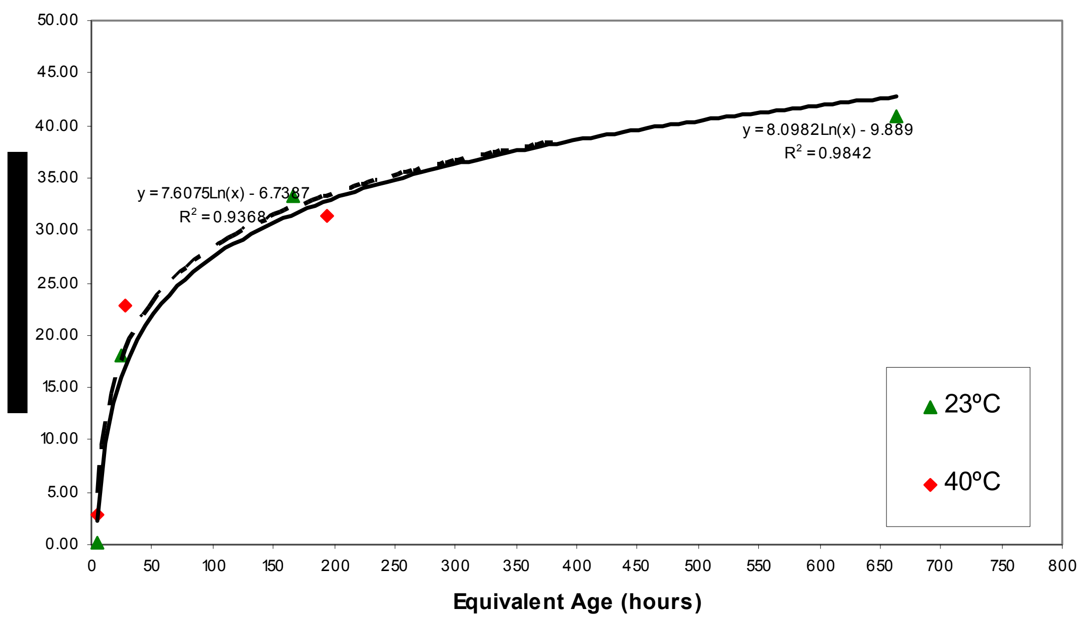

Figure C2-8d. Correlation between compressive strength and t_e, measured *E*, (Mix # 2, laboratory cylinders).

Mix #2 – Riverside I Flexural Strength versus Maturity

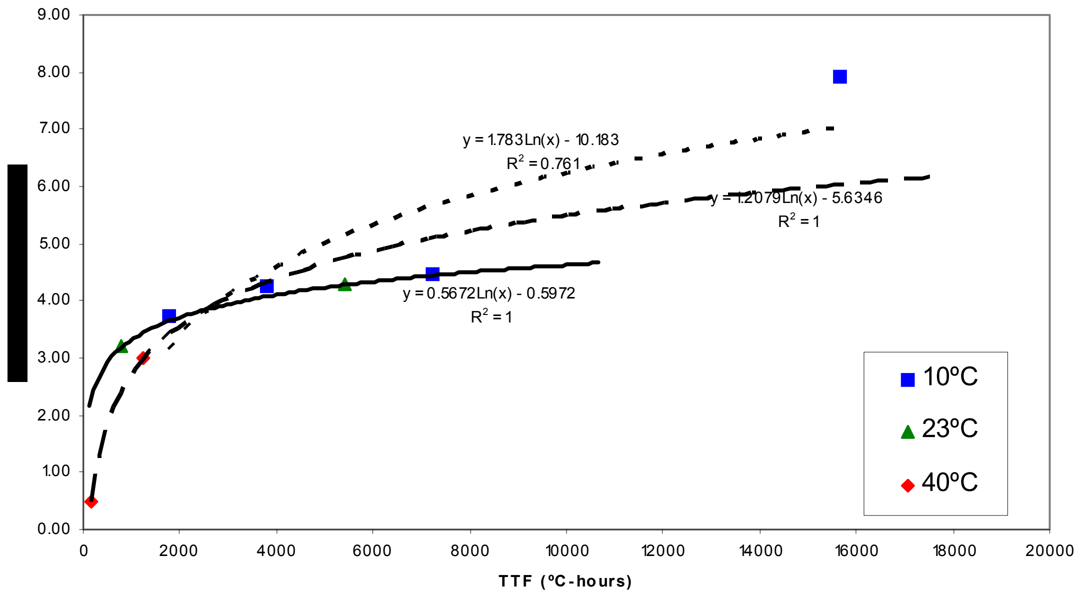

Figure C2-8e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 2, laboratory beams).

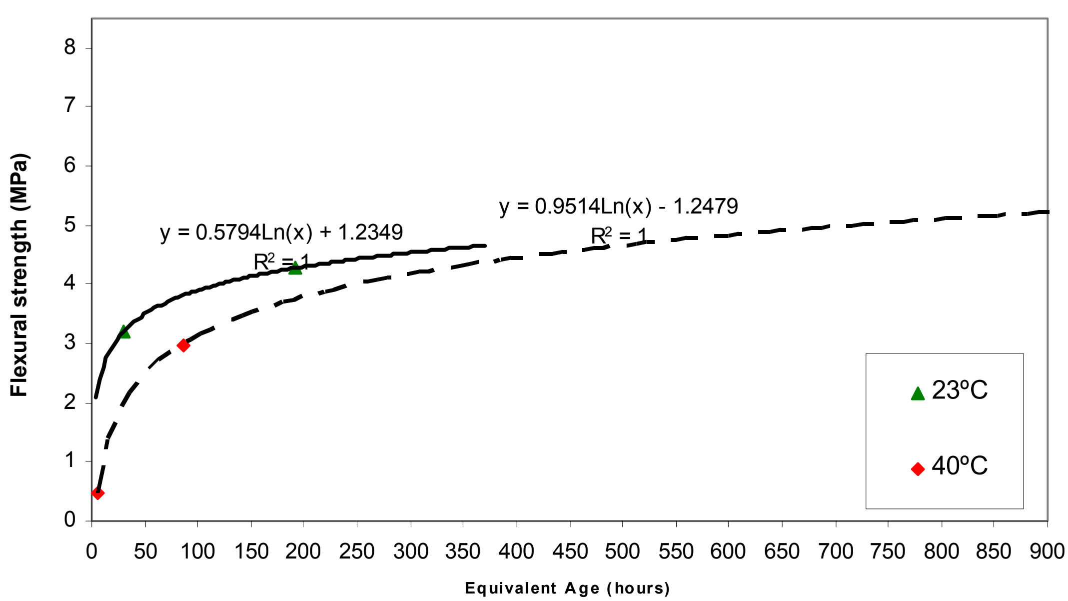

Figure C2-8f. Correlation between flexural strength and t_e, assumed E, (Mix # 2, laboratory beams).

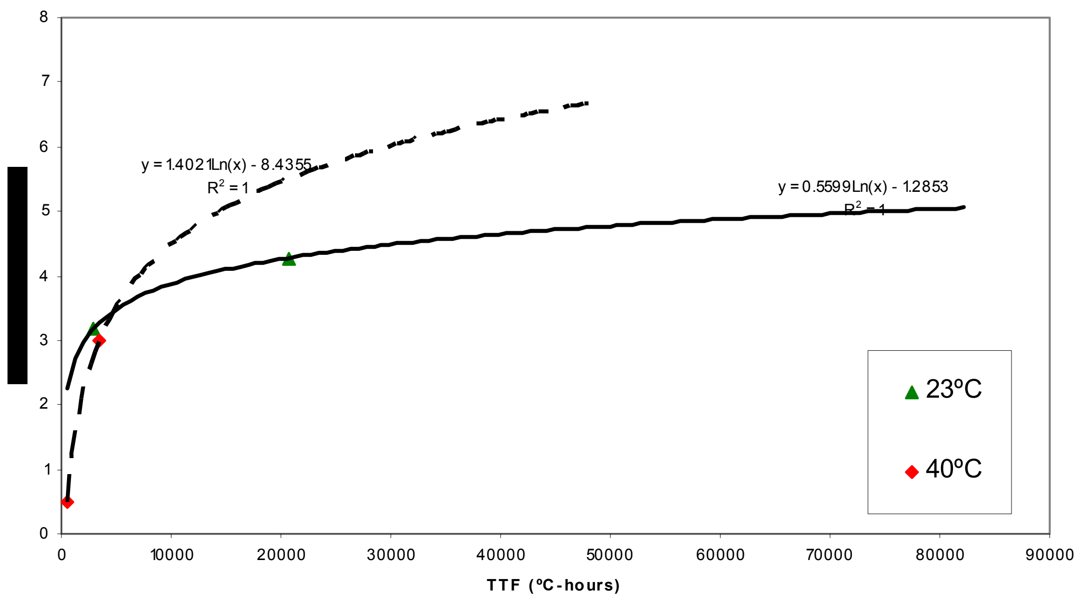

Figure C2-8g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 2, laboratory beams).

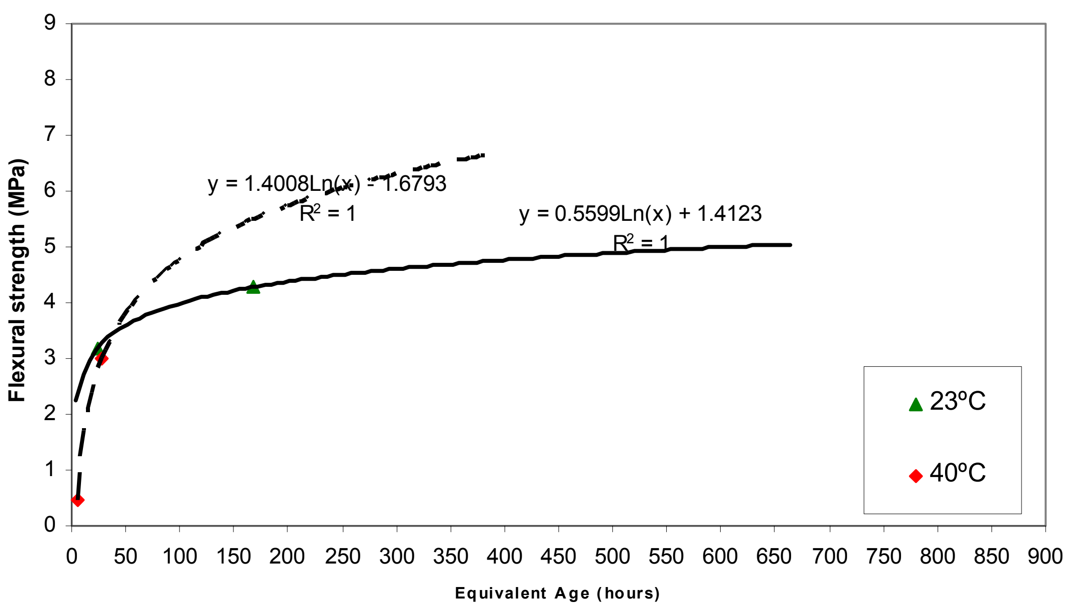

Figure C2-8h. Correlation between flexural strength and t_e, measured *E*, (Mix # 2, laboratory beams).

Mix #3 – Riverside II Compressive Strength versus Maturity

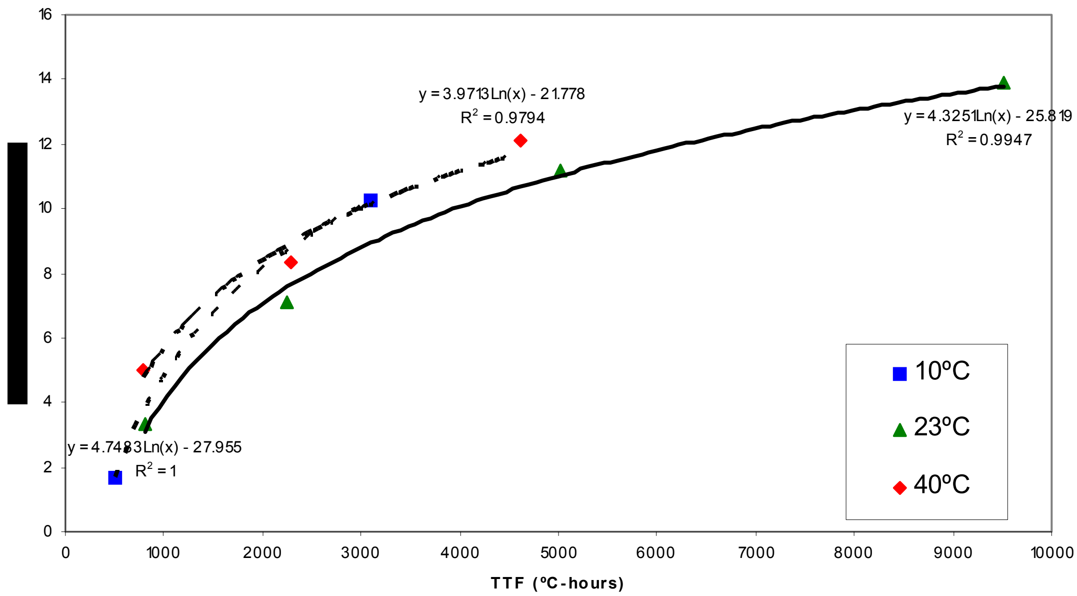

Figure C2-9a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #3, laboratory cylinders).

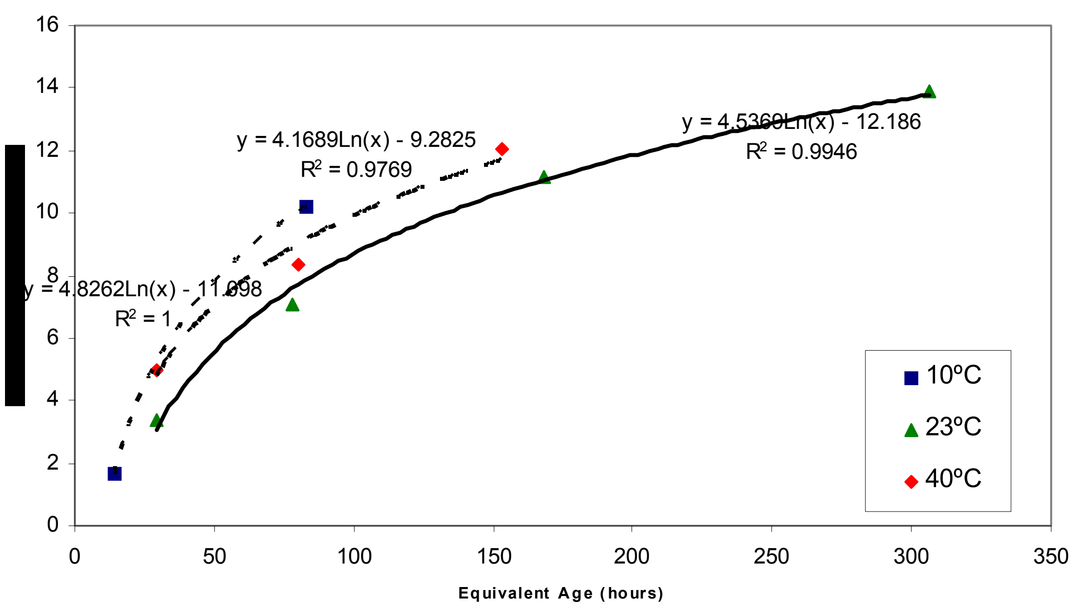

Figure C2-9b. Correlation between compressive strength and t_e, assumed *E* (Mix #3, laboratory cylinders).

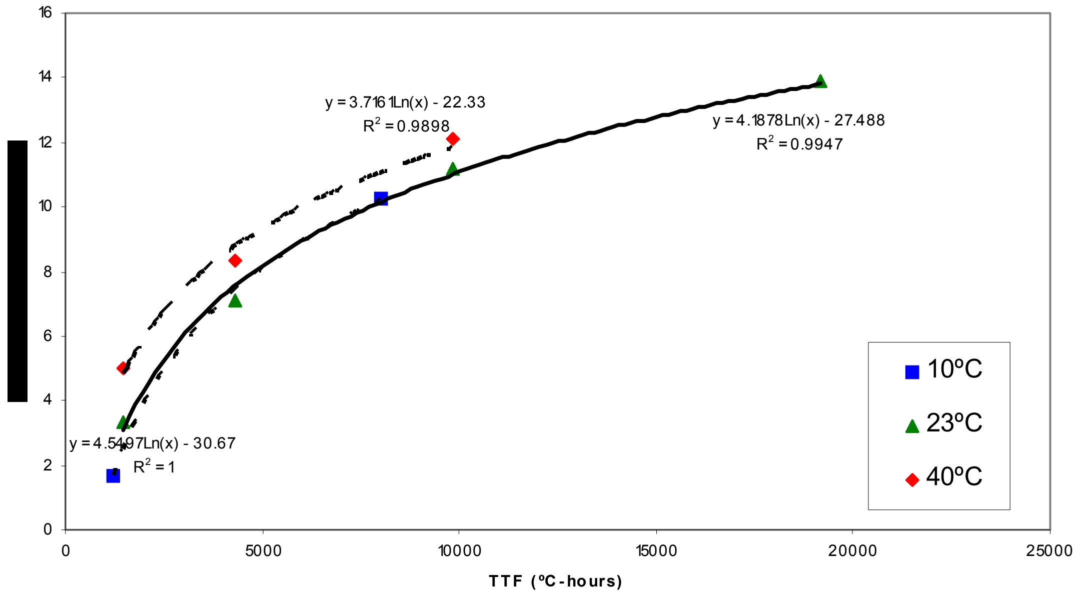

Figure C2-9c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 3, laboratory cylinders).

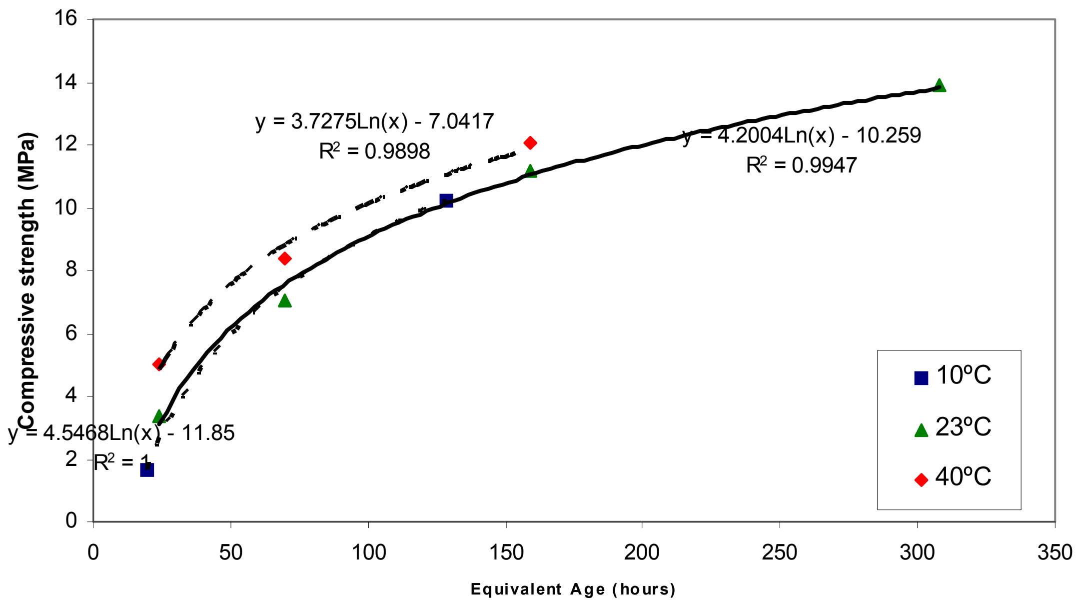

Figure C2-9d. Correlation between compressive strength and t_e, measured *E*, (Mix # 3, laboratory cylinders).

Mix #3 – Riverside II Flexural Strength versus Maturity

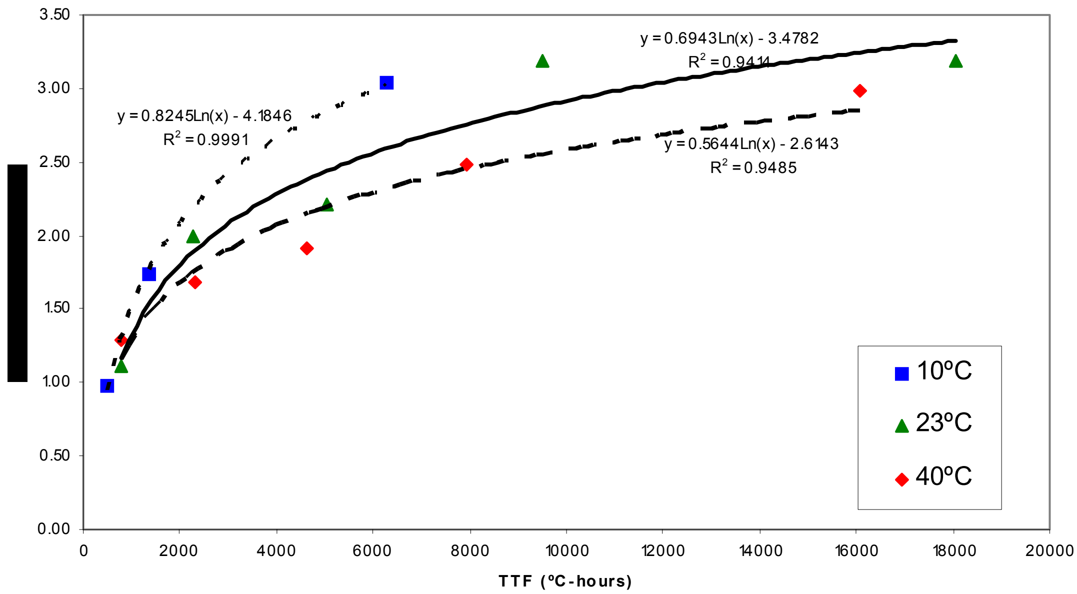

Figure C2-9e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 3, laboratory beams).

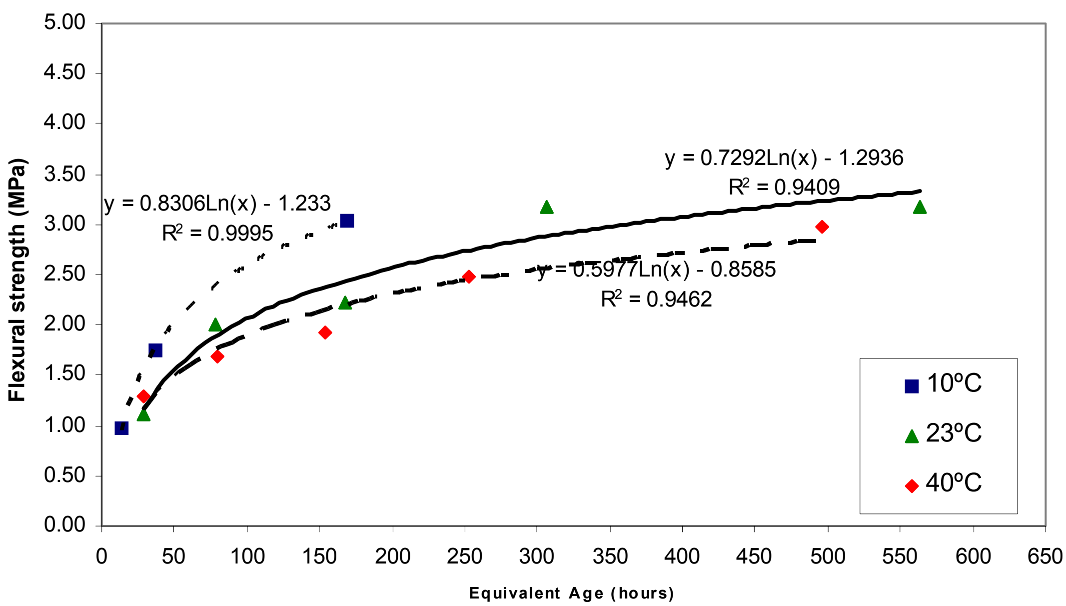

Figure C2-9f. Correlation between flexural strength and t_e, assumed E, (Mix # 3, laboratory beams).

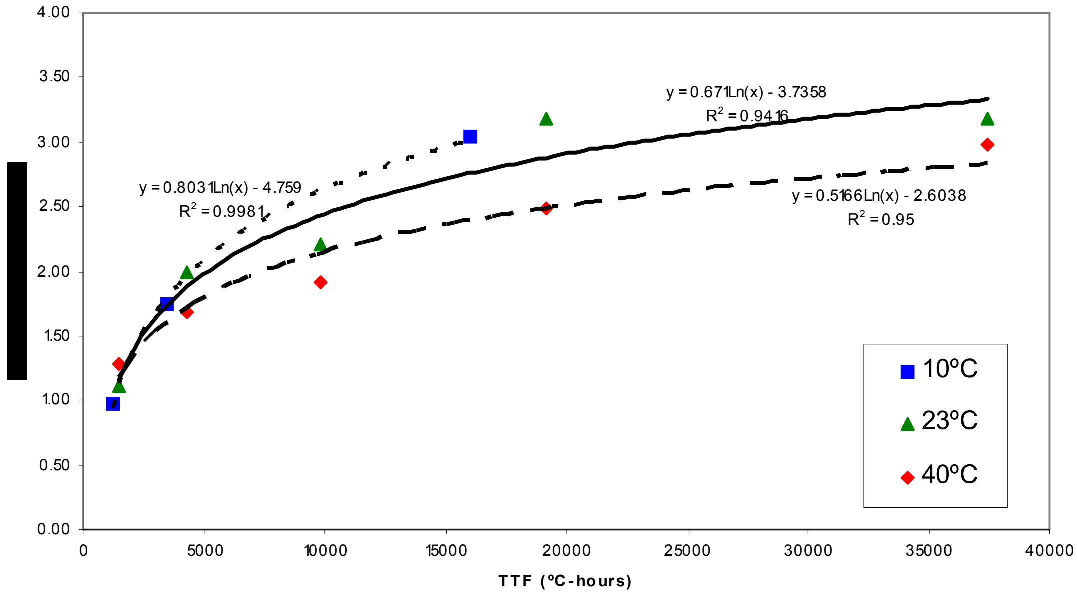

Figure C2-9g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 3, laboratory beams).

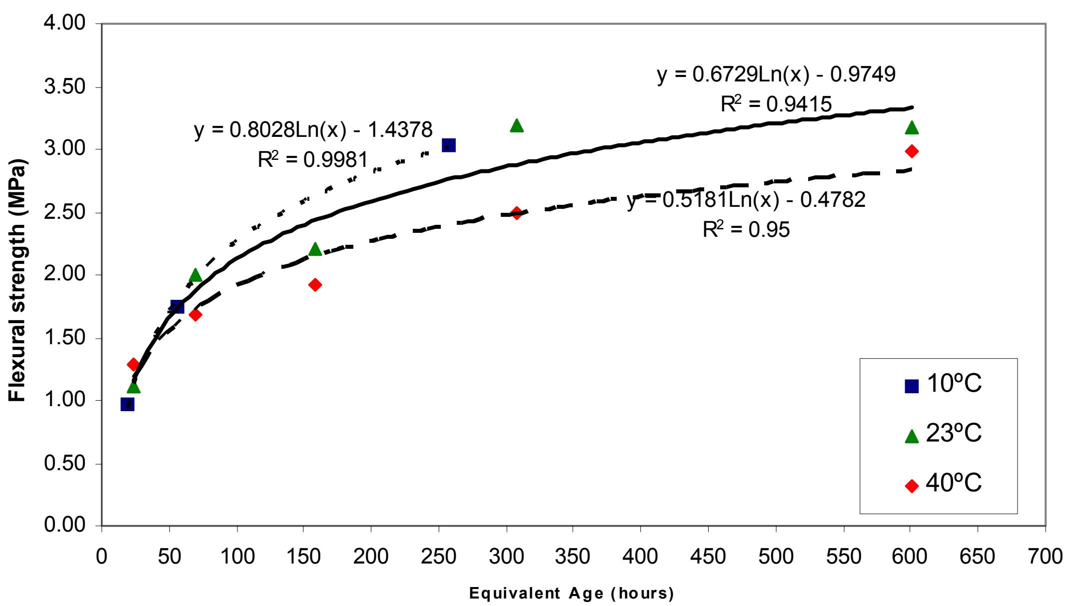

Figure C2-9h. Correlation between flexural strength and t_e, measured *E*, (Mix # 3, laboratory beams).

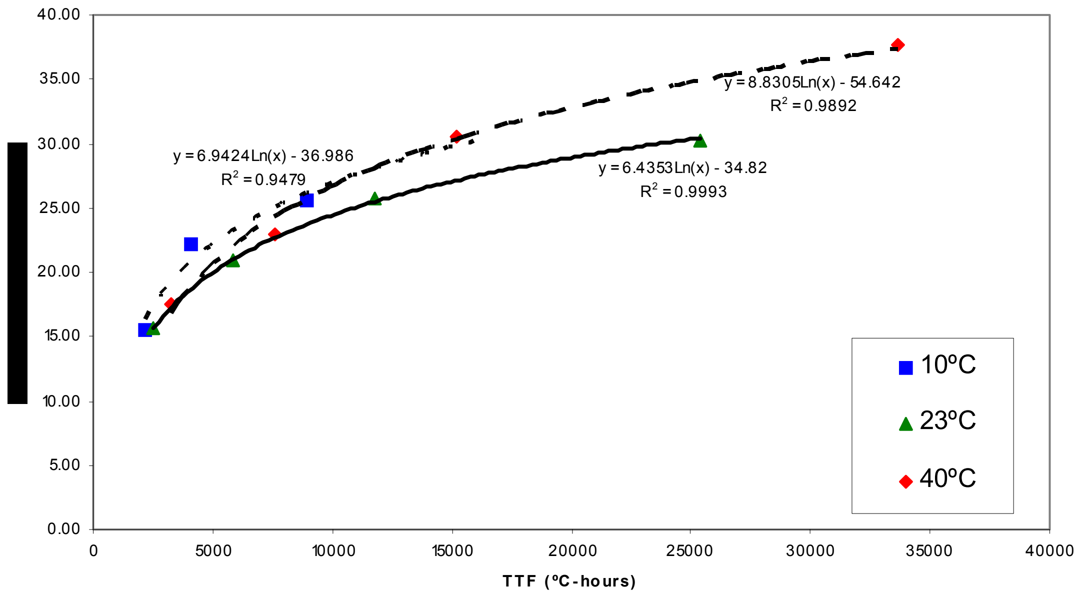

Figure C2-10a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #4, laboratory cylinders).

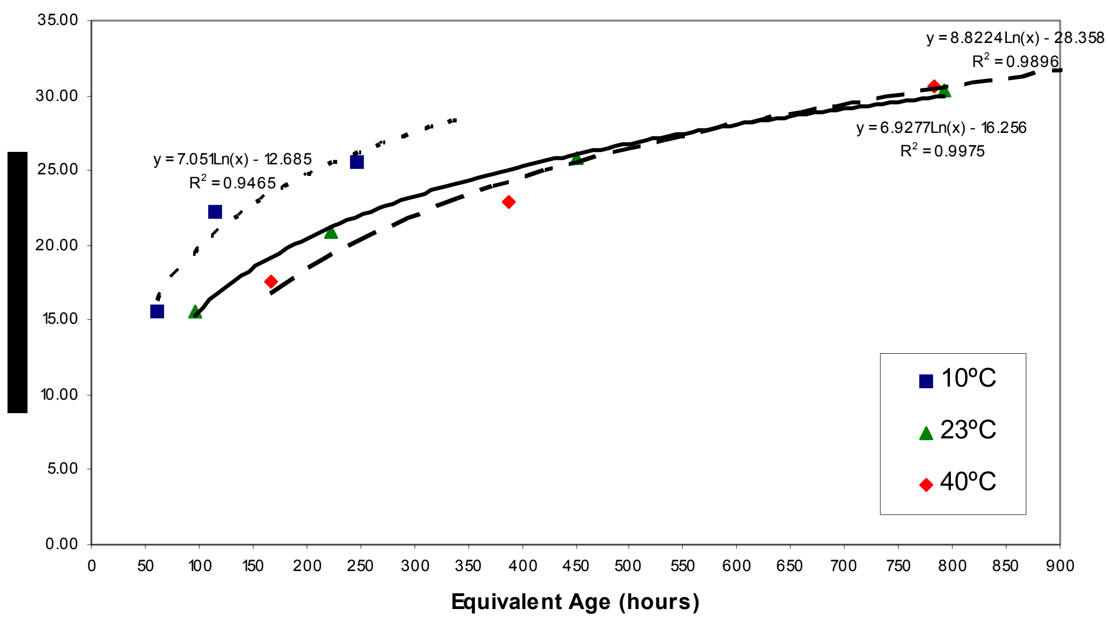

Figure C2-10b. Correlation between compressive strength and t_e, assumed *E* (Mix #4, laboratory cylinders).

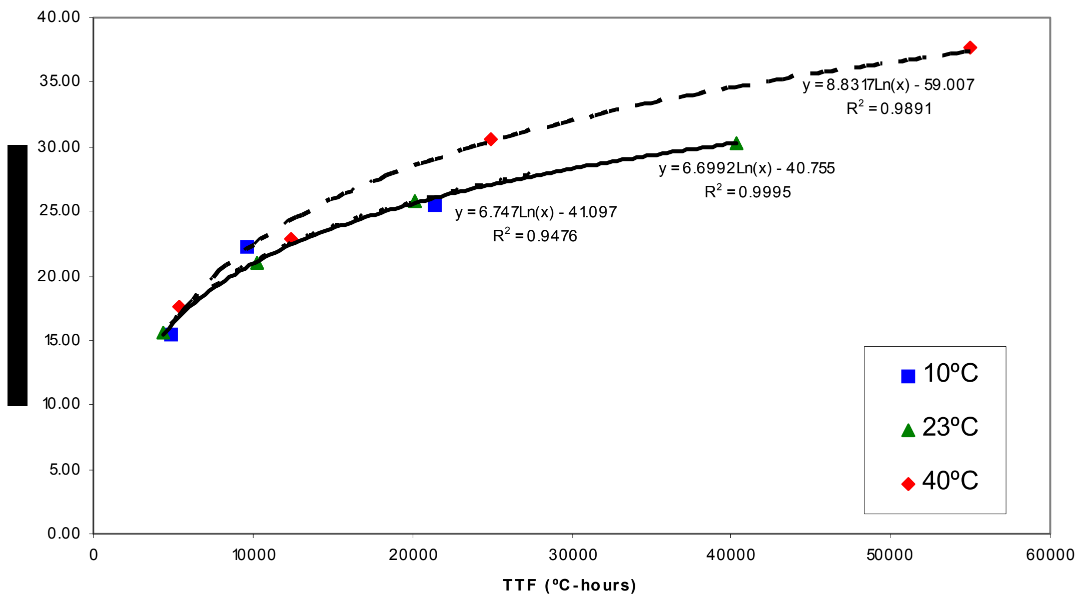

Figure C2-10c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 4, laboratory cylinders).

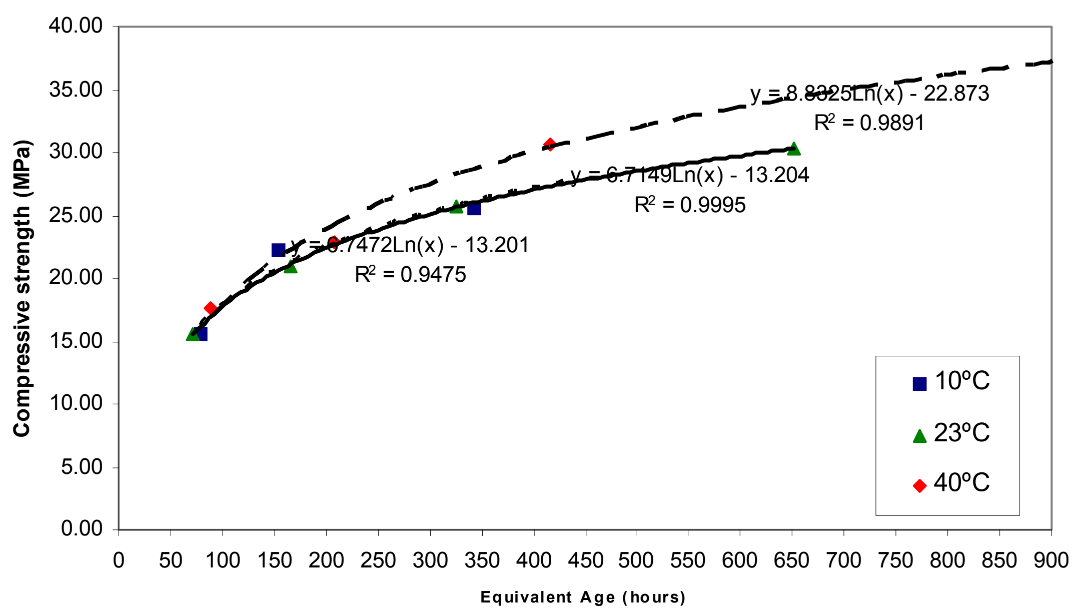

Figure C2-10d. Correlation between compressive strength and t_e, measured *E,* (Mix # 4, laboratory cylinders).

Mix #4 – Victorville Flexural Strength versus Maturity

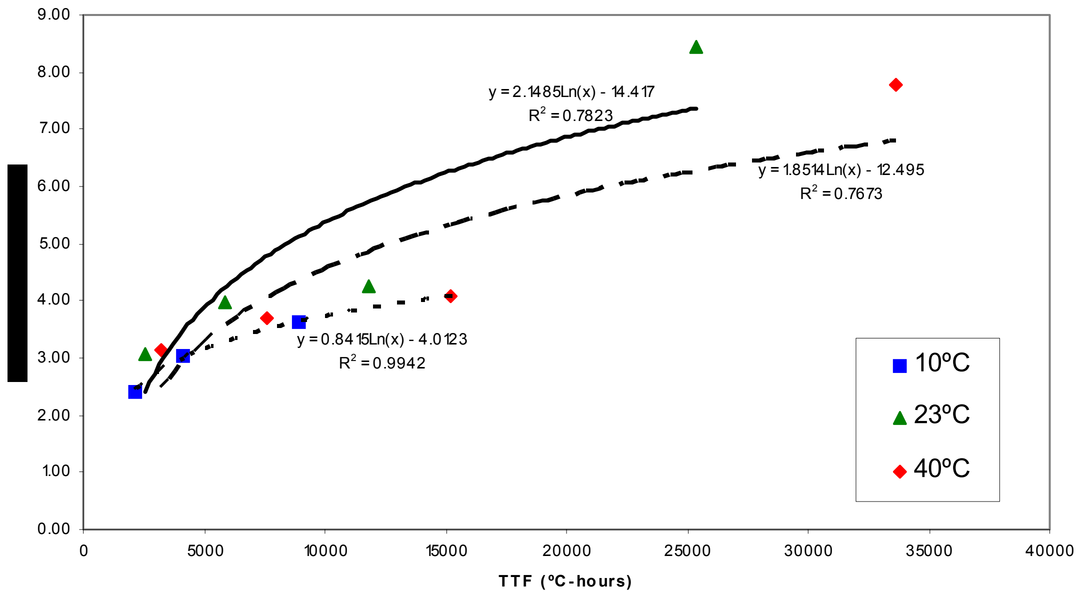

Figure C2-10e. Correlation between flexural strength and *TTF*, assumed T_0, (Mix # 4, laboratory beams).

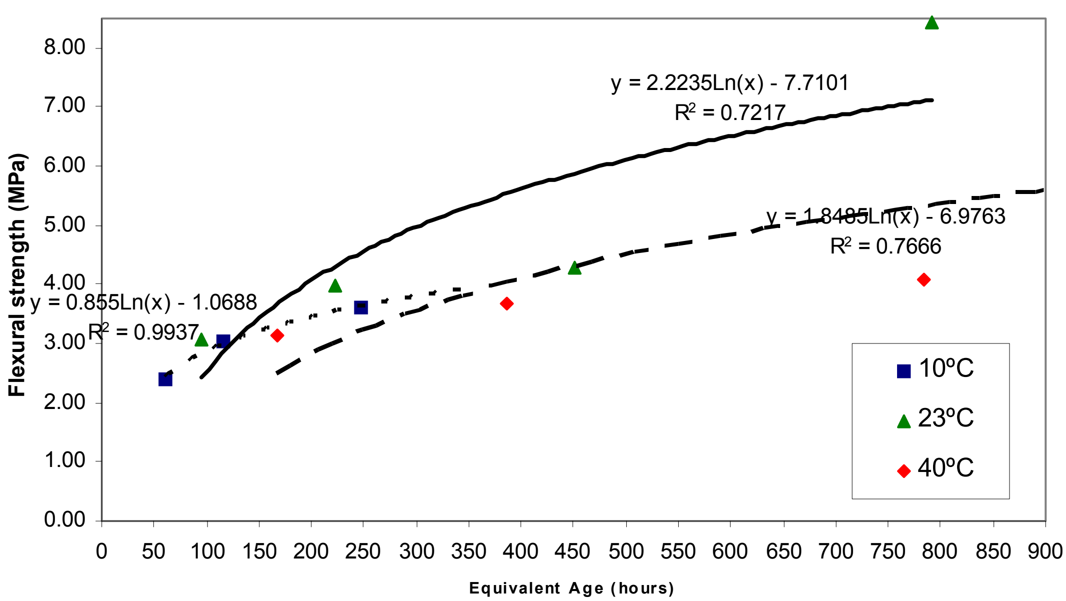

Figure C2-10f. Correlation between flexural strength and t_e, assumed *E*, (Mix # 4, laboratory beams).

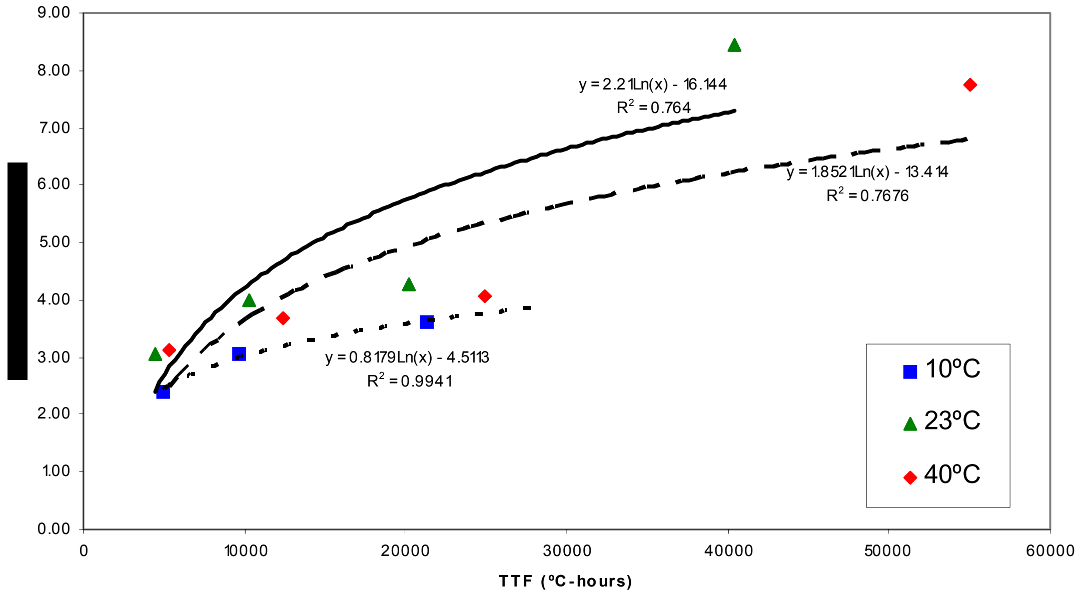

Figure C2-10g. Correlation between flexural strength and *TTF*, measured T_0, (Mix # 4, laboratory beams).

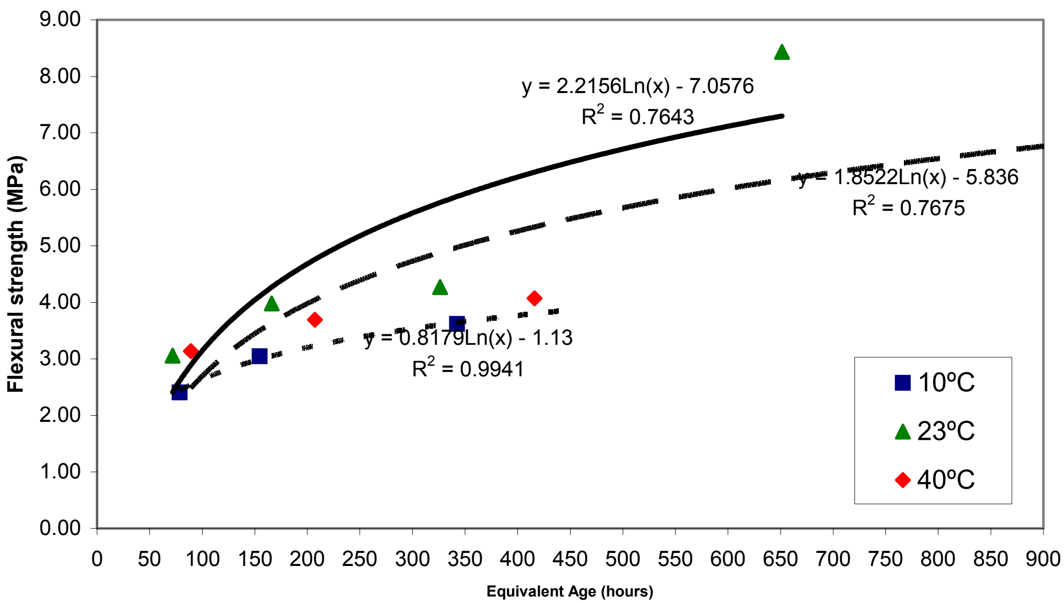

Figure C2-10h. Correlation between flexural strength and t_e, measured *E*, (Mix # 4, laboratory beams).

Mix #4 – Victorville Flexural Strength versus Maturity (Early Age Data Only, up to 14 Days)

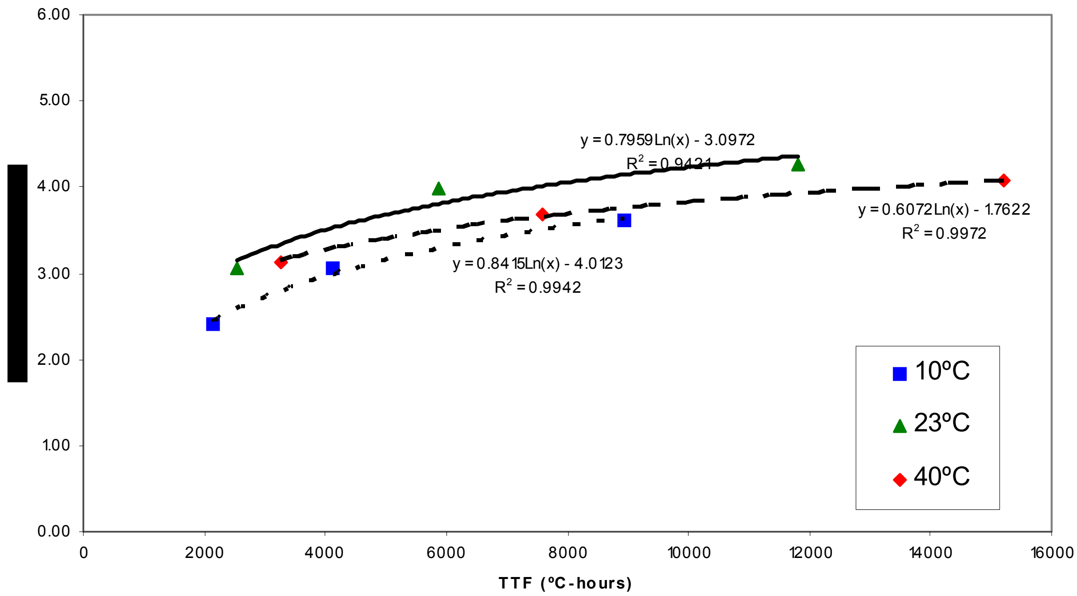

Figure C2-10i. Correlation between flexural strength and *TTF* at earlier ages, assumed T_0, (Mix # 4, laboratory beams).

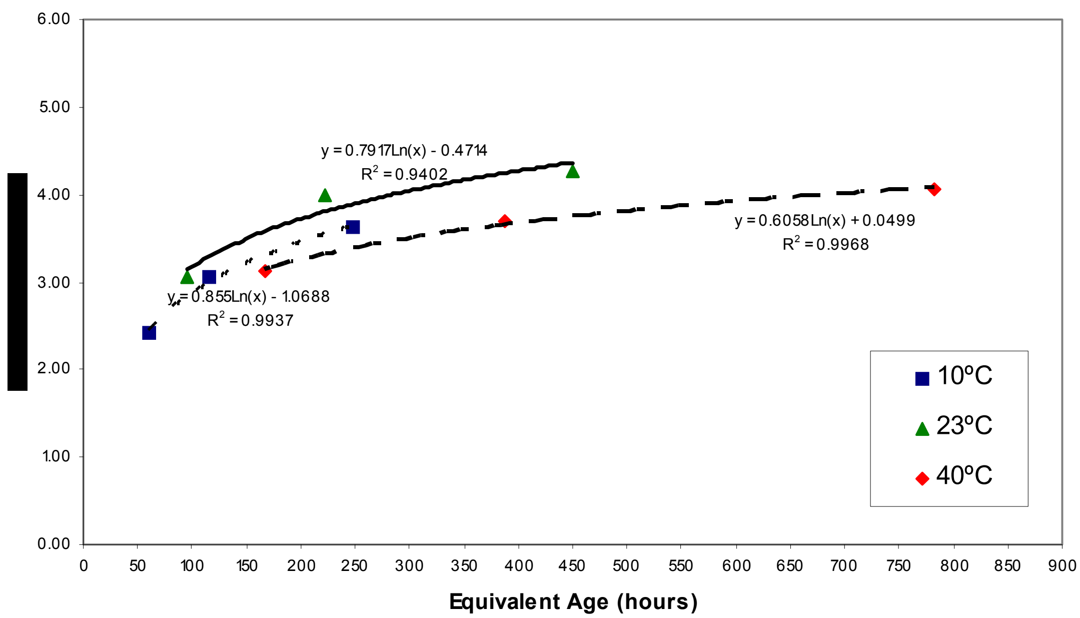

Figure C2-10j. Correlation between flexural strength and t_e at earlier ages, assumed *E*, (Mix # 4, laboratory beams).

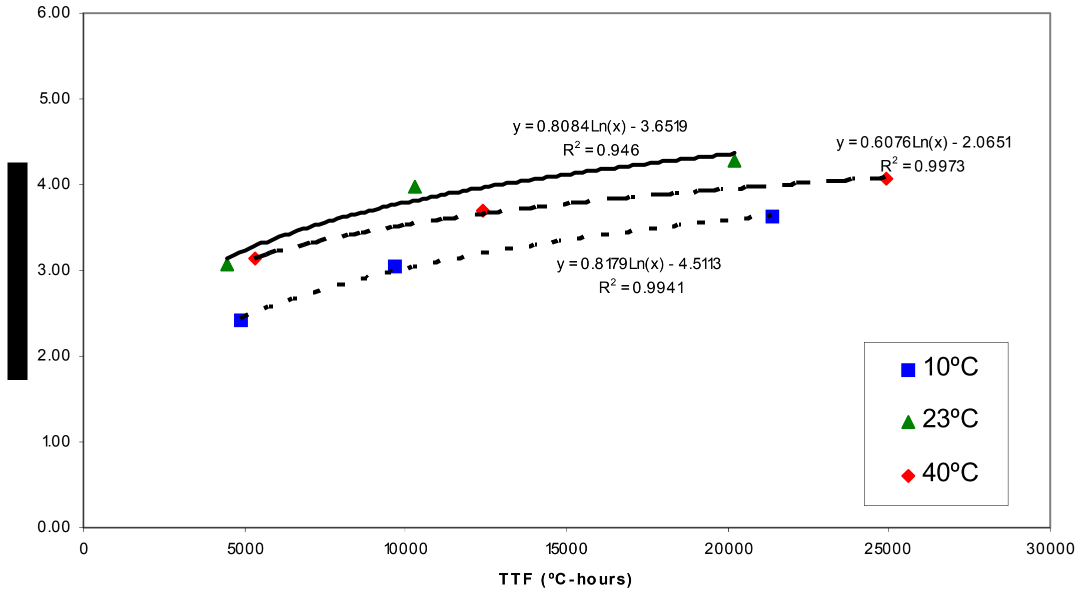

Figure C2-10k. Correlation between flexural strength and *TTF* at earlier ages, measured T_0, (Mix # 4, laboratory beams).

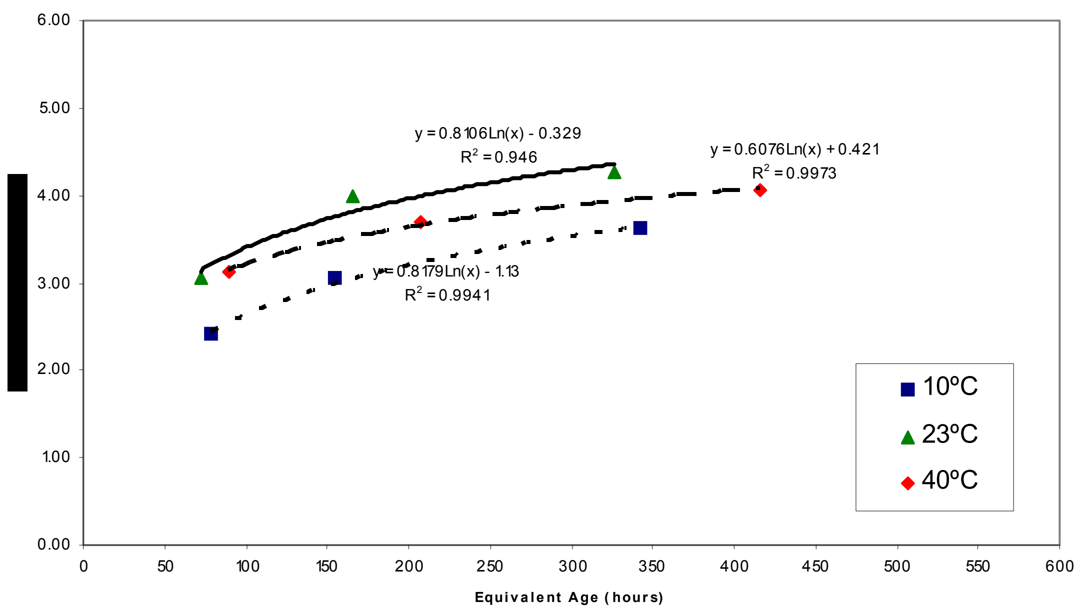

Figure C2-10l. Correlation between flexural strength and t_e at earlier ages, measured *E*, (Mix # 4, laboratory beams).

Appendix C3: Summary of Test Data for Compressive and Flexural Strength Determinations

Table C3-1 Ludlow - Compressive Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
29	**1**	Load (kips)	43.86	45.40	44.63	1.09	2.4%
		fc (psi)	1551.23	1605.70	**1578.46**	38.51	
		fc (MPa)	10.70	11.07	**10.88**	0.27	
80	**3**	Load (kips)	74.08	68.84	71.46	3.71	5.2%
		fc (psi)	2620.04	2434.72	**2527.38**	131.05	
		fc (MPa)	18.06	16.79	**17.43**	0.90	
173	**7**	Load (kips)	101.55	97.01	99.28	3.21	3.2%
		fc (psi)	3591.60	3431.03	**3511.31**	113.54	
		fc (MPa)	24.76	23.66	**24.21**	0.78	
246	**10**	Load (kips)	107.04	108.32	107.68	0.91	0.8%
		fc (psi)	3785.77	3831.04	**3808.40**	32.01	
		fc (MPa)	26.10	26.41	**26.26**	0.22	
342	**14**	Load (kips)	111.58	112.58	112.08	0.71	0.6%
		fc (psi)	3946.34	3981.70	**3964.02**	25.01	
		fc (MPa)	27.21	27.45	**27.33**	0.17	
678	**28**	Load (kips)	135.00	135.80	135.40	0.57	0.4%
		fc (psi)	4774.65	4802.94	**4788.80**	20.01	
		fc (MPa)	32.92	33.11	**33.02**	0.14	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
31	**1**	Load (kips)	14.99	14.98	14.99	0.01	0.0%
		fc (psi)	530.16	529.81	**529.99**	0.25	
		fc (MPa)	3.66	3.65	**3.65**	0.00	
73	**3**	Load (kips)	44.27	46.03	45.15	1.24	2.8%
		fc (psi)	1565.73	1627.98	**1596.85**	44.02	
		fc (MPa)	10.80	11.22	**11.01**	0.30	
176	**7**	Load (kips)	67.66	65.32	66.49	1.65	2.5%
		fc (psi)	2392.98	2310.22	**2351.60**	58.52	
		fc (MPa)	16.50	15.93	**16.21**	0.40	
245	**10**	Load (kips)	62.12	84.45	73.29	15.79	21.5%
		fc (psi)	2197.05	2986.81	**2591.93**	558.45	
		fc (MPa)	15.15	20.59	**17.87**	3.85	
344	**14**	Load (kips)	95.15	94.07	94.61	0.76	0.8%
		fc (psi)	3365.24	3327.05	**3346.14**	27.01	
		fc (MPa)	23.20	22.94	**23.07**	0.19	
673	**28**	Load (kips)	111.50	116.30	113.90	3.39	3.0%
		fc (psi)	3943.51	4113.27	**4028.39**	120.04	
		fc (MPa)	27.19	28.36	**27.77**	0.83	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
25	**1**	Load (kips)	37.59	32.79	35.19	3.39	9.6%
		fc (psi)	1329.47	1159.71	**1244.59**	120.04	
		fc (MPa)	9.17	8.00	**8.58**	0.83	
72	**3**	Load (kips)	36.61	50.00	43.31	9.47	21.9%
		fc (psi)	1294.81	1768.39	**1531.60**	334.87	
		fc (MPa)	8.93	12.19	**10.56**	2.31	
168	**7**	Load (kips)	46.40	75.18	60.79	20.35	33.5%
		fc (psi)	1641.06	2658.95	**2150.01**	719.75	
		fc (MPa)	11.31	18.33	**14.82**	4.96	
336	**14**	Load (kips)	80.50	90.32	85.41	6.94	8.1%
		fc (psi)	2847.11	3194.42	**3020.76**	245.59	
		fc (MPa)	19.63	22.02	**20.83**	1.69	
672	**28**	Load (kips)	109.60	112.80	111.20	2.26	2.0%
		fc (psi)	3876.31	3989.48	**3932.90**	80.03	
		fc (MPa)	26.73	27.51	**27.12**	0.55	

Table C3-2 Ludlow - Flexural Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
29	**1**	Load (kN)	18.11	17.04	17.58	0.75	4.3%
		ft (psi)	339.17	319.19	**329.18**	14.13	
		ft (MPa)	2.34	2.20	**2.27**	0.10	
80	**3**	Load (kN)	21.51	23.76	22.63	1.59	7.0%
		ft (psi)	402.73	444.93	**423.83**	29.83	
		ft (MPa)	2.78	3.07	**2.92**	0.21	
173	**7**	Load (kN)	23.76	28.43	26.09	3.30	6.9%
		ft (psi)	435.90	480.62	**458.26**	31.62	
		ft (MPa)	3.01	3.31	**3.16**	0.22	
246	**10**	Load (kN)	32.87	27.95	30.41	3.48	5.7%
		ft (psi)	555.77	512.70	**534.23**	30.46	
		ft (MPa)	3.83	3.53	**3.68**	0.21	
342	**14**	Load (kN)	30.87	30.87	30.87	0.00	0.0%
		ft (psi)	578.14	578.14	**578.14**	0.00	
		ft (MPa)	3.99	3.99	**3.99**	0.00	
677	**28**	Load (kN)	33.43	28.85	31.14	3.24	10.4%
		ft (psi)	626.06	540.29	**583.17**	60.65	
		ft (MPa)	4.32	3.73	**4.02**	0.42	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
31	**1**	Load (kN)	10.03	8.40	9.22	1.15	11.8%
		ft (psi)	173.06	146.30	**159.68**	18.92	
		ft (MPa)	1.19	1.01	**1.10**	0.13	
73	**3**	Load (kN)	18.62	18.77	18.70	0.11	0.6%
		ft (psi)	348.71	351.51	**350.11**	1.99	
		ft (MPa)	2.40	2.42	**2.41**	0.01	
176	**7**	Load (kN)	22.95	24.27	23.61	0.93	6.9%
		ft (psi)	412.43	454.52	**433.47**	29.76	
		ft (MPa)	2.84	3.13	**2.99**	0.21	
245	**10**	Load (kN)	27.79	26.71	27.25	0.76	2.8%
		ft (psi)	520.44	500.21	**510.32**	14.30	
		ft (MPa)	3.59	3.45	**3.52**	0.10	
344	**14**	Load (kN)	29.10	29.10	29.10	0.00	0.0%
		ft (psi)	544.95	544.95	**544.95**	0.00	
		ft (MPa)	3.76	3.76	**3.76**	0.00	
671	**28**	Load (kN)	29.37	29.12	29.25	0.18	0.6%
		ft (psi)	550.03	545.34	**547.69**	3.31	
		ft (MPa)	3.79	3.76	**3.78**	0.02	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
25	**1**	Load (kN)	12.55	14.24	13.40	1.20	6.1%
		ft (psi)	230.23	250.97	**240.60**	14.66	
		ft (MPa)	1.59	1.73	**1.66**	0.10	
72	**3**	Load (kN)	20.80	15.60	18.20	3.68	20.2%
		ft (psi)	389.53	292.15	**340.84**	68.86	
		ft (MPa)	2.69	2.01	**2.35**	0.47	
168	**7**	Load (kN)	21.69	19.58	20.64	1.49	7.2%
		ft (psi)	397.91	359.20	**378.56**	27.37	
		ft (MPa)	2.74	2.48	**2.61**	0.19	
336	**14**	Load (kN)	27.25	27.55	27.40	0.21	0.8%
		ft (psi)	510.32	515.94	**513.13**	3.97	
		ft (MPa)	3.52	3.56	**3.54**	0.03	
672	**28**	Load (kN)	27.25	27.55	27.40	0.21	0.8%
		ft (psi)	510.32	515.94	**513.13**	3.97	
		ft (MPa)	3.52	3.56	**3.54**	0.03	

Table C3-3 Riverside I - Compressive Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
4.5	**0**	Load (kips)	0.92	1.29	1.11	0.26	23.3%
		fc (psi)	32.66	45.55	**39.11**	9.12	
		fc (MPa)	0.23	0.31	**0.27**	0.06	
24	**1**	Load (kips)	75.85	72.82	74.33	2.14	2.9%
		fc (psi)	2682.47	2575.45	**2628.96**	75.68	
		fc (MPa)	18.49	17.76	**18.13**	0.52	
168	**7**	Load (kips)	133.56	133.56	133.56	0.00	0.0%
		fc (psi)	4723.54	4723.72	**4723.63**	0.13	
		fc (MPa)	32.57	32.57	**32.57**	0.00	
336	**14**	Load (kips)	88.65	88.65	88.65	0.00	0.0%
		fc (psi)	3135.42	3135.42	**3135.42**	0.00	
		fc (MPa)	21.62	21.62	**21.62**	0.00	
672	**28**	Load (kips)	161.13	173.39	167.26	8.67	5.2%
		fc (psi)	5698.63	6132.45	**5915.54**	306.76	
		fc (MPa)	39.29	42.28	**40.79**	2.11	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
72	**3**	Load (kips)	92.68	88.64	90.66	2.86	3.2%
		fc (psi)	3277.88	3135.00	**3206.44**	101.04	
		fc (MPa)	22.60	21.61	**22.11**	0.70	
168	**7**	Load (kips)	126.89	104.50	115.70	15.83	13.7%
		fc (psi)	4487.82	3695.93	**4091.87**	559.95	
		fc (MPa)	30.94	25.48	**28.21**	3.86	
336	**14**	Load (kips)	143.20	139.66	141.43	2.51	1.8%
		fc (psi)	5064.77	4939.46	**5002.12**	88.61	
		fc (MPa)	34.92	34.06	**34.49**	0.61	
672	**28**	Load (kips)	122.29	150.89	136.59	20.22	14.8%
		fc (psi)	4325.12	5336.64	**4830.88**	715.25	
		fc (MPa)	29.82	36.79	**33.31**	4.93	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
4.5	**0**	Load (kips)	11.08	11.72	11.40	0.45	4.0%
		fc (psi)	391.87	414.51	**403.19**	16.01	
		fc (MPa)	2.70	2.86	**2.78**	0.11	
24	**1**	Load (kips)	98.47	98.47	98.47	0.00	0.0%
		fc (psi)	3482.66	3482.66	**3482.66**	0.00	
		fc (MPa)	24.01	24.01	**24.01**	0.00	
171	**7**	Load (kips)	120.49	136.15	128.32	11.07	8.6%
		fc (psi)	4261.46	4815.32	**4538.39**	391.64	
		fc (MPa)	29.38	33.20	**31.29**	2.70	
675	**28**	Load (kips)	85.05	65.52	75.29	13.81	18.3%
		fc (psi)	3008.03	2317.30	**2662.66**	488.42	
		fc (MPa)	20.74	15.98	**18.36**	3.37	

Table C3-4 Riverside I - Flexural Strength

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kN)	22.70	24.34	23.52	1.16	4.9%
		ft (psi)	425.11	455.83	**440.47**	21.72	
		ft (MPa)	2.93	3.14	**3.04**	0.15	
72	**3**	Load (kN)	29.79	28.05	28.92	1.23	4.3%
		ft (psi)	557.89	525.31	**541.60**	23.04	
		ft (MPa)	3.85	3.62	**3.73**	0.16	
168	**7**	Load (kN)	33.55	32.15	32.85	0.99	3.0%
		ft (psi)	628.31	602.09	**615.20**	18.54	
		ft (MPa)	4.33	4.15	**4.24**	0.13	
336	**14**	Load (kN)	36.75	32.50	34.63	3.01	8.7%
		ft (psi)	688.24	608.64	**648.44**	56.28	
		ft (MPa)	4.75	4.20	**4.47**	0.39	
672	**28**	Load (kN)	62.57	59.86	61.22	1.92	3.1%
		ft (psi)	1171.78	1121.03	**1146.40**	35.89	
		ft (MPa)	8.08	7.73	**7.90**	0.25	

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
5	**0**	Load (kN)			#DIV/0!	#DIV/0!	#DIV/0!
		ft (psi)	0.00	0.00	**0.00**	0.00	#DIV/0!
		ft (MPa)	0.00	0.00	**0.00**	0.00	
24	**1**	Load (kN)	25.31	24.19	24.75	0.79	3.2%
		ft (psi)	473.99	453.02	**463.51**	14.83	3.2%
		ft (MPa)	3.27	3.12	**3.20**	0.10	
168	**7**	Load (kN)	34.88	35.55	35.22	0.47	1.3%
		ft (psi)	639.88	601.04	**620.46**	27.46	4.4%
		ft (MPa)	4.41	4.14	**4.28**	0.19	
336	**14**	Load (kN)			#DIV/0!	#DIV/0!	#DIV/0!
		ft (psi)	0.00	0.00	**0.00**	0.00	#DIV/0!
		ft (MPa)	0.00	0.00	**0.00**	0.00	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
5	**0**	Load (kN)	3.50	3.94	3.72	0.31	8.4%
		ft (psi)	65.55	73.79	**69.67**	5.83	8.4%
		ft (MPa)	0.45	0.51	**0.48**	0.04	
24	**1**	Load (kN)	22.71	23.52	23.12	0.57	2.5%
		ft (psi)	425.30	440.47	**432.89**	10.73	2.5%
		ft (MPa)	2.93	3.04	**2.98**	0.07	
168	**7**	Load (kN)			#DIV/0!	#DIV/0!	#DIV/0!
		ft (psi)	0.00	0.00	**0.00**	0.00	#DIV/0!
		ft (MPa)	0.00	0.00	**0.00**	0.00	
336	**14**	Load (kN)			#DIV/0!	#DIV/0!	#DIV/0!
		ft (psi)	0.00	0.00	**0.00**	0.00	#DIV/0!
		ft (MPa)	0.00	0.00	**0.00**	0.00	

Note: In this mix, in the Std and Cold curing conditions, some data points were lost due to problems with the MTS machine's data acquisition system

Table C3-5 Riverside II - Compressive Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kips)	13.14	14.34	13.74	0.85	6.2%
		fc (psi)	464.73	507.17	**485.95**	30.01	
		fc (MPa)	3.20	3.50	**3.35**	0.21	
72	**3**	Load (kips)	26.99	31.05	29.02	2.87	9.9%
		fc (psi)	954.58	1098.17	**1026.37**	101.54	
		fc (MPa)	6.58	7.57	**7.08**	0.70	
168	**7**	Load (kips)	46.83	44.92	45.88	1.35	2.9%
		fc (psi)	1656.27	1588.72	**1622.50**	47.77	
		fc (MPa)	11.42	10.95	**11.19**	0.33	
336	**14**	Load (kips)	59.14	54.85	57.00	3.03	5.3%
		fc (psi)	2091.65	1939.92	**2015.79**	107.29	
		fc (MPa)	14.42	13.38	**13.90**	0.74	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kips)	6.34	7.10	6.72	0.54	8.0%
		fc (psi)	224.23	251.11	**237.67**	19.01	
		fc (MPa)	1.55	1.73	**1.64**	0.13	
72	**3**	Load (kips)			#DIV/0!	#DIV/0!	#DIV/0!
		fc (psi)	0.00	0.00	**0.00**	0.00	
		fc (MPa)	0.00	0.00	**0.00**	0.00	
192	**8**	Load (kips)	44.01	39.88	41.95	2.92	7.0%
		fc (psi)	1556.54	1410.47	**1483.50**	103.29	
		fc (MPa)	10.73	9.72	**10.23**	0.71	
336	**14**	Load (kips)	71.78	70.26	71.02	1.07	1.5%
		fc (psi)	2538.70	2484.94	**2511.82**	38.01	
		fc (MPa)	17.50	17.13	**17.32**	0.26	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kips)	18.79	22.19	20.49	2.40	11.7%
		fc (psi)	664.56	784.81	**724.69**	85.03	
		fc (MPa)	4.58	5.41	**5.00**	0.59	
72	**3**	Load (kips)	35.80	32.84	34.32	2.09	6.1%
		fc (psi)	1266.17	1161.48	**1213.82**	74.03	
		fc (MPa)	8.73	8.01	**8.37**	0.51	
168	**7**	Load (kips)	50.64	48.42	49.53	1.57	3.2%
		fc (psi)	1791.02	1712.51	**1751.77**	55.52	
		fc (MPa)	12.35	11.81	**12.08**	0.38	
336	**14**	Load (kips)	46.14	36.34	41.24	6.93	16.8%
		fc (psi)	1631.87	1285.26	**1458.57**	245.09	
		fc (MPa)	11.25	8.86	**10.06**	1.69	

Table C3-6 Riverside II - Flexural Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kN)	9.46	7.83	8.65	1.15	13.3%
		ft (psi)	177.16	146.64	**161.90**	21.59	
		ft (MPa)	1.22	1.01	**1.12**	0.15	
72	**3**	Load (kN)	15.05	15.91	15.48	0.61	3.9%
		ft (psi)	281.85	297.95	**289.90**	11.39	
		ft (MPa)	1.94	2.05	**2.00**	0.08	
168	**7**	Load (kN)	18.51	17.89	18.20	0.44	8.2%
		ft (psi)	339.57	302.47	**321.02**	26.24	
		ft (MPa)	2.34	2.09	**2.21**	0.18	
336	**14**	Load (kN)	24.65	24.64	24.65	0.01	0.0%
		ft (psi)	461.63	461.45	**461.54**	0.13	
		ft (MPa)	3.18	3.18	**3.18**	0.00	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kN)	8.03	7.07	7.55	0.68	9.0%
		ft (psi)	150.38	132.40	**141.39**	12.71	
		ft (MPa)	1.04	0.91	**0.97**	0.09	
72	**3**	Load (kN)	13.15	13.81	13.48	0.47	3.5%
		ft (psi)	246.27	258.63	**252.45**	8.74	
		ft (MPa)	1.70	1.78	**1.74**	0.06	
192	**8**	Load (kN)	33.24	28.96	31.10	3.03	9.7%
		ft (psi)	622.50	542.35	**582.42**	56.68	
		ft (MPa)	4.29	3.74	**4.02**	0.39	
336	**14**	Load (kN)	22.71	24.35	23.53	1.16	4.9%
		ft (psi)	425.30	456.01	**440.66**	21.72	
		ft (MPa)	2.93	3.14	**3.04**	0.15	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
24	**1**	Load (kN)	10.13	9.82	9.98	0.22	2.2%
		ft (psi)	189.71	183.90	**186.81**	4.11	
		ft (MPa)	1.31	1.27	**1.29**	0.03	
72	**3**	Load (kN)	12.03	14.11	13.07	1.47	11.3%
		ft (psi)	225.29	264.24	**244.77**	27.54	
		ft (MPa)	1.55	1.82	**1.69**	0.19	
168	**7**	Load (kN)	14.00	15.71	14.86	1.21	8.1%
		ft (psi)	262.18	294.21	**278.20**	22.64	
		ft (MPa)	1.81	2.03	**1.92**	0.16	
336	**14**	Load (kN)	19.58	18.94	19.26	0.45	2.3%
		ft (psi)	366.68	354.70	**360.69**	8.48	
		ft (MPa)	2.53	2.45	**2.49**	0.06	
672	**28**	Load (kN)	22.71	23.52	23.12	0.57	2.5%
		ft (psi)	425.30	440.47	**432.89**	10.73	
		ft (MPa)	2.93	3.04	**2.98**	0.07	

Table C3-7 Victorville - Compressive Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
72	**3**	Load (kips)	59.89	67.98	63.93	5.72	9.0%
		fc (psi)	2118.00	2404.30	**2261.15**	202.45	
		fc (MPa)	14.60	16.58	**15.59**	1.40	
168	**7**	Load (kips)	87.81	83.88	85.85	2.78	3.2%
		fc (psi)	3105.64	2966.65	**3036.15**	98.28	
		fc (MPa)	21.41	20.45	**20.93**	0.68	
336	**14**	Load (kips)	99.33	111.99	105.66	8.95	8.5%
		fc (psi)	3513.08	3960.84	**3736.96**	316.61	
		fc (MPa)	24.22	27.31	**25.77**	2.18	
744	**31**	Load (kips)	113.10	135.44	124.27	15.80	12.7%
		fc (psi)	4000.09	4790.21	**4395.15**	558.70	
		fc (MPa)	27.58	33.03	**30.30**	3.85	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
96	**4**	Load (kips)	56.84	70.33	63.58	9.54	15.0%
		fc (psi)	2010.25	2487.44	**2248.85**	337.42	
		fc (MPa)	13.86	17.15	**15.51**	2.33	
192	**8**	Load (kips)	88.42	93.38	90.90	3.51	3.9%
		fc (psi)	3127.06	3302.56	**3214.81**	124.10	
		fc (MPa)	21.56	22.77	**22.17**	0.86	
432	**18**	Load (kips)	110.36	99.20	104.78	7.89	7.5%
		fc (psi)	3903.03	3508.52	**3705.77**	278.96	
		fc (MPa)	26.91	24.19	**25.55**	1.92	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
72	**3**	Load (kips)	72.90	71.18	72.04	1.22	1.7%
		fc (psi)	2578.31	2517.48	**2547.89**	43.02	
		fc (MPa)	17.78	17.36	**17.57**	0.30	
168	**7**	Load (kips)	86.22	101.73	93.97	10.96	11.7%
		fc (psi)	3049.41	3597.82	**3323.61**	387.79	
		fc (MPa)	21.02	24.81	**22.92**	2.67	
336	**14**	Load (kips)	124.08	126.85	125.47	1.96	1.6%
		fc (psi)	4388.43	4486.40	**4437.42**	69.27	
		fc (MPa)	30.26	30.93	**30.59**	0.48	
744	**31**	Load (kips)	154.53	155.07	154.80	0.38	0.2%
		fc (psi)	5465.38	5484.48	**5474.93**	13.50	
		fc (MPa)	37.68	37.81	**37.75**	0.09	

Table C3-8 Victorville - Flexural Strength

Standard Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
72	**3**	Load (kN)	25.13	23.45	24.29	1.19	4.9%
		ft (psi)	470.62	439.16	**454.89**	22.25	
		ft (MPa)	3.24	3.03	**3.14**	0.15	
168	**7**	Load (kN)	30.70	31.01	30.86	0.22	0.7%
		ft (psi)	574.93	580.74	**577.84**	4.11	
		ft (MPa)	3.96	4.00	**3.98**	0.03	
336	**14**	Load (kN)	34.37	31.75	33.06	1.85	5.6%
		ft (psi)	643.66	594.60	**619.13**	34.69	
		ft (MPa)	4.44	4.10	**4.27**	0.24	
744	**31**	Load (kN)	64.97	65.65	65.31	0.48	0.7%
		ft (psi)	1216.72	1229.46	**1223.09**	9.00	
		ft (MPa)	8.39	8.48	**8.43**	0.06	

Cold Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
96	**4**	Load (kN)	20.94	19.38	20.16	1.10	5.5%
		ft (psi)	361.26	337.59	**349.42**	16.74	
		ft (MPa)	2.49	2.33	**2.41**	0.12	
192	**8**	Load (kN)	21.53	25.67	23.60	2.93	12.4%
		ft (psi)	403.20	480.73	**441.97**	54.82	
		ft (MPa)	2.78	3.31	**3.05**	0.38	
432	**18**	Load (kN)	27.86	29.31	28.59	1.03	3.6%
		ft (psi)	500.67	548.90	**524.79**	34.11	
		ft (MPa)	3.45	3.78	**3.62**	0.24	

Hot Curing							
Age (hours)	**Age (days)**		**A**	**B**	**Average**	**Std. Dev.**	**Coef. Var.**
72	**3**	Load (kN)	22.72	24.69	23.71	1.39	5.9%
		ft (psi)	425.49	462.38	**443.94**	26.09	
		ft (MPa)	2.93	3.19	**3.06**	0.18	
168	**7**	Load (kN)	28.14	29.02	28.58	0.62	2.2%
		ft (psi)	526.99	543.47	**535.23**	11.65	
		ft (MPa)	3.63	3.75	**3.69**	0.08	
336	**14**	Load (kN)	33.34	31.01	32.18	1.65	5.1%
		ft (psi)	611.63	568.89	**590.26**	30.22	
		ft (MPa)	4.22	3.92	**4.07**	0.21	
744	**31**	Load (kN)	57.17	63.12	60.15	4.21	7.0%
		ft (psi)	1070.65	1182.08	**1126.36**	78.79	
		ft (MPa)	7.38	8.15	**7.77**	0.54	

Appendix C4: Compressive and Flexural Strength Maturity Relationships, Field Specimens

Each section contains 8 figures for a given mix. For each set of figures, the first four figures (a-d) present compressive strength results for field cylinders. The second 4 figures (e-h) present flexural strength results for field beams.

In one of the projects, (Riverside II – Mix #3), a different maturity meter was tested, and this meter did not provide the temperature history of the concrete. Instead, it only calculated *TTF* values at a few programmed ages. Unaware of the limitations of this meter, the strength tests in the field, performed by a third party laboratory, were performed at different ages. This made it impossible to plot the field curves for this particular mix (see Table C4-1).

Table C4-1 Summary of Data from Field Curves.

Site	Age (days)	Age (hours)	Downloaded TTF (ºC-hours)	Calculated TTF (ºC-hours)	Downloaded Equiv Age (hours)	Calculated Equiv Age (hours)	Compressive strength (MPa)	Downloaded TTF (ºC-hours)	Calculated TTF (ºC-hours)	Downloaded Equiv Age (hours)	Calculated Equiv Age (hours)	Flexural strength (MPa)
Ludlow	1	24	705	513	26	22	**7.56**	668	476	24	21	**1.82**
Ludlow	3	72	2013	1436	68	60	**14.21**	1977	1415	67	60	**2.49**
Ludlow	7	168	4509	3161	148	133	**16.96**	4439	3107	144	132	**2.69**
Ludlow	10	240	6731	4807	226	200	**21.59**	6627	4717	219	197	**3.25**
Ludlow	14	336	9574	6986	321	293	**22.46**	9466	6990	316	318	**3.15**
Ludlow	28	672	20024	14739	683	606	**29.13**	20101	14869	675	637	**3.72**
Riverside I	1	24	792	3016	29	24	**15.37**	792	3016	29	24	**2.41**
Riverside I	4	96	2821	11542	95	93	**28.41**	2821	11542	95	93	**2.94**
Riverside I	9	216	5664	25283	178	204	**28.96**	5664	25283	178	204	**3.86**
Riverside I	14	336	8579	39128	263	316	**30.27**	8579	39128	263	316	
Riverside I	28	672	16479	77516	492	627	**31.75**	16479	77516	492	627	**3.84**
Riverside II	2	48	1217				**12.75**	1217				**1.65**
Riverside II	4	96	2458	Nomadics meter, no E and no T history			**19.90**	2458	Nomadics meter, no E and no T history			**1.91**
Riverside II	9	216	Maturity and strength data recorded at different ages				**20.78**	Maturity and strength data recorded at different ages				**2.47**
Riverside II	14	336					**22.96**					**1.80**
Riverside II	28	672					**32.28**					**2.10**
Victorville	3	72	2564	4610	88	75	**23.5**	2564	4610	88	75	**2.7**
Victorville	7	168	6539	11352	246	187	**31.7**	6539	11352	246	187	**3.7**
Victorville	10	240	9479	16367	360	270	**33.6**	9479	16367	360	270	**4.1**
Victorville	28	672	27971	47309	1126	784	**37.2**	27971	47309	1126	784	**4.4**

Note that for mix #3 no temperature history was recorded.

Mix #1 – Ludlow Field Compressive Strength Curves

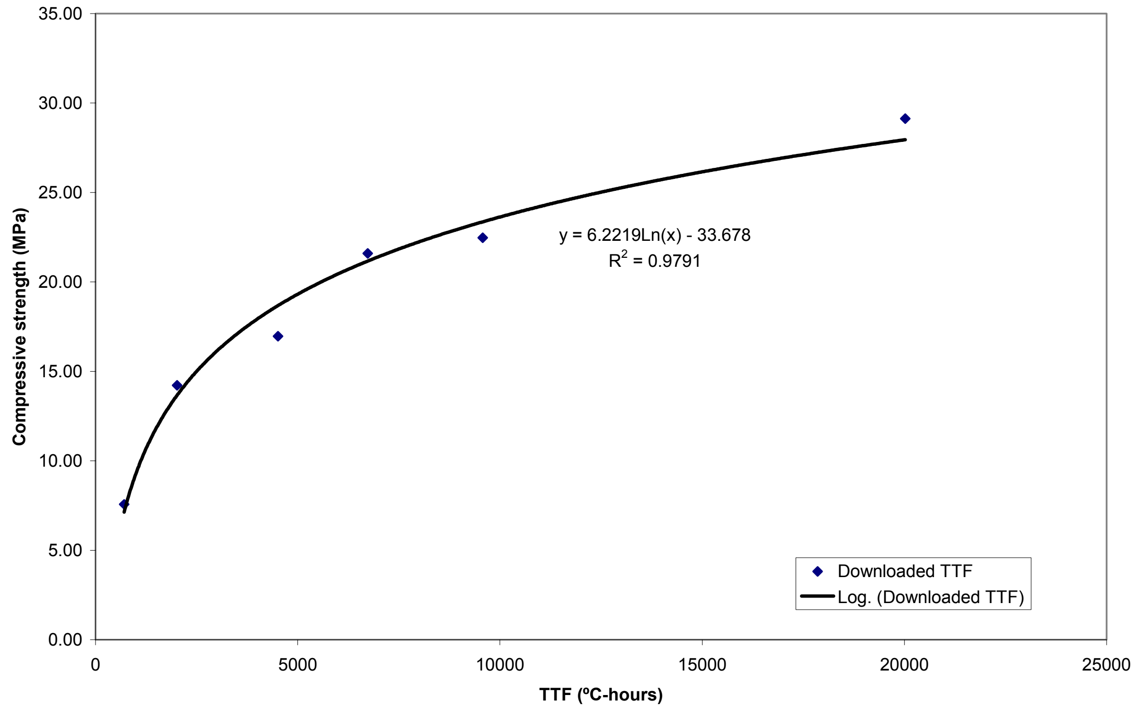

Figure C4-1a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix # 1, field cylinders).

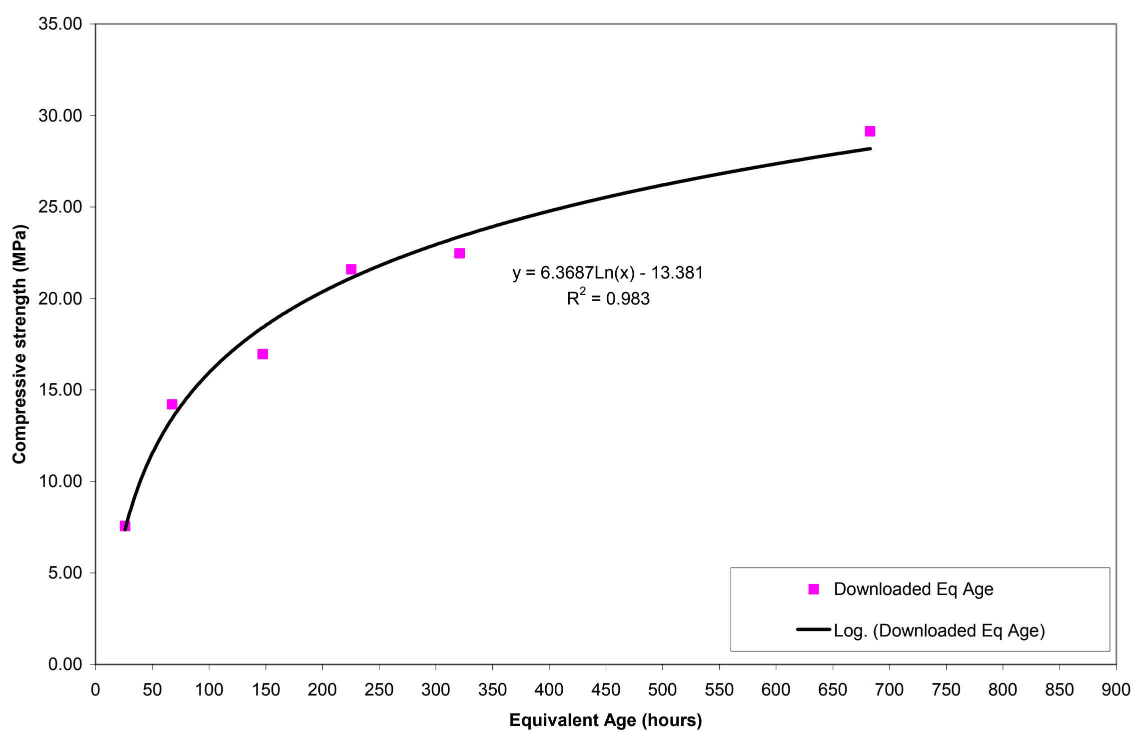

Figure C4-1b. Correlation between compressive strength and t_e, assumed *E* (Mix # 1, field cylinders).

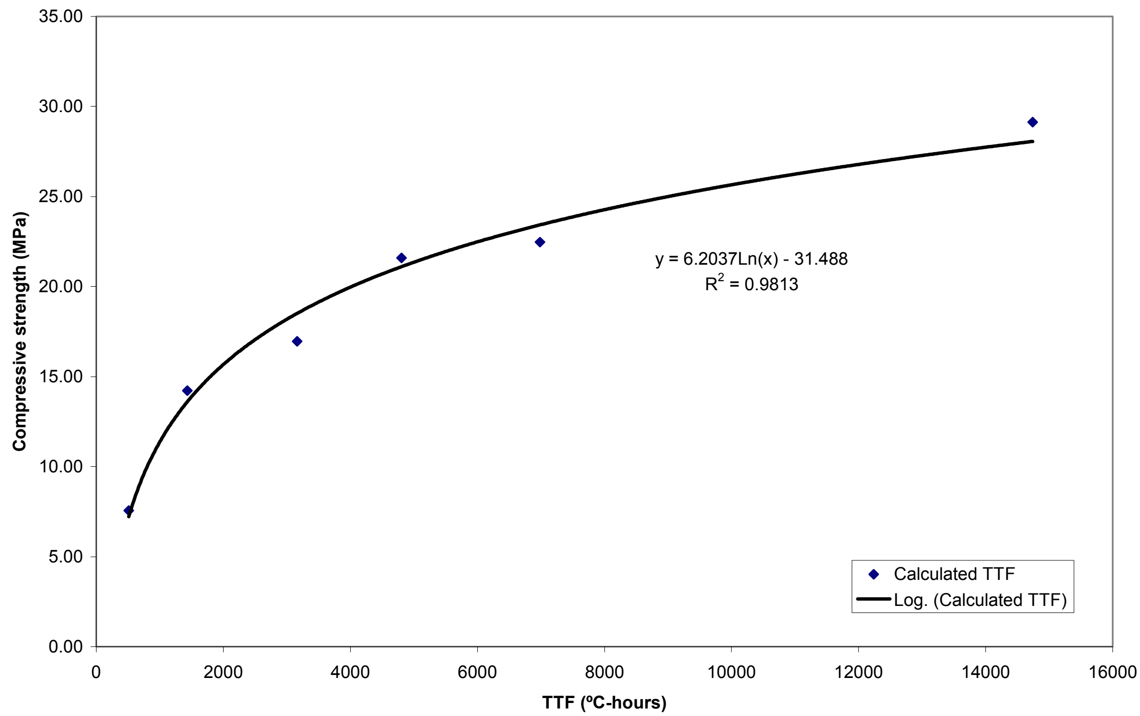

Figure C4-1c. Correlation between compressive strength and *TTF*, measured T_0 (Mix # 1 field cylinders).

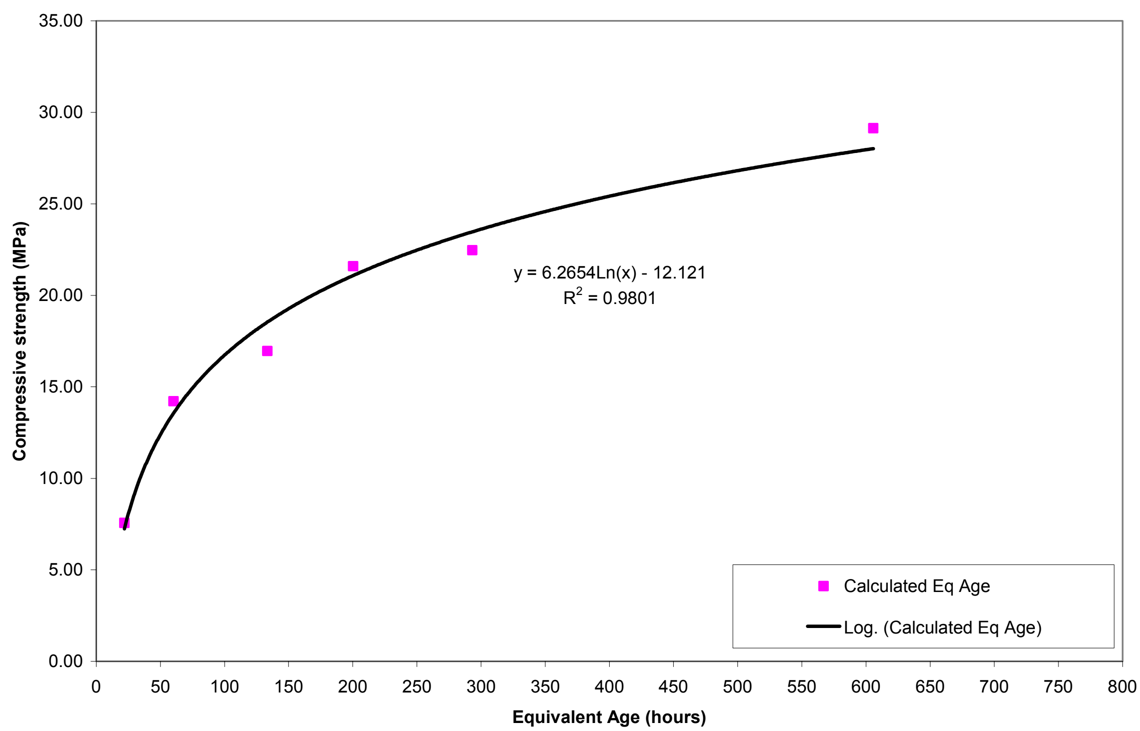

Figure C4-1d. Correlation between compressive strength and t_e, measured *E* (Mix # 1 field cylinders).

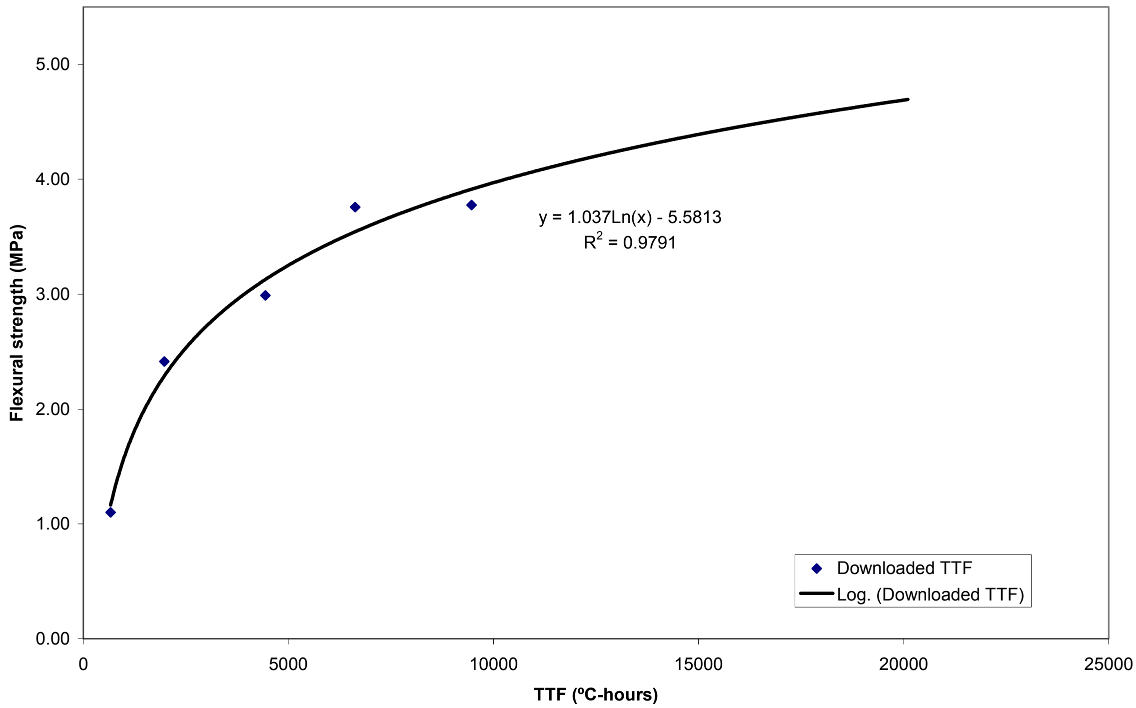

Figure C4-1e. Correlation between flexural strength and *TTF*, assumed T_0 (Mix #1, field beams).

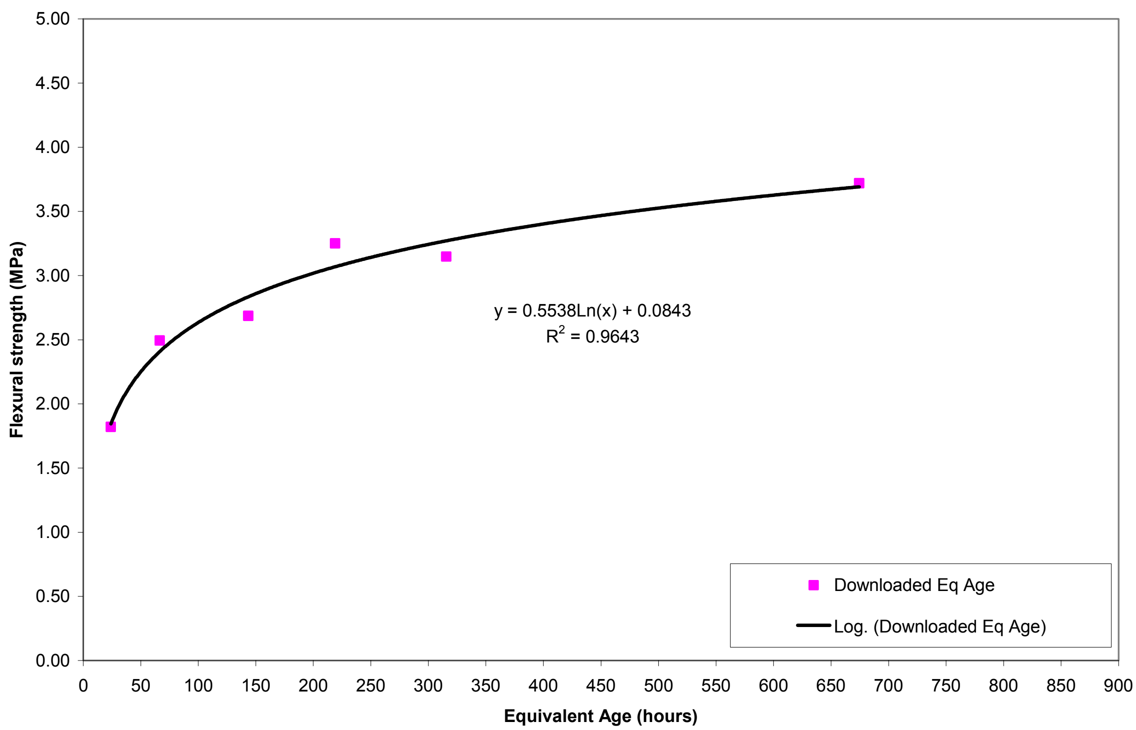

Figure C4-1f. Correlation between flexural strength and t_e, assumed *E* (Mix #1, field beams).

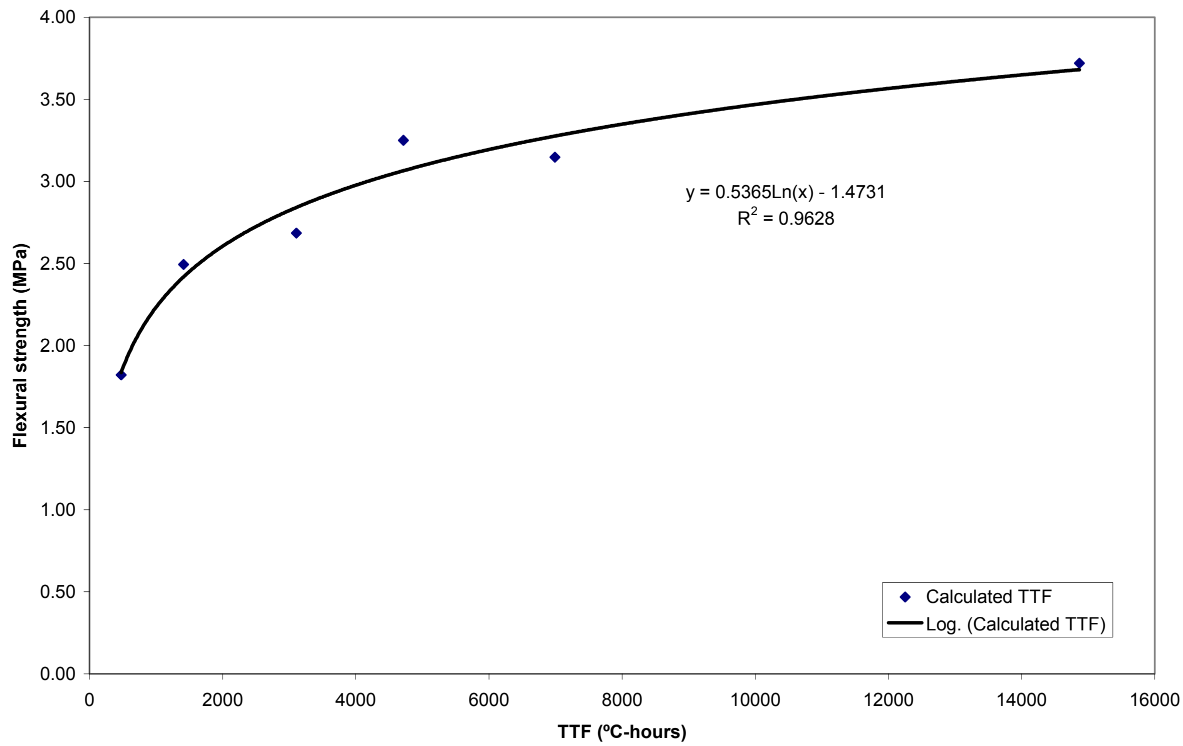

Figure C4-1g. Correlation between flexural strength and *TTF*, measured T_0 (Mix #1, field beams).

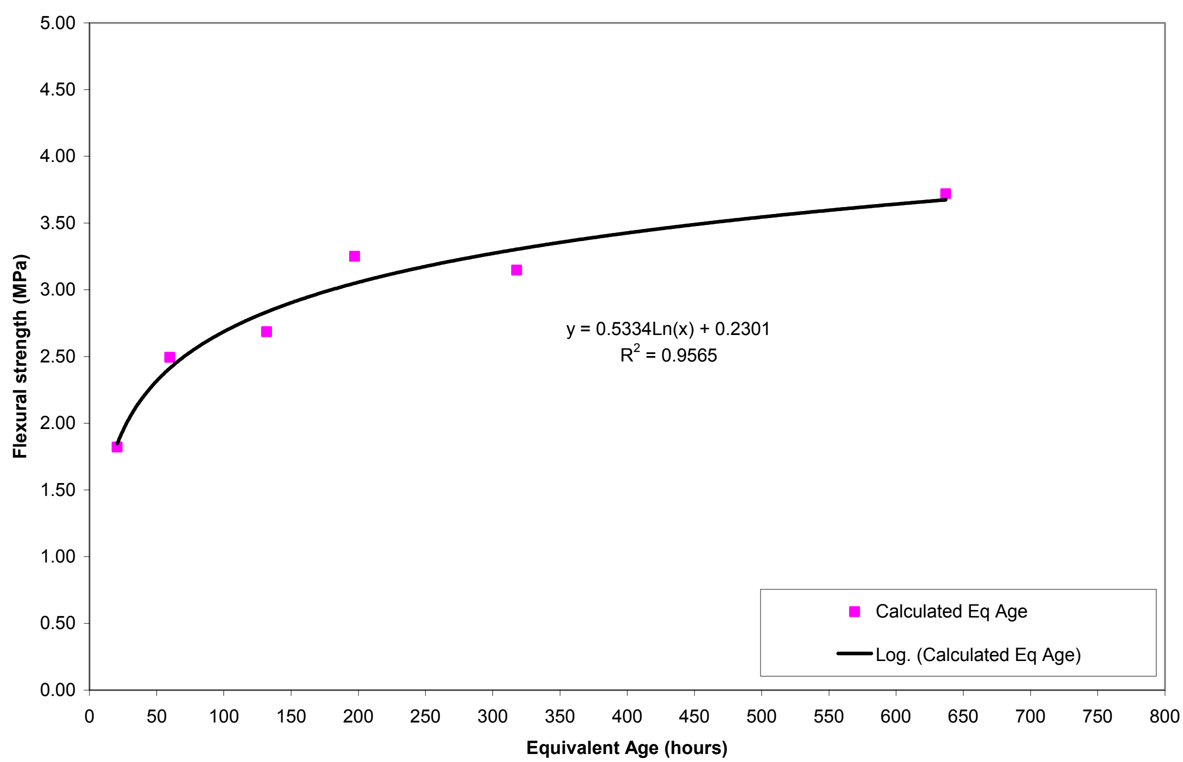

Figure C4-1h. Correlation between flexural strength and t_e, measured *E* (Mix #1, field beams).

Mix #2 – Riverside I Compressive Strength Curves

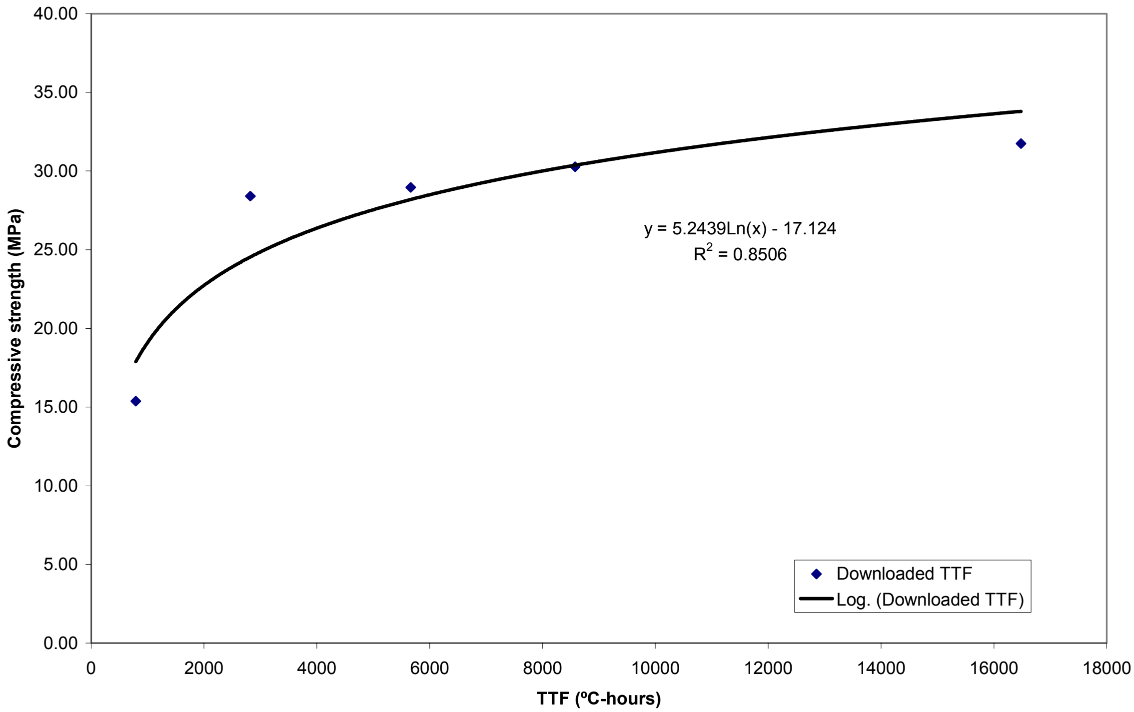

Figure C4-2a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #2, field cylinders).

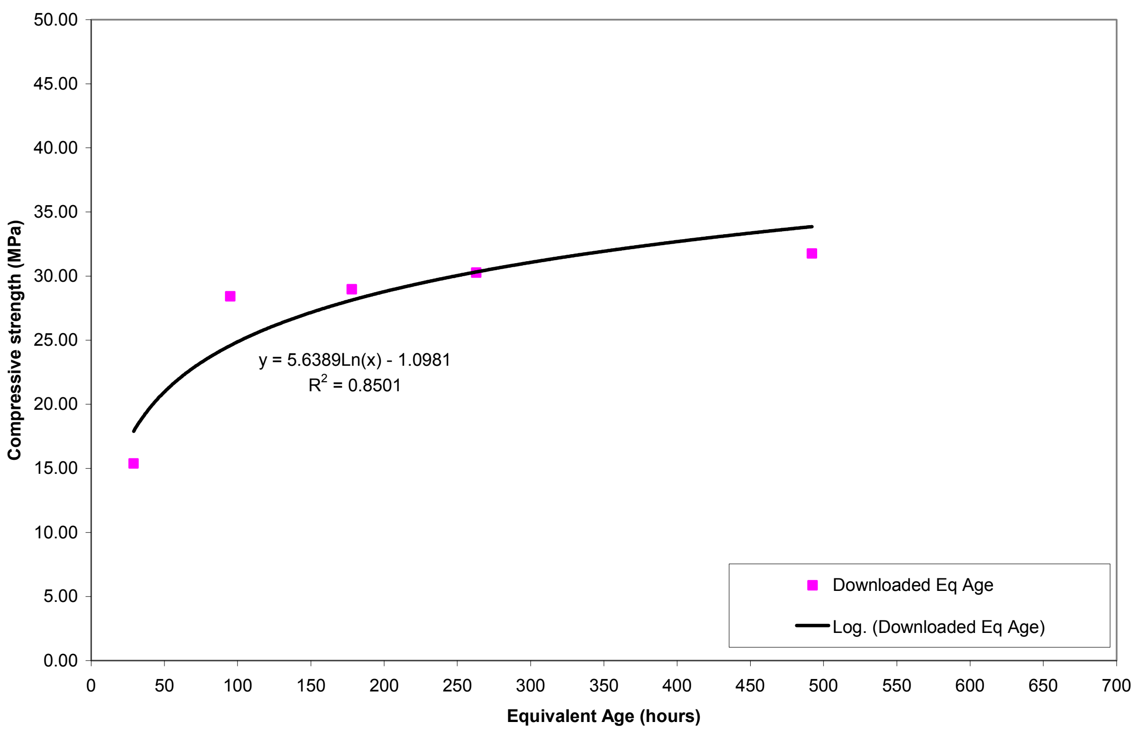

Figure C4-2b. Correlation between compressive strength and t_e, assumed *E* (Mix #2, field cylinders).

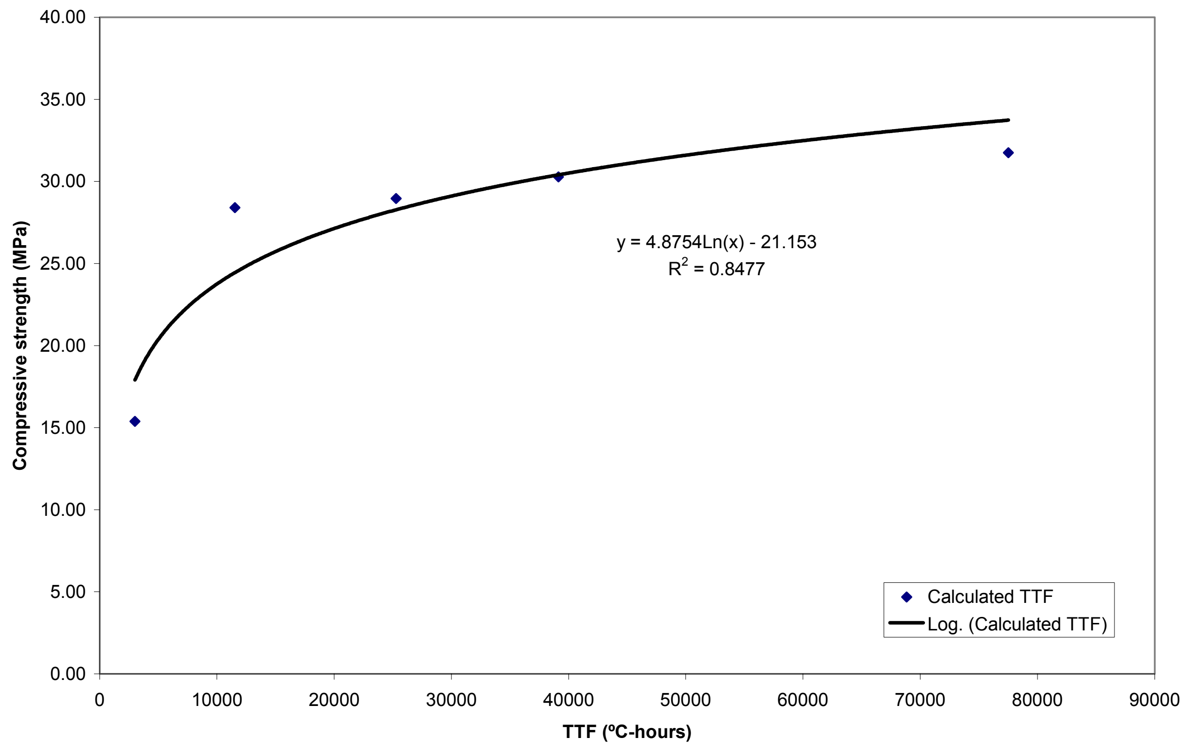

Figure C4-2c. Correlation between compressive strength and *TTF*, measured T_0 (Mix #2, field cylinders).

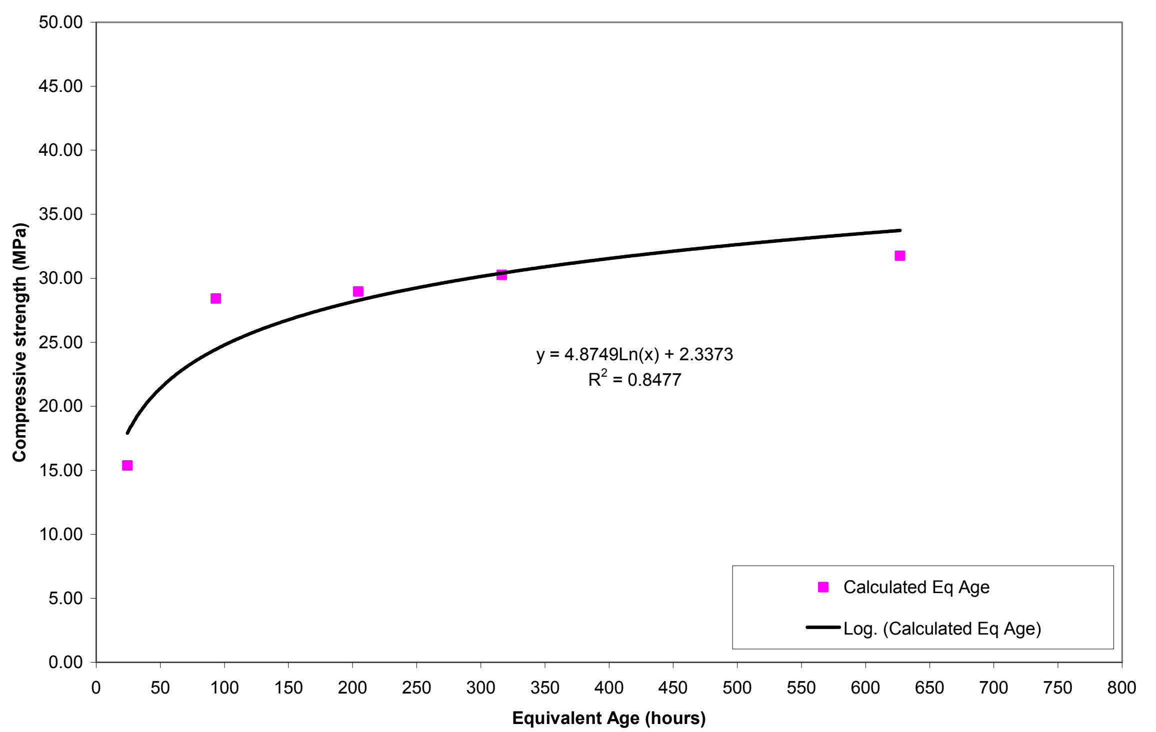

Figure C4-2d. Correlation between compressive strength and t_e, measured E (Mix #2, field cylinders).

Mix #2 – Riverside I Flexural Strength Curves

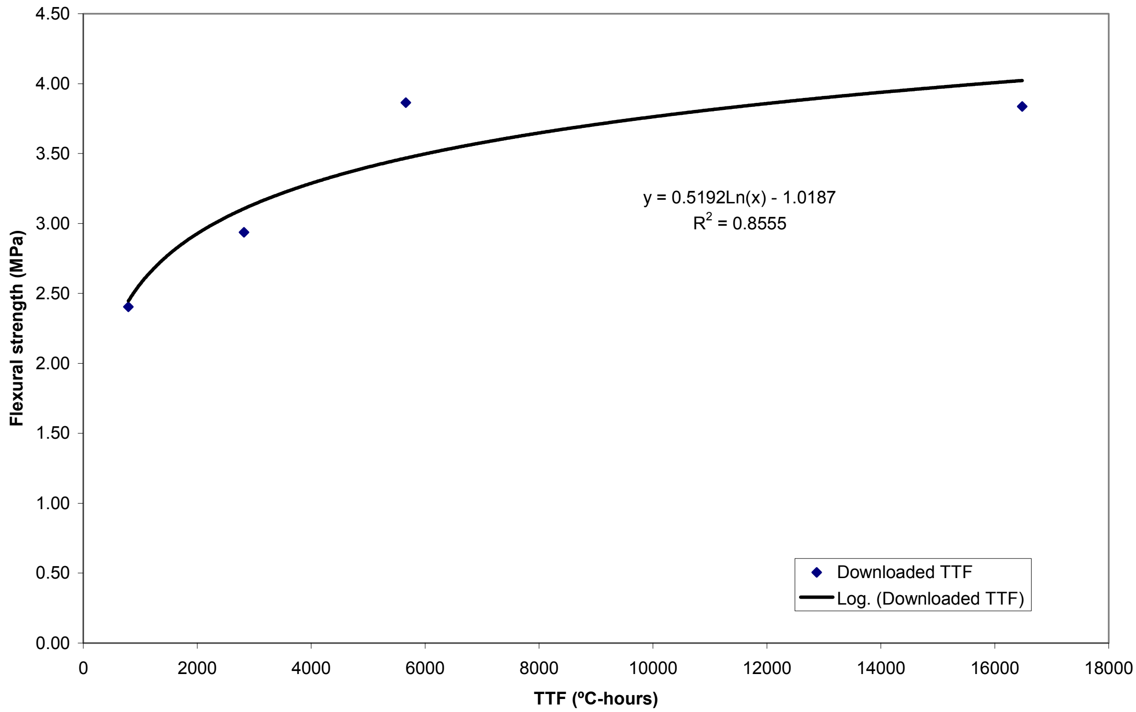

Figure C4-2e. Correlation between flexural strength and *TTF*, assumed T_0 (Mix #2, field beams).

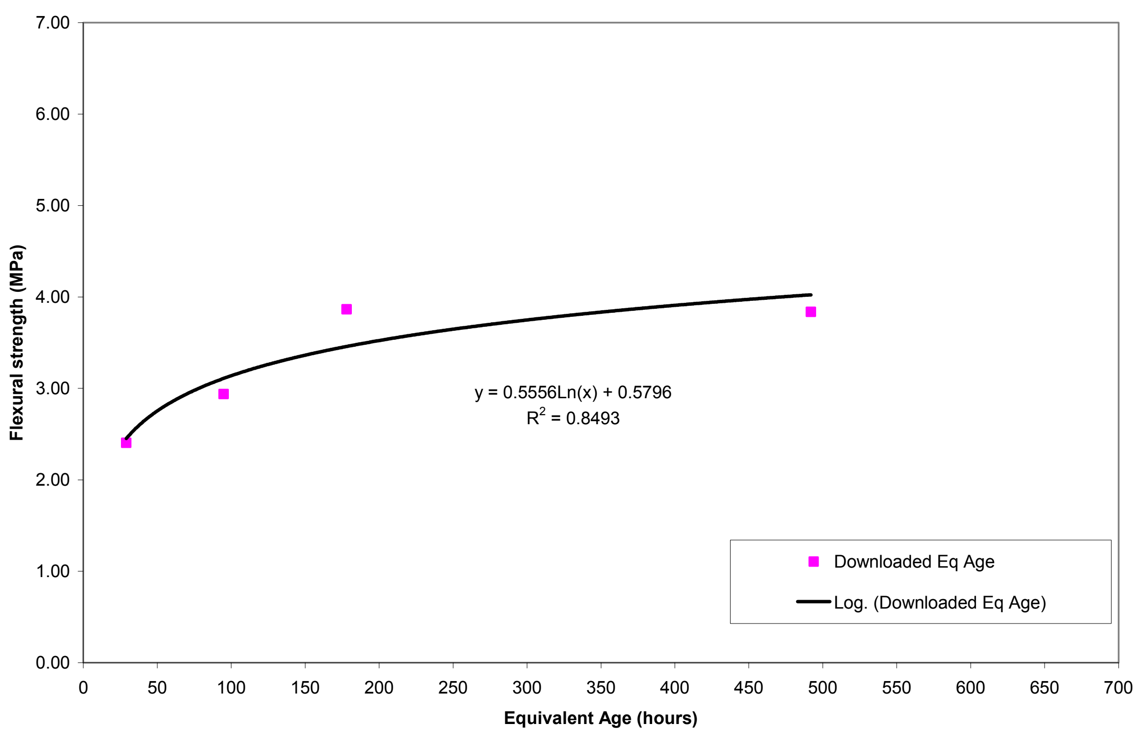

Figure C4-2f. Correlation between flexural strength and t_e, assumed *E* (Mix #2, field beams).

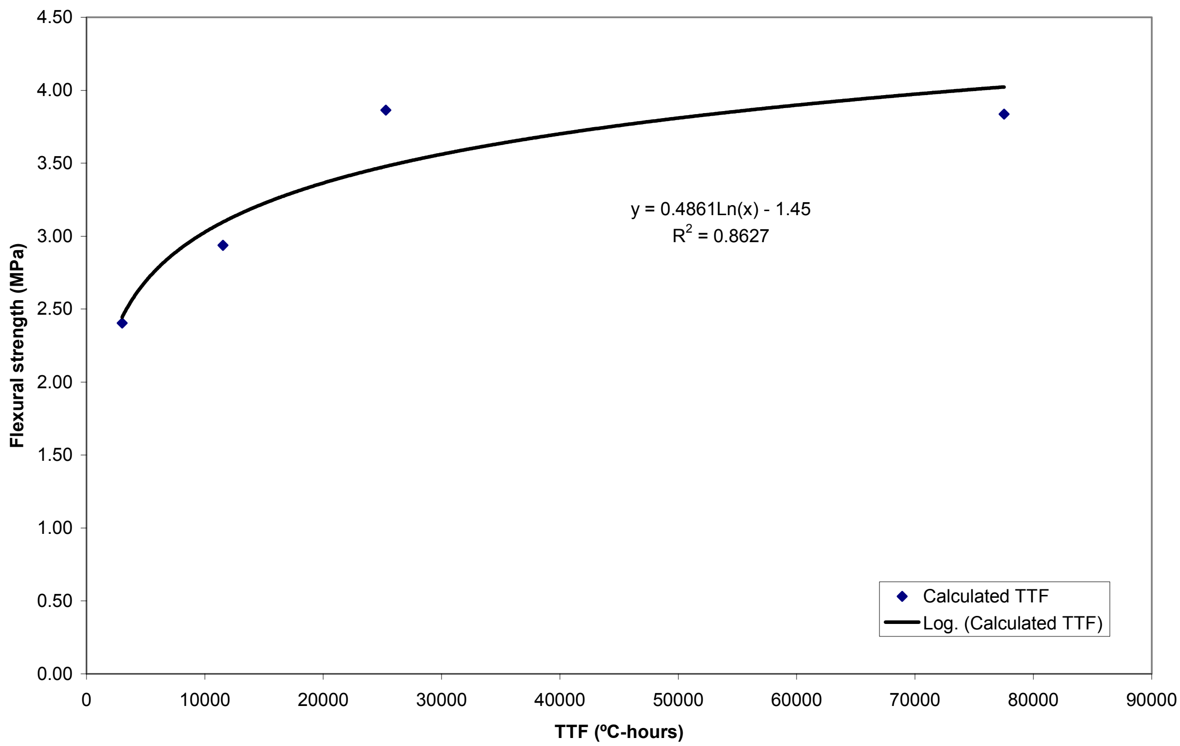

Figure C4-2g. Correlation between flexural strength and *TTF*, measured T_0 (Mix #2, field beams).

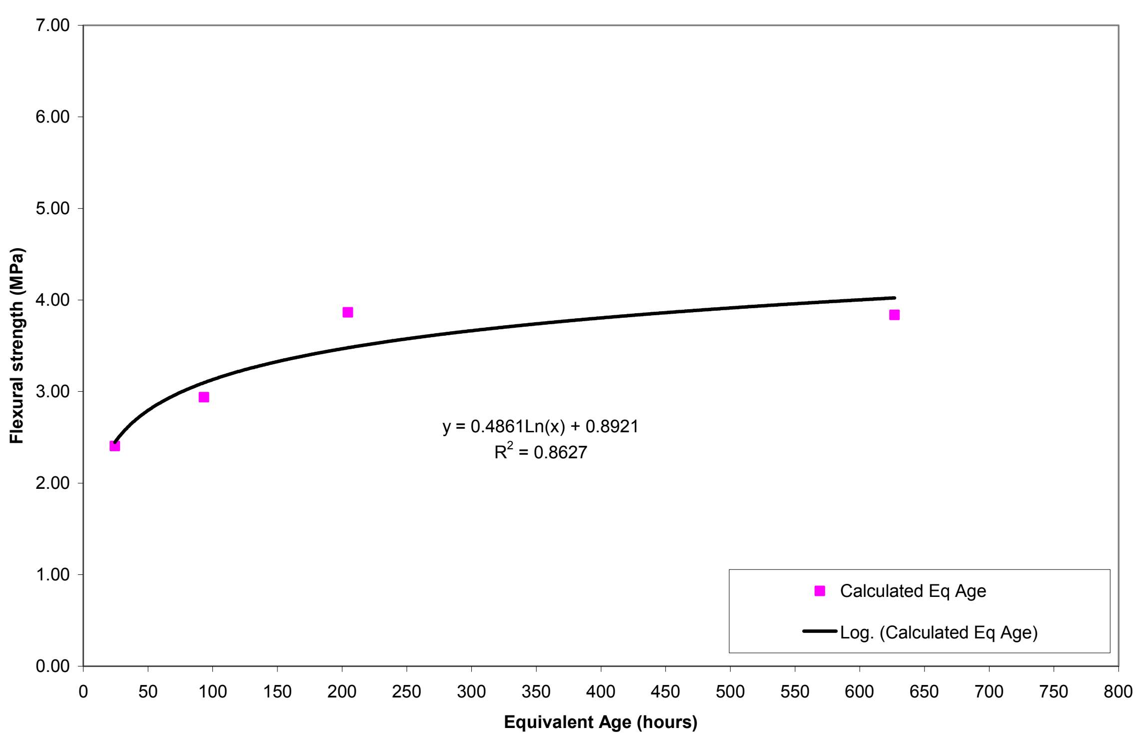

Figure C4-2h. Correlation between flexural strength and t_e, measured *E* (Mix #2, field beams).

Mix #4 – Victorville Field Compressive Strength Curves

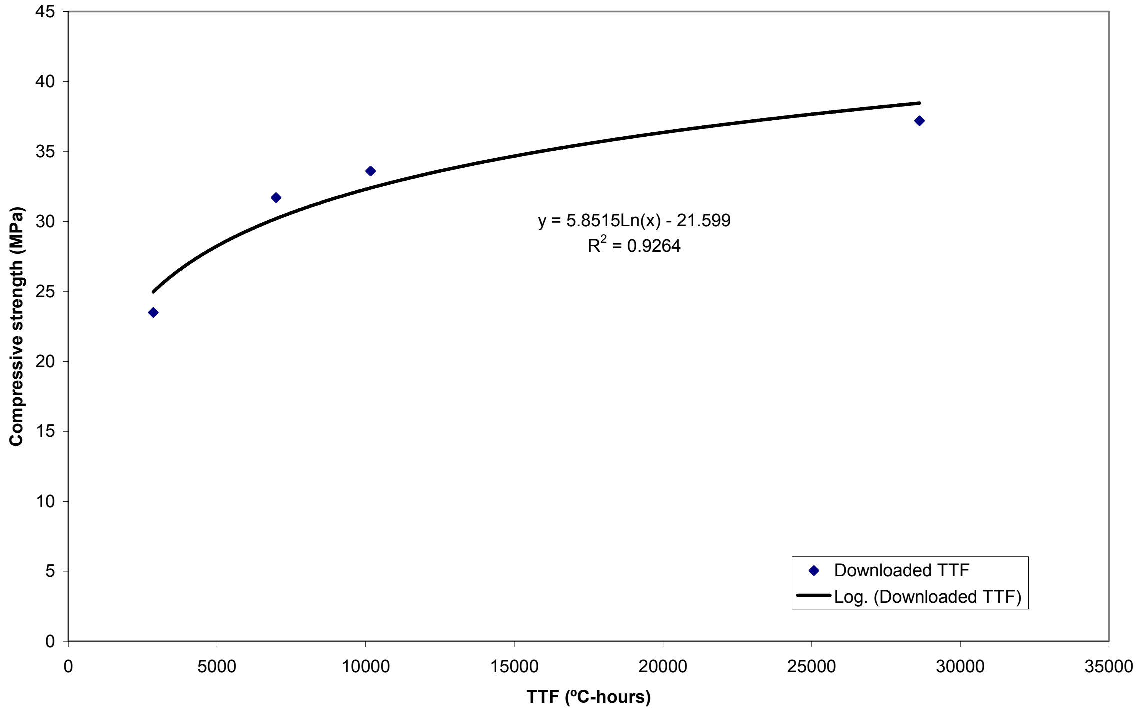

Figure C4-3a. Correlation between compressive strength and *TTF*, assumed T_0 (Mix #4, field cylinders).

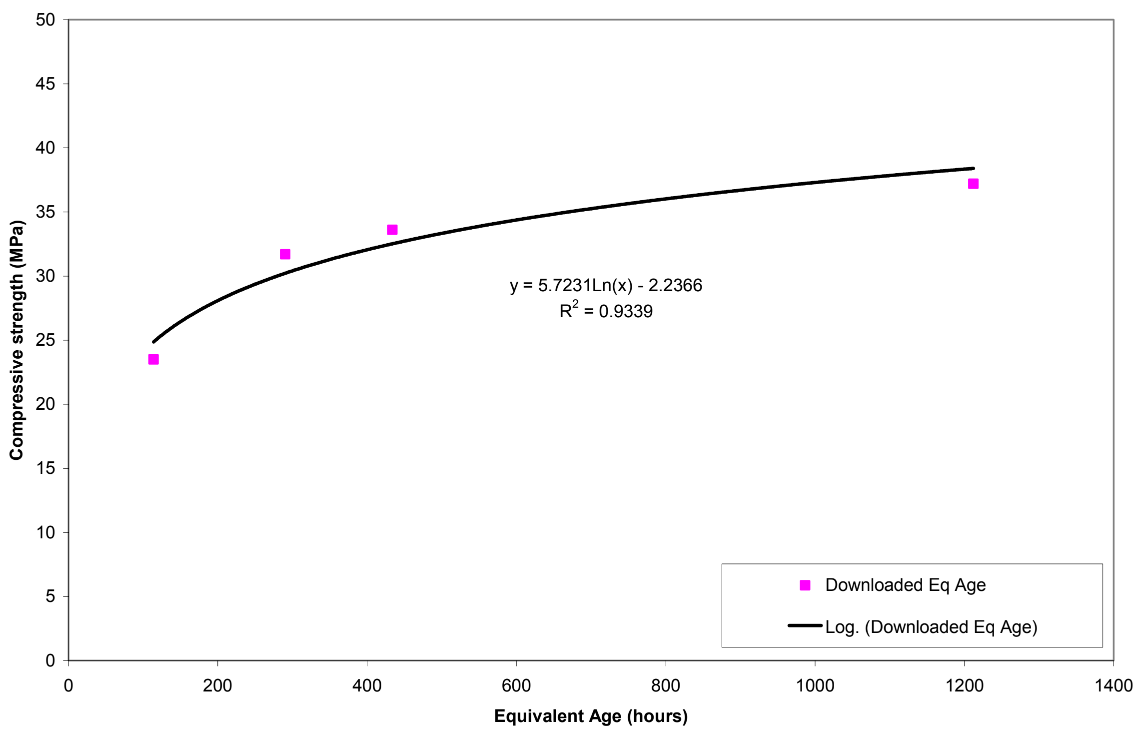

Figure C4-3b. Correlation between compressive strength and t_e, assumed *E* (Mix #4, field cylinders).

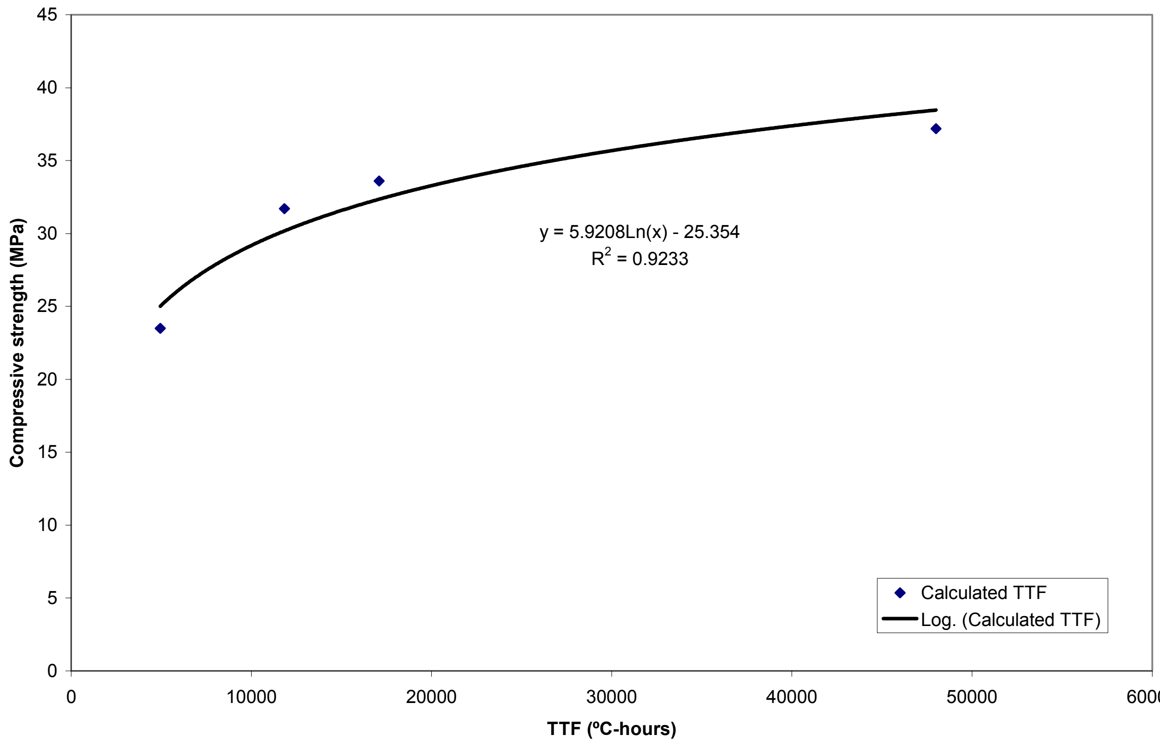

Figure C4-3c. Correlation between compressive strength and *TTF*, measured T_0 (Mix #4, field cylinders).

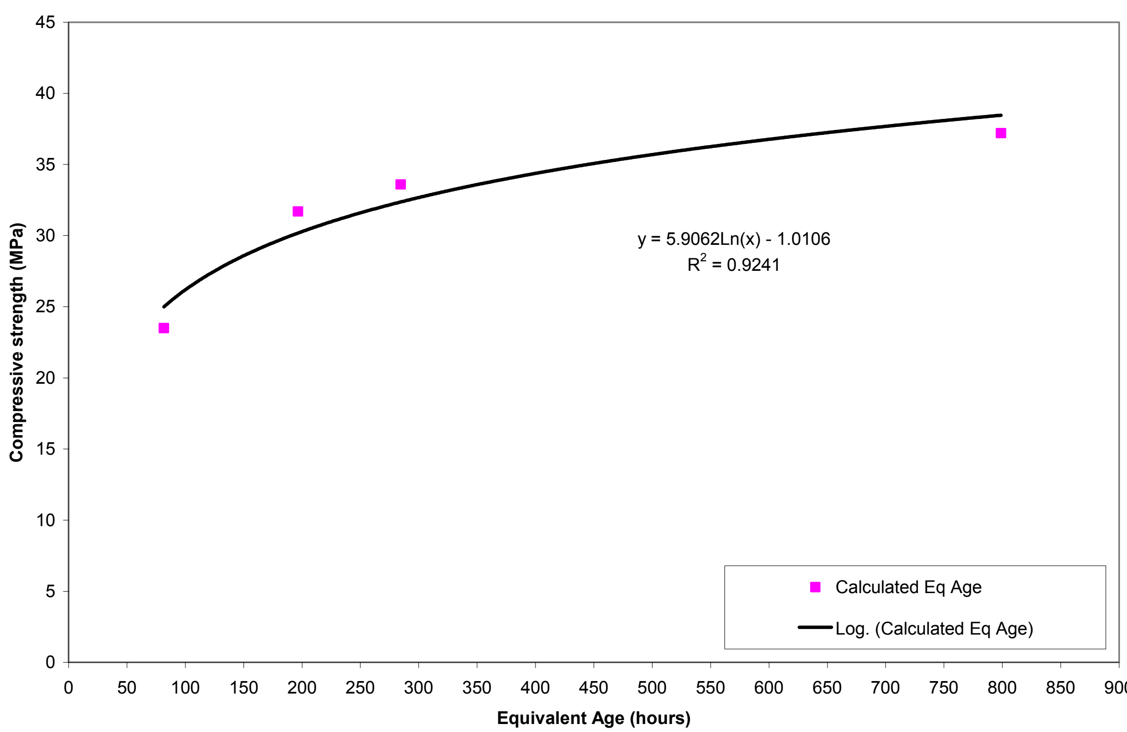

Figure C4-3d. Correlation between compressive strength and t_e, measured *E* (Mix #4, field cylinders).

Mix #4 Victorville Flexural Strength Curves

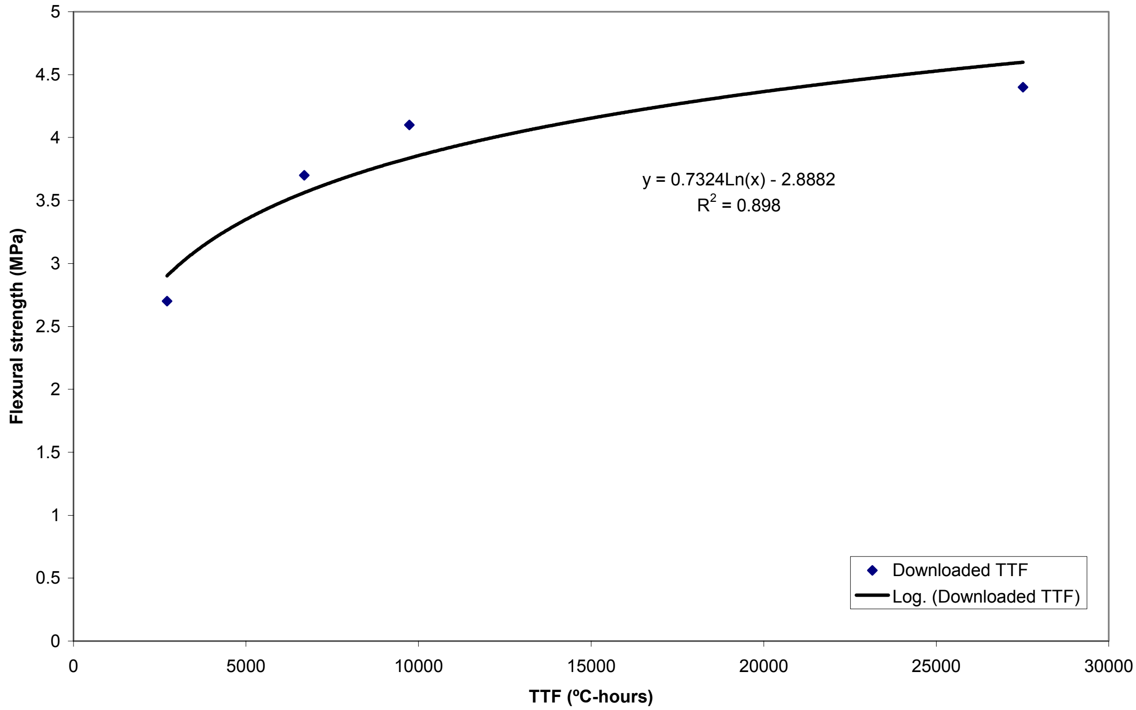

Figure C4-3e. Correlation between flexural strength and *TTF*, assumed T_0 (Mix #4, field beams).

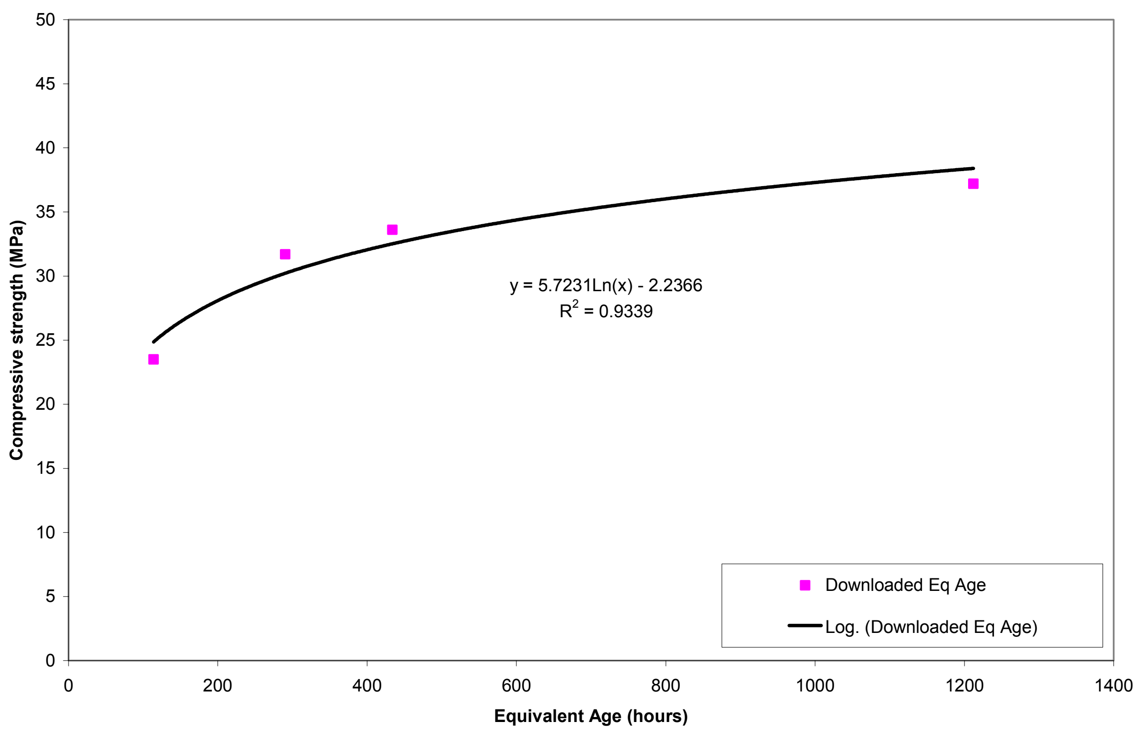

Figure C4-3f. Correlation between flexural strength and t_e, assumed *E* (Mix #4, field beams).

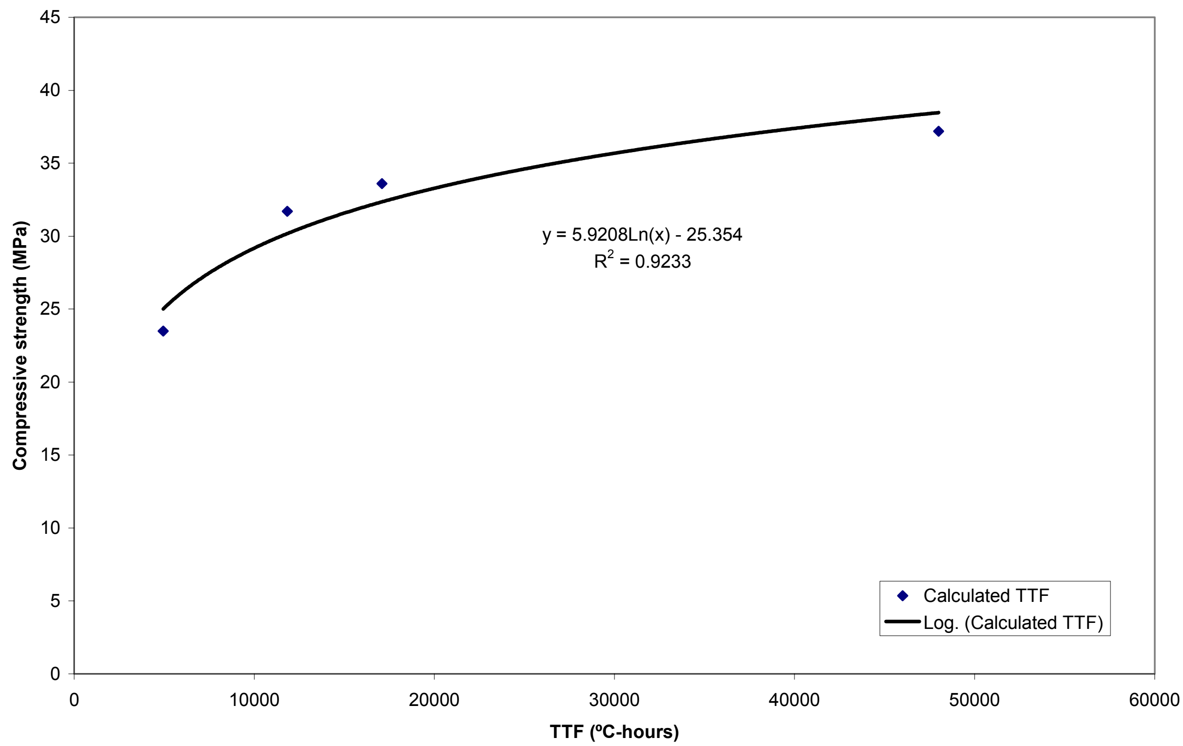

Figure C4-3g. Correlation between flexural strength and *TTF*, measured T_0 (Mix #4, field beams).

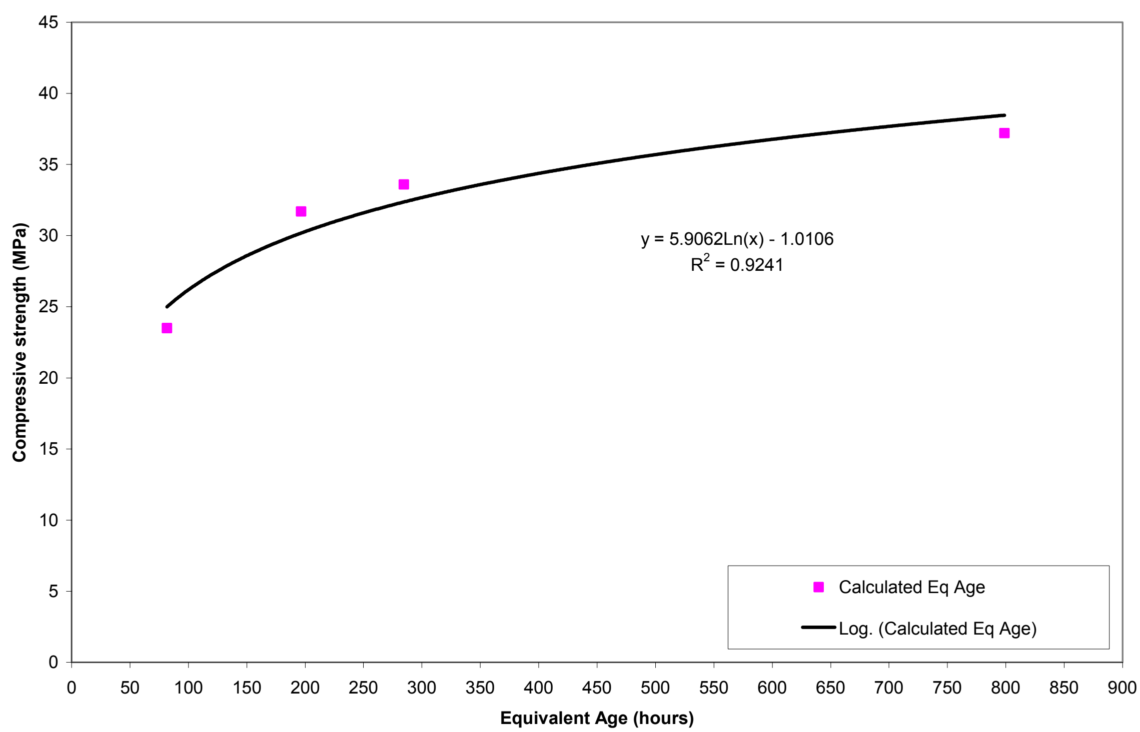

Figure C4-3h. Correlation between flexural strength and t_e, measured *E* (Mix #4, field beams).

Appendix C5: Comparison of Strength Estimates for Field Specimens from Laboratory Determined Measures of Maturity with Measured Strengths

Estimates Based on Laboratory Curves Developed from 10, 23, and 40ºC Data

Tables C5-1 through C5-7 present the compressive and flexural strength estimates of field specimens based on laboratory-measured curves developed using the combined data from the three laboratory curing temperatures, for each of the three mixes for which adequate data is available (Mix #1 - Ludlow, Mix #2 – Riverside I, and Mix #4 – Victorville). These tables are organized in the following way: the upper part presents estimates based on *TTF*, and the lower half shows estimates based on equivalent age (t_e). On the left-hand side, estimates are made using assumed values of T_0 and *E*, while on the right-hand side the estimates consider the measured values of such parameters.

Estimates Based on Laboratory Curves Developed from 23ºC Data

Strength relationships for field specimens were estimated using the laboratory curves developed from only the 23ºC data. Tables C5-8 through C5-13 present the compressive and flexural strength estimates (field-cast and cured specimens).

Table C5-1 Mix #1 (Ludlow) Compressive Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
705	6.02	**7.56**	-20.5%	513	6.12	**7.56**	-19.2%	-1.7%
2013	13.25	**14.21**	-6.8%	1436	13.22	**14.21**	-7.0%	0.3%
4509	18.81	**16.96**	10.9%	3161	18.66	**16.96**	10.0%	0.8%
6731	21.57	**21.59**	-0.1%	4807	21.55	**21.59**	-0.2%	0.1%
9574	24.00	**22.46**	6.8%	6986	24.13	**22.46**	7.4%	-0.5%
20024	29.09	**29.13**	-0.1%	14739	29.28	**29.13**	0.5%	-0.6%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Fc (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc te)
26	6.45	**7.56**	-14.7%	22	6.07	**7.56**	-19.8%	6.0%
68	13.04	**14.21**	-8.3%	60	13.10	**14.21**	-7.8%	-0.5%
148	18.43	**16.96**	8.7%	133	18.64	**16.96**	9.9%	-1.1%
226	21.36	**21.59**	-1.1%	200	21.47	**21.59**	-0.6%	-0.5%
321	23.80	**22.46**	5.9%	293	24.12	**22.46**	7.4%	-1.4%
683	29.01	**29.13**	-0.4%	606	29.18	**29.13**	0.2%	-0.6%

Table C5-2 Mix #1 (Ludlow) Flexural Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
668	1.59	**1.82**	-12.7%	476	1.58	**1.82**	-13.0%	0.3%
1977	2.41	**2.49**	-3.6%	1415	2.41	**2.49**	-3.5%	0.0%
4439	3.01	**2.69**	12.2%	3107	3.00	**2.69**	11.7%	0.5%
6627	3.31	**3.25**	2.0%	4717	3.31	**3.25**	1.9%	0.0%
9466	3.58	**3.15**	13.8%	6990	3.61	**3.15**	14.7%	-0.8%
20101	4.15	**3.72**	11.6%	14869	4.18	**3.72**	12.4%	-0.7%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc te)
24	1.62	**1.82**	-11.3%	21	1.59	**1.82**	-12.7%	1.6%
67	2.39	**2.49**	-4.3%	60	2.40	**2.49**	-3.9%	-0.4%
144	2.97	**2.69**	10.5%	132	3.00	**2.69**	11.7%	-1.0%
219	3.29	**3.25**	1.1%	197	3.31	**3.25**	1.7%	-0.6%
316	3.56	**3.15**	13.2%	318	3.67	**3.15**	16.5%	-3.0%
675	4.14	**3.72**	11.3%	637	4.20	**3.72**	12.9%	-1.5%

Note that in this case, the strength estimates were very close to the actual values except at early ages, and are somewhat conservative in the early ages. Note also that (right column) it is clear that the experimental determination of T_0 and E did not improve the accuracy of the estimates.

Table C5-3 Mix #2 (Riverside I) Compressive Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
792	15.71	**15.37**	2.2%	3016	16.76	**15.37**	9.0%	-6.7%
2821	25.23	**28.41**	-11.2%	11542	27.31	**28.41**	-3.9%	-8.3%
5664	30.45	**28.96**	5.1%	25283	33.48	**28.96**	15.6%	-9.9%
8579	33.56	**30.27**	10.9%	39128	36.91	**30.27**	22.0%	-10.0%
16479	38.46	**31.75**	21.1%	77516	42.29	**31.75**	33.2%	-10.0%
Downloaded t_e (hours)	**Estimate based on downloaded t_e (MPa)**	**Measured Fc (MPa)**	**Difference (%)**	**Calculated t_e (hours)**	**Estimate based on calculated t_e (MPa)**	**Measured Fc (MPa)**	**Difference (%)**	**Diff. between estimates (downl x calc te)**
29	14.51	**15.37**	-5.6%	24	16.75	**15.37**	9.0%	-15.4%
95	23.54	**28.41**	-17.1%	93	27.31	**28.41**	-3.9%	-16.0%
178	28.32	**28.96**	-2.2%	204	33.48	**28.96**	15.6%	-18.2%
263	31.30	**30.27**	3.4%	316	36.91	**30.27**	21.9%	-17.9%
492	36.06	**31.75**	13.6%	627	42.29	**31.75**	33.2%	-17.3%

Table C5-4 Mix #2 (Riverside I) Flexural Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
792	2.47	**2.41**	2.7%	3016	2.63	**2.41**	9.4%	-6.5%
2821	3.86	**2.94**	31.5%	11542	4.04	**2.94**	37.5%	-4.5%
5664	4.63	**3.86**	19.8%	25283	4.86	**3.86**	25.8%	-5.0%
8579	5.08	**-**	-	39128	5.32	**-**	-	-4.7%
16479	5.80	**3.84**	51.1%	77516	6.04	**3.84**	57.3%	-4.1%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc te)
29	2.22	**2.41**	-7.7%	24	2.63	**2.41**	9.4%	-18.5%
95	3.52	**2.94**	19.8%	93	4.04	**2.94**	37.5%	-14.7%
178	4.21	**3.86**	8.9%	204	4.86	**3.86**	25.8%	-15.5%
263	4.64	**-**	-	316	5.32	**-**	-	-14.7%
492	5.32	**3.84**	38.7%	627	6.04	**3.84**	57.4%	-13.4%

For Mix #2, a Type III cement mix, the estimate was not as accurate as with Mix #1. Also, instead of being a conservative estimate, in this case estimated strengths are 38 percent higher than the measured value, even for the early ages. Also, for this mix, the maturity indexes calculated based on assumed and measured values of T_0 and E did not match as for the other mixes.

Table C5-5 Mix #4 (Victorville) Compressive Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
2564	16.17	**23.5**	-31.2%	4610	15.41	**23.5**	-34.4%	4.7%
6539	23.02	**31.7**	-27.4%	11352	22.52	**31.7**	-28.9%	2.2%
9479	25.74	**33.6**	-23.4%	16367	25.41	**33.6**	-24.4%	1.3%
27971	33.66	**37.2**	-9.5%	47309	33.79	**37.2**	-9.2%	-0.4%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Fc (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
88	16.45	**23.5**	-30.0%	75	15.43	**23.5**	-34.3%	6.2%
246	23.04	**31.7**	-27.3%	187	22.60	**31.7**	-28.7%	1.9%
360	25.48	**33.6**	-24.2%	270	25.49	**33.6**	-24.1%	0.0%
1126	32.76	**37.2**	-11.9%	784	33.90	**37.2**	-8.9%	-3.5%

Table C5-6 Mix #4 (Victorville) Flexural Strength Estimates of Field Specimens Based on Laboratory Calculated Curves

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
2713	2.42	**2.7**	-10.2%	4798	2.30	**2.7**	-14.9%	5.2%
6689	4.09	**3.7**	10.7%	11540	3.98	**3.7**	7.5%	2.9%
9732	4.79	**4.1**	16.8%	16658	4.68	**4.1**	14.1%	2.3%
27516	6.71	**4.4**	52.6%	46893	6.66	**4.4**	51.4%	0.8%
Downloaded t_e (hours)	**Estimate based on downloaded t_e (MPa)**	**Measured Ft (MPa)**	**Difference (%)**	**Calculated t_e (hours)**	**Estimate based on calculated t_e (MPa)**	**Measured Ft (MPa)**	**Difference (%)**	**Diff. between estimates (downl x calc te)**
97	2.62	**2.7**	-3.0%	79	2.31	**2.7**	-14.3%	11.6%
255	4.13	**3.7**	11.5%	190	4.00	**3.7**	8.0%	3.1%
380	4.75	**4.1**	15.8%	275	4.70	**4.1**	14.7%	1.0%
1078	6.38	**4.4**	45.0%	775	6.67	**4.4**	51.7%	-4.6%

In this case, the flexural strength estimates were satisfactory for early ages. For later ages (28 days), unacceptable differences were observed. These differences are non-conservative.

Table C5-7 Mix # 4 (Victorville) Flexural Strength Estimates of Field Specimens Based on Laboratory Calculated Curves Calibrated without Later Age Data

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
2564	2.86	**2.7**	**6.0%**	4610	2.87	**2.7**	**6.2%**	-0.1%
6689	3.62	**3.7**	**-2.1%**	11352	3.53	**3.7**	**-4.5%**	2.4%
9732	3.92	**4.1**	**-4.5%**	16367	3.81	**4.1**	**-7.2%**	2.8%
27516	4.74	**4.4**	**7.7%**	47309	4.59	**4.4**	**4.4%**	3.1%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
88	2.88	**2.7**	**6.8%**	75	2.87	**2.7**	**6.1%**	0.7%
246	3.58	**3.7**	**-3.3%**	187	3.54	**3.7**	**-4.3%**	1.0%
360	3.84	**4.1**	**-6.5%**	270	3.82	**4.1**	**-6.9%**	0.5%
1126	4.60	**4.4**	**4.6%**	784	4.61	**4.4**	**4.8%**	-0.2%

Table C5-8 Mix #1 (Ludlow) Compressive Strength Estimates of Field Specimens Based on Laboratory Calculated Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
705	9.08	**7.56**	20.0%	513	8.53	**7.56**	12.7%	6.1%
2013	16.45	**14.21**	15.7%	1436	15.90	**14.21**	11.9%	3.3%
4509	22.11	**16.96**	30.4%	3161	21.56	**16.96**	27.1%	2.5%
6731	24.93	**21.59**	15.4%	4807	24.56	**21.59**	13.7%	1.5%
9574	27.40	**22.46**	22.0%	6986	27.24	**22.46**	21.3%	0.6%
20024	32.58	**29.13**	11.9%	14739	32.59	**29.13**	11.9%	0.0%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Fc (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
26	8.31	**7.56**	9.8%	22	8.85	**7.56**	17.0%	-6.5%
68	15.42	**14.21**	8.5%	60	16.13	**14.21**	13.5%	-4.6%
148	21.24	**16.96**	25.3%	133	21.85	**16.96**	28.9%	-2.9%
226	24.41	**21.59**	13.0%	200	24.78	**21.59**	14.7%	-1.5%
321	27.04	**22.46**	20.4%	293	27.52	**22.46**	22.5%	-1.8%
683	32.67	**29.13**	12.1%	606	32.75	**29.13**	12.4%	-0.3%

Table C5-9 Mix #1 (Ludlow) Flexural Strength Estimates of Field Specimens Based on Laboratory Calculated Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
668	2.12	**1.82**	16.6%	476	2.07	**1.82**	13.6%	2.5%
1977	2.76	**2.49**	10.7%	1415	2.72	**2.49**	9.1%	1.4%
4439	3.24	**2.69**	20.5%	3107	3.19	**2.69**	18.9%	1.3%
6627	3.47	**3.25**	6.8%	4717	3.44	**3.25**	5.9%	0.8%
9466	3.68	**3.15**	16.9%	6990	3.68	**3.15**	16.8%	0.1%
20101	4.12	**3.72**	10.8%	14869	4.13	**3.72**	11.0%	-0.1%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
24	1.87	**1.82**	2.8%	21	1.53	**1.82**	-16.1%	18.4%
67	2.50	**2.49**	0.3%	60	2.16	**2.49**	-13.3%	13.6%
144	2.98	**2.69**	10.9%	132	2.64	**2.69**	-1.8%	11.4%
219	3.24	**3.25**	-0.3%	197	2.88	**3.25**	-11.4%	11.1%
316	3.47	**3.15**	10.1%	318	3.17	**3.15**	0.6%	8.7%
675	3.94	**3.72**	5.8%	637	3.58	**3.72**	-3.7%	9.0%

Table C5-10 Mix #2 (Riverside I) Compressive Strength Estimates of Field Specimens Based on Laboratory Measured Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
792	16.13	15.37	**4.9%**	3016	15.98	15.37	**3.9%**	1.0%
2821	26.32	28.41	**-7.4%**	11542	26.84	28.41	**-5.5%**	-2.0%
5664	31.91	28.96	**10.2%**	25283	33.19	28.96	**14.6%**	-4.0%
8579	35.24	30.27	**16.4%**	39128	36.73	30.27	**21.4%**	-4.2%
16479	40.48	**31.75**	**27.5%**	77516	42.27	31.75	**33.1%**	-4.4%
Downloaded t_e (hours)	**Estimate based on downloaded t_e (MPa)**	**Measured Fc (MPa)**	**Difference (%)**	**Calculated t_e (hours)**	**Estimate based on calculated t_e (MPa)**	**Measured Fc (MPa)**	**Difference (%)**	**Diff. between estimates (downl x calc TTF)**
29	16.43	15.37	**6.9%**	24	15.98	15.37	**3.9%**	2.7%
95	25.96	28.41	**-8.6%**	93	26.85	28.41	**-5.5%**	-3.4%
178	31.01	28.96	**7.1%**	204	33.20	28.96	**14.6%**	-7.1%
263	34.14	30.27	**12.8%**	316	36.73	30.27	**21.4%**	-7.6%
492	39.18	31.75	**23.4%**	627	42.27	31.75	**33.1%**	-7.9%

Table C5-11 Mix #2 (Riverside I) Flexural Strength Estimates of Field Specimens Based on Laboratory Measured Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
792	3.19	2.41	**32.6%**	3016	3.20	2.41	**33.1%**	-0.4%
2821	3.91	2.94	**33.1%**	11542	3.95	2.94	**34.5%**	-1.1%
5664	4.30	3.86	**11.4%**	25283	4.39	3.86	**13.7%**	-2.0%
8579	4.54	-	**-**	39128	4.64	-	**-**	-2.1%
16479	4.91	3.84	**28.0%**	77516	5.02	3.84	**30.8%**	-2.2%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
29	3.19	2.41	**32.5%**	24	3.20	2.41	**33.1%**	-0.5%
95	3.87	2.94	**31.9%**	93	3.95	2.94	**34.5%**	-2.0%
178	4.24	3.86	**9.7%**	204	4.39	3.86	**13.7%**	-3.6%
263	4.46	-	**-**	316	4.64	-	**-**	-3.9%
492	4.83	3.84	**25.8%**	627	5.02	**3.84**	**30.8%**	-4.0%

For this mix, although quite reasonable estimates were obtained for compressive strength (Table 13), the estimated flexural strength was in general ~30 percent higher than the measured values.

Table C5-12 Mix #4 (Victorville) Compressive Strength Estimates of Field Specimens Based on Laboratory Measured Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Fc (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
2564	15.69	**23.5**	-33.2%	4610	15.76	**23.5**	-32.9%	-0.4%
6539	21.72	**31.7**	-31.5%	11352	21.80	**31.7**	-31.2%	-0.4%
9479	24.11	**33.6**	-28.3%	16367	24.25	**33.6**	-27.8%	-0.6%
27971	31.07	**37.2**	-16.5%	47309	31.36	**37.2**	-15.7%	-0.9%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Fc (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Fc (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
88	14.74	**23.5**	-37.3%	75	15.81	**23.5**	-32.7%	-7.3%
246	21.88	**31.7**	-31.0%	187	21.92	**31.7**	-30.9%	-0.2%
360	24.53	**33.6**	-27.0%	270	24.38	**33.6**	-27.4%	0.6%
1126	32.42	**37.2**	-12.8%	784	31.55	**37.2**	-15.2%	2.7%

Table C5-13 Mix #4 (Victorville) Flexural Strength Estimates of Field Specimens Based on Laboratory Measured Curves (23ºC Data)

Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Ft (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
2564	3.15	**2.7**	**16.7%**	4610	3.17	**2.7**	**17.3%**	-0.6%
6689	3.91	**3.7**	**5.8%**	11352	3.90	**3.7**	**5.3%**	0.4%
9732	4.21	**4.1**	**2.7%**	16367	4.19	**4.1**	**2.2%**	0.5%
27516	5.04	**4.4**	**14.5%**	47309	5.05	**4.4**	**14.8%**	-0.2%

Downloaded t_e (hours)	Estimate based on downloaded t_e (MPa)	Measured Ft (MPa)	Difference (%)	Calculated t_e (hours)	Estimate based on calculated t_e (MPa)	Measured Ft (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
88	3.07	**2.7**	**13.7%**	75	3.17	**2.7**	**17.5%**	-3.4%
246	3.89	**3.7**	**5.0%**	187	3.91	**3.7**	**5.7%**	-0.6%
360	4.19	**4.1**	**2.2%**	270	4.21	**4.1**	**2.6%**	-0.4%
1126	5.09	**4.4**	**15.7%**	784	5.07	**4.4**	**15.3%**	0.4%

Appendix C6: Estimates of Strengths of Laboratory Specimens at 10ºC and 40ºC Based on 23ºC Laboratory Relationships

Table C6-1 Mix #1 (Ludlow) Compressive Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	581.5	7.73	**3.65**	111.5%	389	6.56	**3.65**	79.4%	15.2%
	1629	14.96	**11.01**	35.9%	1052	13.68	**11.01**	24.2%	8.6%
	3641.5	20.61	**16.21**	27.1%	2294	19.26	**16.21**	18.8%	6.5%
	7011	25.21	**23.07**	9.3%	4316	23.79	**23.07**	3.1%	5.6%
	13691	29.91	**27.77**	7.7%	8317	28.49	**27.77**	2.6%	4.8%
40ºC	960	11.25	**8.58**	31.1%	767	11.41	**8.58**	33.0%	-1.4%
	2638	18.35	**10.56**	73.8%	2060	18.49	**10.56**	75.1%	-0.8%
	5512.5	23.52	**14.82**	58.7%	4164	23.53	**14.82**	58.7%	0.0%
	10839.5	28.27	**20.83**	35.8%	8144	28.34	**20.83**	36.1%	-0.2%
	22002.5	33.25	**27.12**	22.6%	16612	33.44	**27.12**	23.3%	-0.6%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
10ºC	17	5.14	**3.65**	40.6%	17	6.96	**3.65**	90.4%	-35.4%
	47	12.72	**11.01**	15.5%	47	14.32	**11.01**	30.1%	-12.6%
	102.5	18.53	**16.21**	14.3%	105	20.10	**16.21**	24.0%	-8.5%
	194.5	23.30	**23.07**	1.0%	202	24.83	**23.07**	7.6%	-6.6%
	377.5	28.25	**27.77**	1.7%	395	29.67	**27.77**	6.8%	-5.0%
40ºC	45	12.39	**8.58**	44.4%	33	11.72	**8.58**	36.5%	5.5%
	110.5	19.09	**10.56**	80.8%	85	18.61	**10.56**	76.2%	2.5%
	207.5	23.79	**14.82**	60.5%	170	23.61	**14.82**	59.3%	0.7%
	397.5	28.63	**20.83**	37.5%	331	28.40	**20.83**	36.4%	0.8%
	813	33.97	**27.12**	25.3%	674	33.52	**27.12**	23.6%	1.3%

Table C6-2 Mix #1 (Ludlow) Flexural Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	605.5	2.07	**1.10**	87.6%	414	1.99	**1.10**	80.3%	3.9%
	1616.5	2.64	**2.41**	9.4%	1040	2.54	**2.41**	5.1%	4.0%
	3536.5	3.10	**2.99**	3.8%	2190	2.98	**2.99**	-0.2%	3.8%
	6822	3.49	**3.76**	-7.2%	4127	3.36	**3.76**	-10.5%	3.6%
	13310.5	3.88	**3.78**	2.8%	7945	3.75	**3.78**	-0.6%	3.3%
40ºC	960	2.34	**1.66**	40.8%	800	2.38	**1.66**	43.5%	-1.9%
	2773	2.96	**2.35**	25.9%	2228	2.99	**2.35**	27.4%	-1.1%
	5789	3.39	**2.61**	29.9%	4474	3.41	**2.61**	30.6%	-0.5%
	11176	3.78	**3.54**	6.8%	8514	3.79	**3.54**	7.3%	-0.5%
	22293	4.18	**3.54**	18.2%	16935	4.21	**3.54**	18.8%	-0.5%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	18	1.69	**1.10**	53.8%	18	1.43	**1.10**	29.9%	15.5%
	46.5	2.28	**2.41**	-5.5%	47	2.01	**2.41**	-16.5%	11.7%
	99	2.75	**2.99**	-8.0%	102	2.48	**2.99**	-16.9%	9.6%
	188.5	3.15	**3.76**	-16.2%	197	2.88	**3.76**	-23.4%	8.5%
	365	3.56	**3.78**	-5.8%	385	3.28	**3.78**	-13.1%	7.7%
40ºC	47	2.29	**1.66**	37.9%	34	1.83	**1.66**	10.5%	19.9%
	122	2.88	**2.35**	22.5%	93	2.43	**2.35**	3.2%	15.7%
	227	3.26	**2.61**	25.0%	183	2.83	**2.61**	8.6%	13.1%
	417	3.64	**3.54**	2.8%	345	3.21	**3.54**	-9.1%	11.6%
	821	4.06	**3.54**	14.6%	683	3.62	**3.54**	2.4%	10.7%

Table C6-3 Mix #2 (Riverside I) Compressive Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	1892	23.11	**22.11**	4.6%					
	3943	29.01	**28.21**	2.8%		Maturity meter used provided no T history			
	7426	34.08	**34.49**	-1.2%					
	16016	40.25	**33.31**	20.8%					
40ºC	185	4.46	**2.78**	60.3%	578	2.59	**2.78**	-6.7%	41.8%
	1290	20.04	**22.84**	-12.2%	3446	17.06	**22.84**	-25.3%	14.9%
	8721	35.37	**31.29**	13.0%	23933	32.75	**31.29**	4.7%	7.4%
	17521	40.97	-	-	47969	38.38	-	-	6.3%

Temp.* (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
40ºC	9	7.25	**2.78**	160.7%	5	2.60	**2.78**	-6.6%	64.2%
	91	25.57	**22.84**	12.0%	28	17.07	**22.84**	-25.2%	33.2%
	556	40.15	**31.29**	28.3%	194	32.76	**31.29**	4.7%	18.4%
	1120	45.79	-	-	388	38.39	-	-	16.1%

* Maturity meter used for the cold samples (10ºC) provided only TTF.

Table C6-4 Mix #2 (Riverside I) Flexural Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	1761	3.64	**3.73**	-2.5%					
	3781	4.08	**4.24**	-3.9%		Maturity meter used provided no T history			
	7250	4.44	**4.47**	-0.6%					
	15662	4.88	**7.90**	-38.2%					
40ºC	158	2.27	**0.48**	373.5%	578	2.28	**0.48**	373.7%	0.0%
	1256	3.45	**2.98**	15.6%	3446	3.28	**2.98**	9.7%	5.1%
	8686	4.55	**-**	-	23933	4.36	**-**	-	4.1%
	17511	4.94	**-**	-	47969	4.75	**-**	-	3.9%

Temp.* (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
40ºC	6	2.29	**0.48**	376.2%	5	2.28	**0.48**	373.7%	0.5%
	86	3.81	**2.98**	27.7%	28	3.28	**2.98**	9.8%	14.1%
	550	4.89	**-**	-	194	4.36	**-**	-	10.8%
	1116	5.30	**-**	-	388	4.75	**-**	-	10.4%

* Maturity meter used for the cold samples (10ºC) provided only TTF.

Table C6-5 Mix #3 (Riverside II) Compressive Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	509	1.14	**1.64**	-30.6%	1214	2.25	**1.64**	37.4%	-98.0%
	1379	5.45	**-**	-	3493	6.68	**-**	-	-22.6%
	3107	8.96	**10.23**	-12.4%	8016	10.16	**10.23**	-0.7%	-13.3%
	6272	12.00	17.32	-30.7%	16032	13.06	17.32	-24.6%	-8.8%
40ºC	799	3.09	**8.58**	-64.0%	1488	3.10	**8.58**	-63.8%	-0.5%
	2294	7.65	**10.56**	-27.6%	4324	7.57	**10.56**	-28.3%	1.0%
	4613	10.67	**14.82**	-28.0%	9861	11.02	**14.82**	-25.6%	-3.3%
	7952	13.03	**20.83**	-37.5%	19183	13.81	**20.83**	-33.7%	-6.0%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
10ºC	14	-0.21	**1.64**	-113.0%	19	2.20	**1.64**	34.4%	1134.6%
	37	4.20	**-**	-	56	6.65	**-**	-	-58.4%
	83	7.86	**10.23**	-23.1%	128	10.14	**10.23**	-0.9%	-28.9%
	169	11.09	17.32	-36.0%	257	13.05	17.32	-24.7%	-17.7%
40ºC	29	3.09	**8.58**	-64.0%	24	3.10	**8.58**	-63.8%	-0.4%
	80	7.69	**10.56**	-27.1%	70	7.57	**10.56**	-28.3%	1.6%
	153.5	10.65	**14.82**	-28.1%	159	11.03	**14.82**	-25.6%	-3.5%
	252.5	12.91	**20.83**	-38.0%	308	13.81	**20.83**	-33.7%	-7.0%

Table C6-6 Mix #3 (Riverside II) Flexural Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	509	0.85	**0.97**	-12.9%	1214	1.03	**0.97**	5.6%	-21.2%
	1379	1.54	**1.74**	-11.5%	3493	1.74	**1.74**	-0.1%	-12.8%
	3107	2.10	**-**	-	8016	2.30	**-**	-	-9.1%
	6272	2.59	**3.04**	-14.7%	16032	2.76	**3.04**	-9.1%	-6.5%
40ºC	799	1.16	**1.29**	-9.8%	1488	1.17	**1.29**	-9.5%	-0.3%
	2294	1.89	**1.69**	12.3%	4324	1.88	**1.69**	11.5%	0.7%
	4613	2.38	**1.92**	24.0%	9861	2.43	**1.92**	26.9%	-2.3%
	7952	2.76	**2.49**	10.9%	19183	2.88	**2.49**	15.9%	-4.5%
	16093	3.25	**2.98**	8.8%	37424	3.33	**2.98**	11.6%	-2.6%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
10ºC	14	0.63	**0.97**	-35.3%	19	1.02	**0.97**	4.8%	-61.9%
	37	1.34	**1.74**	-23.0%	56	1.73	**1.74**	-0.4%	-29.4%
	83	1.93	**-**	-	128	2.29	**-**	-	-18.9%
	169	2.45	**3.04**	-19.5%	257	2.76	**3.04**	-9.2%	-12.7%
40ºC	29	1.16	**1.29**	-9.8%	24	1.17	**1.29**	-9.5%	-0.4%
	80	1.90	**1.69**	12.7%	70	1.88	**1.69**	11.5%	1.1%
	153.5	2.38	**1.92**	23.9%	159	2.43	**1.92**	26.9%	-2.4%
	252.5	2.74	**2.49**	10.2%	308	2.88	**2.49**	15.9%	-5.2%
	497	3.23	**2.98**	8.3%	600	3.33	**2.98**	11.6%	-3.0%

Table C6-7 Mix #4 (Victorville) Compressive Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	2133	14.51	**15.51**	-6.4%	4900	16.17	**15.51**	4.3%	-11.4%
	4131	18.76	**22.17**	-15.4%	9665	20.72	**22.17**	-6.5%	-10.4%
	8931	23.72	**25.55**	-7.1%	21381	26.04	**25.55**	1.9%	-9.8%
	10371	24.69	**-**	-	24896	27.06	**-**	-	-9.6%
40ºC	3258	17.23	**17.57**	-1.9%	5334	16.74	**17.57**	-4.7%	2.9%
	7578	22.67	**22.92**	-1.1%	12418	22.40	**22.92**	-2.3%	1.2%
	15221.5	27.15	**30.59**	-11.2%	24895	27.06	**30.59**	-11.6%	0.4%
	33619	32.25	**37.75**	-14.6%	55042	32.37	**37.75**	-14.2%	-0.4%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Compressive strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
10ºC	60.5	12.17	**15.51**	-21.5%	78	16.09	**15.51**	3.8%	-32.3%
	115.5	16.65	**22.17**	-24.9%	155	20.65	**22.17**	-6.8%	-24.0%
	247.5	21.93	**25.55**	-14.2%	342	25.98	**25.55**	1.7%	-18.5%
	286.5	22.94	**-**	-	399	27.01	**-**	-	-17.8%
40ºC	167	19.20	**17.57**	9.3%	89	16.95	**17.57**	-3.5%	11.7%
	387	25.02	**22.92**	9.2%	207	22.62	**22.92**	-1.3%	9.6%
	783	29.90	**30.59**	-2.3%	416	27.29	**30.59**	-10.8%	8.7%
	1724.5	35.37	**37.75**	-6.3%	919	32.62	**37.75**	-13.6%	7.8%

Table C6-8 Mix #4 (Victorville) Flexural Strength Estimates of Laboratory Specimens, Based on Laboratory Curves Developed Using 23ºC Data

Temp. (ºC)	Downloaded TTF (ºC-hours)	Estimate based on downloaded TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated TTF (ºC-hours)	Estimate based on calculated TTF (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc TTF)
10ºC	2133	3.00	**2.41**	24.7%	4900	3.22	**2.41**	33.5%	-7.1%
	4131	3.53	**3.05**	15.8%	9665	3.77	**3.05**	23.6%	-6.7%
	8931	4.14	**3.62**	14.5%	21381	4.41	**3.62**	21.8%	-6.4%
	10371	4.26	**-**	-	24896	4.53	**-**	-	-6.3%
40ºC	3258	3.34	**3.14**	6.5%	5334	3.29	**3.14**	4.8%	1.6%
	7578	4.01	**3.69**	8.7%	12418	3.97	**3.69**	7.5%	1.1%
	15221.5	4.57	**4.07**	12.2%	24895	4.53	**4.07**	11.3%	0.8%
	33619	5.20	**7.77**	-33.1%	55042	5.17	**7.77**	-33.4%	0.5%

Temp. (ºC)	Downloaded Equiv Age (days)	Estimate based on downl. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Calculated Equiv Age (days)	Estimate based on calc. Equiv Age (MPa)	Measured Flexural strength (MPa)	Difference (%)	Diff. between estimates (downl x calc t_e)
10ºC	60.5	2.78	**2.41**	15.3%	78	3.21	**2.41**	33.1%	-15.5%
	115.5	3.29	**3.05**	7.9%	155	3.76	**3.05**	23.3%	-14.3%
	247.5	3.89	**3.62**	7.6%	342	4.40	**3.62**	21.6%	-13.1%
	286.5	4.01	**-**	-	399	4.53	**-**	-	-12.9%
40ºC	167	3.58	**3.14**	14.2%	89	3.31	**3.14**	5.6%	7.5%
	387	4.25	**3.69**	15.1%	207	4.00	**3.69**	8.3%	5.9%
	783	4.80	**4.07**	18.0%	416	4.56	**4.07**	12.0%	5.1%
	1724.5	5.43	**7.77**	-30.1%	919	5.20	**7.77**	-33.0%	4.2%