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Fast Track Concrete For Construction Repair

FINAL REPORT
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Submitted by

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16. Abstract

Under the sponsorship of the New Jersey Department of Transportation a unique concrete mix was developed. This concrete mix attains a significant strength in a period of six to nine hours for use on pavement repair in high-traffic areas. It is not a "rapid setting" formulation, but is Portland cement based, relying on chemical admixtures and insulated coverings to attain very high temperature levels, very quickly.

The mix, which is designated as "fast track mix", has been shown to be effective in reaching its target compressive and flexural strengths of 3000 and 350 psi, respectively in as little as six hours. Several full-scale demonstration slabs have been completed both in the laboratory and in the field with satisfactory results.

The strength gain is primarily dependent on its temperature history, over time. All other factors being equal, higher curing temperatures result in concrete of greater maturity, at any point in time. One application of this is the maturity method. The maturity method is a means of estimating the in-place strength of concrete, based on its temperature history. Two different types of maturity functions are in current use: the equivalent age and the temperature-time factor. A correlation between either strength and equivalent age or between strength and temperature-time factor must be established experimentally. Once the correlation has been established thermoprobes are embedded in freshly placed concrete and connected to specially designed field computers for continual maturity determination. Knowing the maturity; in terms of either the equivalent age r the temperature-time factor, the strength of in-place concrete is estimated.

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Table of Contents

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The contribution of Mr. Jon Rudolph during the experimental phase and the support of Charlie Stockhausen of Weldon Materials are also gratefully acknowledged.

List of Figures

List of Tables

Terminology

Datum Temperature - the temperature, below which, cement hydration is determined to cease. It is the temperature that is subtracted from the measured temperature, when calculating the temperature-time factor.

Equivalent Age - One of two conventional measures of concrete maturity. It reflects "the number of days or hours at a specified (constant) temperature (typically, 20° C) required to produce a maturity value equal to the value achieved by a curing period at temperatures different from the specified temperature" [1].

Maturity - "The extent of cement hydration in a concrete mixture. Provided there is sufficient moisture, maturity at a given age is primarily a function of temperature history." [1] Two conventional measures of concrete maturity are the equivalent age and the temperature-time factor. A third measure of concrete maturity, termed factored maturity, is introduced in this report and it is used because it provides better correlation with strength then the conventional methods.

Maturity Function - "The mathematical expression for evaluating maturity from the recorded temperature history of the concrete" [1]. There are two conventional maturity functions - equivalent age and the temperature-time factor. A third maturity function is used in this report, termed factored maturity.

Temperature-Time Factor - One of two conventional measures of concrete maturity. It is equal to the product of temperature and time, where temperature is the number of degrees above the datum temperature.

Factored Maturity - An alternate maturity function that is introduced in this report. It combines the concepts of equivalent age and the temperature-time factor and generally provides better fit with strength data. Its form is specific to the fast-track mix with constants determined by a multiple regression model.

Temperature Rate - The rate at which the temperature of a concrete mass increases due to hydration. This rate was determined experimentally, accounting for heat losses by conduction. The variation of the temperature rate with time or maturity was determined using a calibrated calorimeter.

Temperature Rate Function - The temperature rate varies with time and with maturity. For use in the computer simulation, this variation was expressed as functions of the factored maturity.

Heat Rate - The rate at which a concrete mass generates heat by hydration. Given the specific heat and density of concrete, this term is equivalent to the temperature rate, which was determined experimentally.

1. Introduction

Under the sponsorship of the New Jersey Department of Transportation a unique concrete mix was developed. This concrete mix attains a significant strength in a period of six to nine hours for use on pavement repair in high-traffic areas. It is not a "rapid-setting" formulation, but is Portland cement based, relying on chemical admixtures and insulated coverings to attain very high temperature levels, very quickly.

The mix, which is designated as "fast-track mix", has been shown to be effective in reaching its target compressive and flexural strengths of 3,000 and 350 psi, respectively in as little as six hours. Several full-scale demonstration slabs have been completed both in the laboratory and in the field with satisfactory results.

The strength gain is primarily dependent on its temperature history, over time. All other factors being equal, higher curing temperatures result in concrete of greater maturity, at any point in time. One application of this is the *maturity method.* The maturity method is a means of estimating the in-place strength of concrete, based on its temperature history. Two different types of maturity functions are in current use: the *equivalent age* and the *temperature-time factor*. A correlation between either strength and equivalent age or between strength and the temperature-time factor must be established experimentally. Once the correlation has been established thermoprobes are embedded in freshly placed concrete and connected to specially designed field computers for continual maturity determination. Knowing the maturity, in terms of either the equivalent age or the temperature-time factor, the strength of in-place concrete is estimated

The maturity functions have been useful in estimating the strength of concrete after it has been placed, on many fast-track projects. However, no effort has yet been made to predict the strength of concrete *before* it has been placed. Using the same principles, it is possible to estimate the strength-gain of concrete, prior to commencing with the pour, provided that its thermal properties of heat transfer and heat generation are known. The heat transfer properties of concrete are its thermal conductance and specific heat; these properties are readily obtainable from handbooks [3]. The heat generation properties, however, are characteristics that are unique to this mix design and must be determined experimentally. It is necessary to obtain an experimental description of the variation of heat rate, either as a function of time or as a function of maturity.

The primary purpose of the research carried out at Rutgers was to develop a computer simulation of the heat generation and transfer within a fast-track concrete slab. This computer simulation enables the determination of the temperature history of a hypothetical slab, based on its geometry, insulation, initial temperature and air temperature. By predicting the time-temperature profile of the slab in advance, it is possible to predict the time required to reach a target strength, prior to commencing with the pour. The simulation may be used to study the sensitivity of important variables. Based on the simulation results, it is possible to examine the effect of various initial mix temperatures, air temperatures, insulation thickness', and slab thickness' on time required to reach the target strength.

2. Fast-Track Concrete and Strength Correlation

A. Mix Design

Materials Used

Cement: Hercules Type I

Aggregates: ¾" No. 57 Crushed Stone (Trap Rock) from Weldon Materials
Natural Sand - Fineness Modulus = 2.92 from Weldon Materials

Chemical Admixtures: all admixtures were products of Sika Chemical Corporation
AER Air Entraining Admixture
Sikament86 High-Range Water-Reducing admixture
Rapid-1 Accelerating admixture

A sieve analysis was performed on the sand. Its size distribution is shown in Figure 1.1. Seven batches of concrete were made for evaluating at various temperatures. The differences between mixes are significant. The water reducing and air entraining admixtures were adjusted to attain the desired slump.

Mix I	
Hercules Type I cement	799 lb/yd^3
3/4" Crushed Trap Rock	1800 lb/yd^3
Natural Sand (FM = 2.92)	1200 lb/yd^3
Water	292 lb/yd^3
AER Air Entraining Admixture	1.25 fl. oz./cwt.
Sikament86 Superplasticizer	16 fl. oz./cwt.
Rapid-1 Accelerator	32 fl. oz./cwt.
water-cement ratio: 0.365	

Table 1.2 Mix Proportions of Mix II

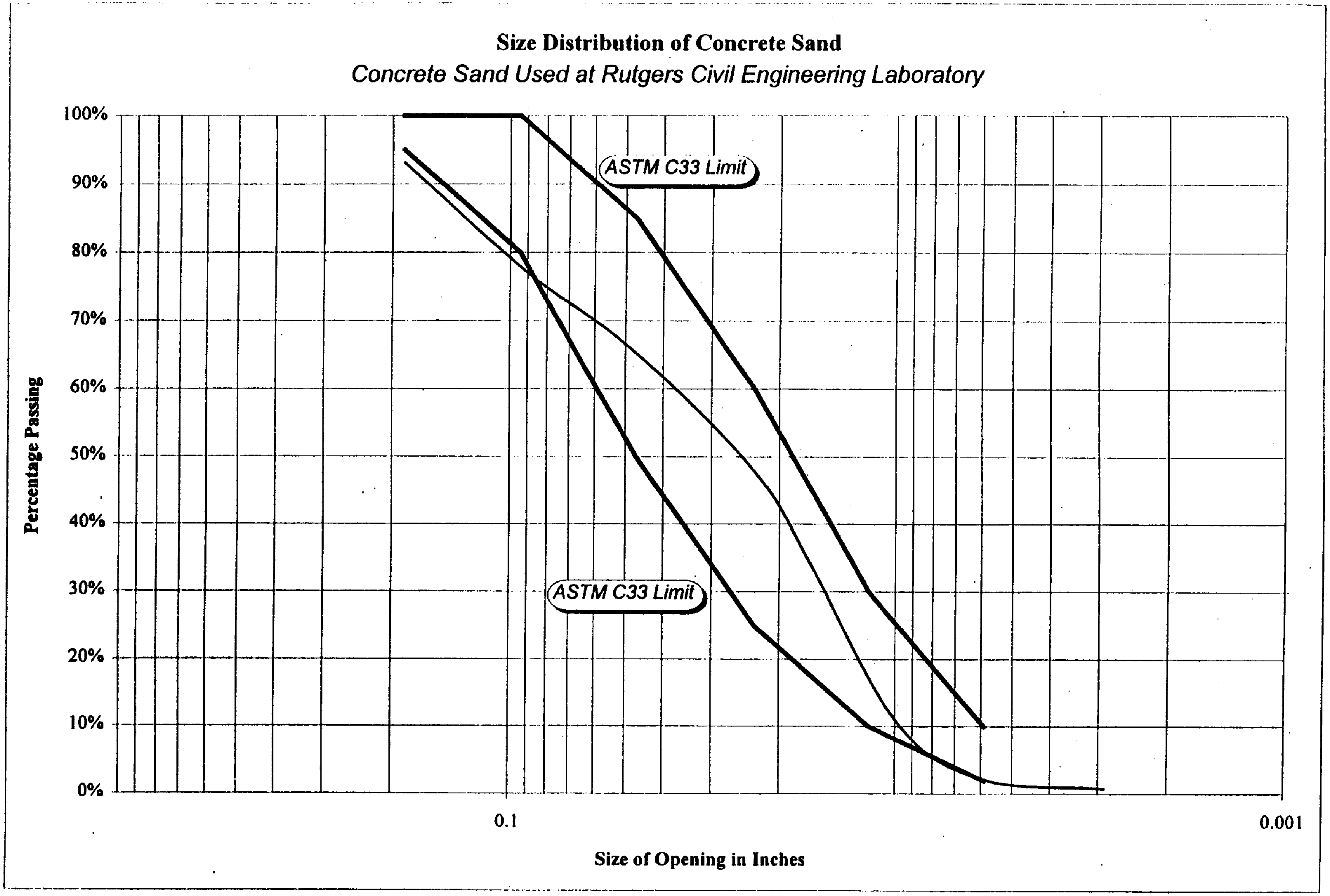

Size Distribution of Concrete Sand
Concrete Sand Used at Rutgers Civil Engineering Laboratory
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percentage Passing
ASTM C33 Limit
ASTM C33 Limit
0.1
0.001
Size of Opening in Inches

Figure 1.1

Table 1.2 Mix Proportions of Mix II

Mix II	
Hercules Type I cement	799 lb/yd^3
3/4" Crushed Trap Rock	1800 lb/yd^3
Natural Sand (FM = 2.92)	1200 lb/yd^3
Water	308 lb/yd^3
AER Air Entraining Admixture	1.25 fl. oz./cwt.
Sikament86 Superplasticizer	20 fl. oz./cwt.
Rapid-1 Accelerator	32 fl. oz./cwt.
water-cement ratio: 0.385	

Beginning with Mix III, the proportions remained fixed. The only variable for these mixes was the initial temperature. The final five mixes, having the same proportions, were designated III, IV, V, VI, VII, respectively. The proportions of these mixes are shown in Table 1.3

Table 1.3 Mix Proportions for Mixes III, IV, V, VI, VII

Mixes III, IV, V, VI, VII	
Hercules Type I cement	799 lb/yd^3
3/4" Crushed Trap Rock	1800 lb/yd^3
Natural Sand (FM = 2.92)	1200 lb/yd^3
Water	308 lb/yd^3
AER Air Entraining Admixture	1 fl. oz./cwt.
Sikament86 Superplasticizer	18 fl. oz./cwt.
Rapid-1 Accelerator	32 fl. oz./cwt.
water-cement ratio: 0.385	

For each mix slump, air content (via pressure method), and initial temperature were taken. When possible, later slumps were taken, after some elapsed time. Details of the fresh concrete properties are found in Table 1.4.

Table 1.4 Fresh Concrete Properties

Mix Designation	Initial Slump	Later Slump: Elapsed Time	Initial Temperature	Air Content	Comments
Mix I	2 1/2"	NA	22.0° C (71.6° F)	3.0%	
Mix II	7 1/2"	2": 40 minutes	24.8° C (76.6° F)	7.5%	
Mix III	9"	NA	24.5° C (76.1° F)	5.7%	
Mix IV	8"	4": 15 minutes 2": 30 minutes	31.0° C (87.8° F)	5.2%	40° C water (104.0° F) 35° C aggregates (95° F)
Mix V	8 1/4"	NA	16.0° C (60.8° F)	7.0%	Ice water @3° C (37.4° F) 10° C sand (50° F)
Mix VI	7 1/2"	NA	27.0° C (80.6° F)	6.4%	
Mix VII	5 1/2"	Not measured. ≈ 2" after 15 min.	35.0° C (95.0° F)	4.1%	Heated water and heated sand

B. Determination of Datum Temperature

Datum temperature is most simply described as the temperature below which the rate of cement hydration may be considered negligible. It is necessary to experimentally determine the datum temperature for a concrete mix when establishing a correlation between maturity and strength. Incorrect specification of the datum temperature can introduce bias; the strength-maturity relationship may not be universal for all temperatures. Incorrect datum specification, for example, may overestimate the strength of a particular pour if it is substantially colder or warmer than average.

In general, ASTM C1074 guidelines were followed for the purpose of determining the datum temperature for the fast-track concrete. The ASTM procedure consists of maintaining sets of concrete (or mortar) samples at different (constant) temperatures, then comparing the strength-gain rates of different temperatures graphically to extrapolate the temperature at which the strength-gain rate is zero (or, hydration ceases). The ASTM standard suggests the use of 2" mortar cubes submersed in a temperature-controlled bath. A temperature-controlled bath is employed, rather than air, because the conductive medium is much more effective at maintaining the concrete temperature. The justification for mortar cube samples is that they are sufficiently small so that there is negligible temperature gradient across the sample.

The ASTM procedure was followed, with the exception of the samples used. Rather than mortar cubes, 3" x 6" concrete cylinders were used. It was felt that the use of mortar samples is somewhat "artificial" and is an unnecessary compromise; the final product of this research is concrete, not mortar. Though 2" cubes were not used, the 3" x 6" cylinders are still sufficiently small so that negligible gradient was found across the samples, as measured by embedded temperature probes. The temperature differential between the center of a cylinder and the bath temperature never exceeded 1° C.

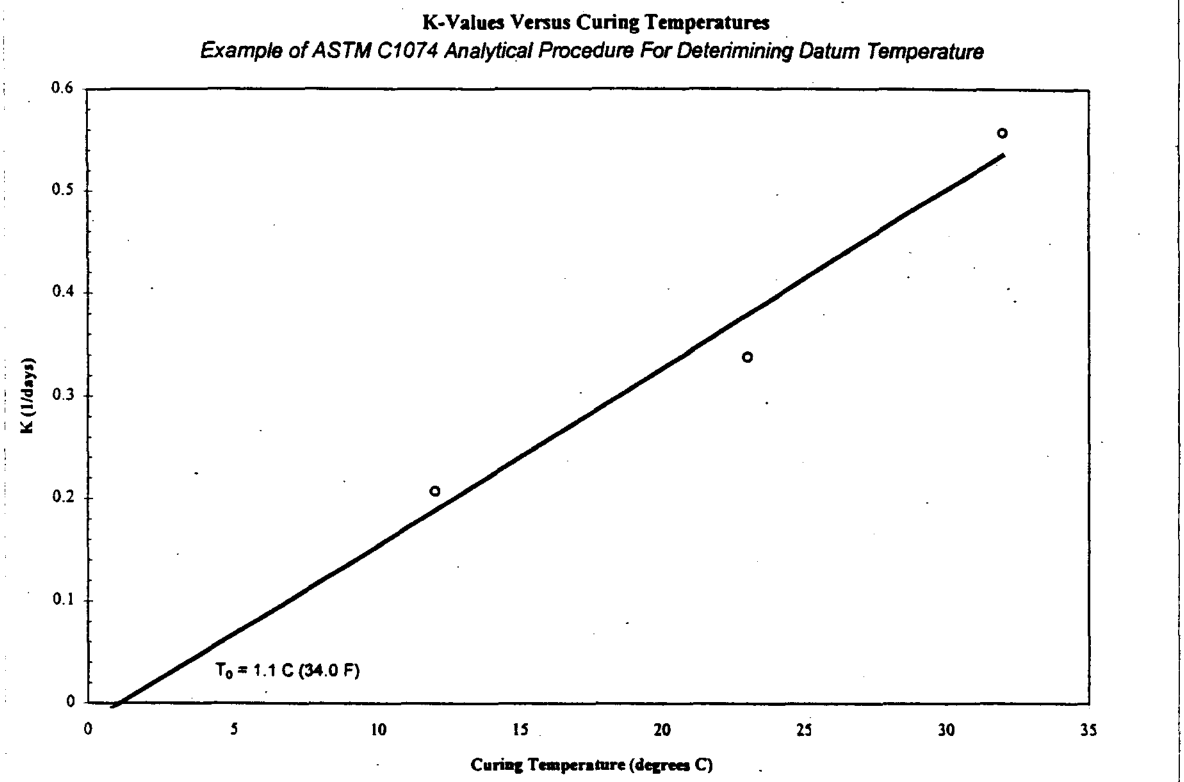
The concrete cylinders were maintained at a constant temperature in a 55 gallon drum of water. The drum was wrapped with a 20' length of electrical heating tape, providing up to 2000 watts of uniform heating to the drum. The heating tape was controlled by a temperature switch. The temperature was maintained within about 0.5° C of a constant temperature. To assure uniform temperature throughout the drum, compressed air was forced through a filter at the bottom of the drum, aerating and circulating the water.

Five different temperature-controlled baths were used: 22.5° C (72.5° F), 24.4° C (75.9° F), 24.1° C (75.4° F), 32.5° C (90.5° F), 10.9° C (51.6° F).

The experimental procedure was as follows:

1. After molding the cylinders, the tops were tightly covered with plastic. A temperature probe was inserted into one cylinder.
2. The cylinders were placed into the bath. The temperature of the bath and one of the cylinders was continually monitored and the data recorded for a period of 24 hours.
3. Beginning soon after concrete setting, cylinders were removed from the bath, usually in groups of three, for testing. The cylinders were capped with molten sulfur and were tested in compression. Cylinders were typically tested at increasing time intervals. Example: 8 hours, 12 hours, 24 hours, 48 hours, 96 hours, 384 hours.
4. After 24 hours, the bath temperature continued to be controlled for up to 28 days. However, temperature data collection stopped at 24 hours

The analytical procedure for determining the datum temperature by the ASTM standard is as follows:

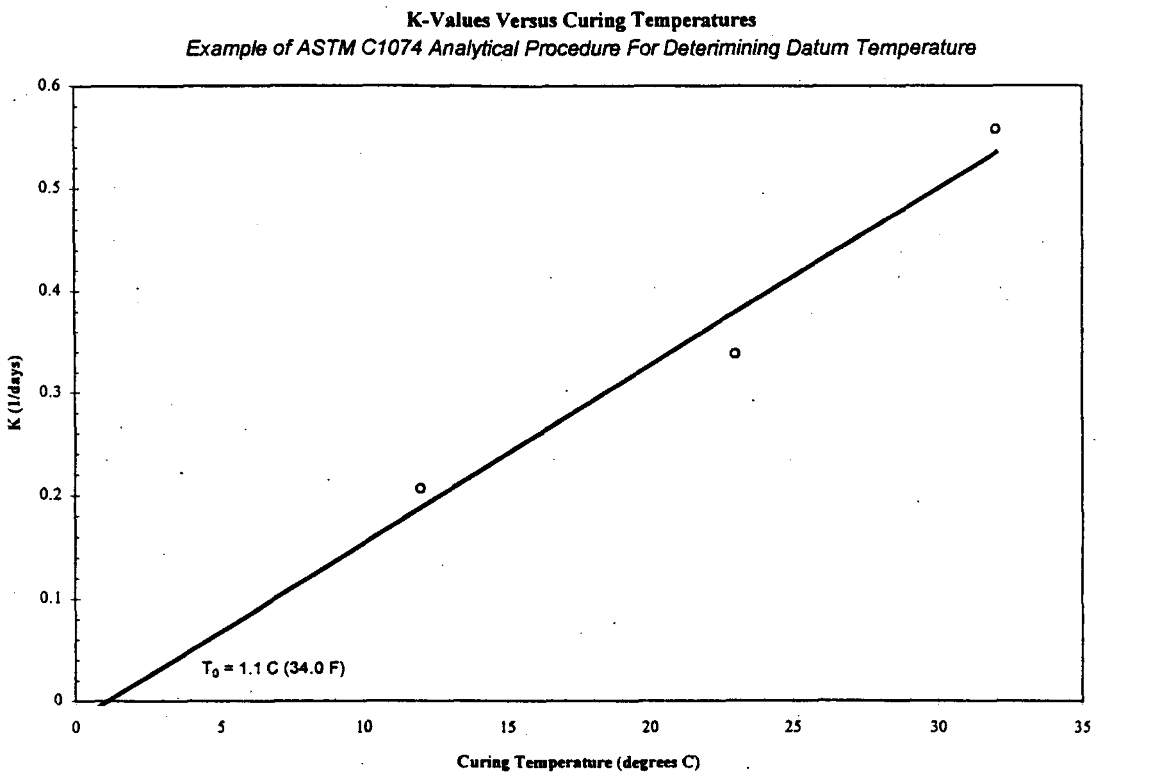


Comments: In this figure, the K-Values, determined in Figure 1.2, are graphed versus the curing temperature. The x-intercept represents a K-value of zero (a reaction rate of zero). This x-intercept gives a datum temperature, for this example, of 1.1 degrees C.

Figure 1.3 Example of ASTM C1074 Procedure for Determining Datum Temperature

Application of ASTM C1074 Procedure to Fast-Track Concrete

As stated previously, the ASTM procedure for determining the datum temperature is applicable when the relevant time period is reached in several days. However, for the fast-track concrete, ***the relevant time period is not reached in several days. It is reached in several hours***. Consequently, datum temperature calculations are not typical. A graph of the reciprocal of strength versus the reciprocal of age is shown in Figure 1.4. Note that the experimental curves are not straight lines, as they were in Figure 1.2, the example case.



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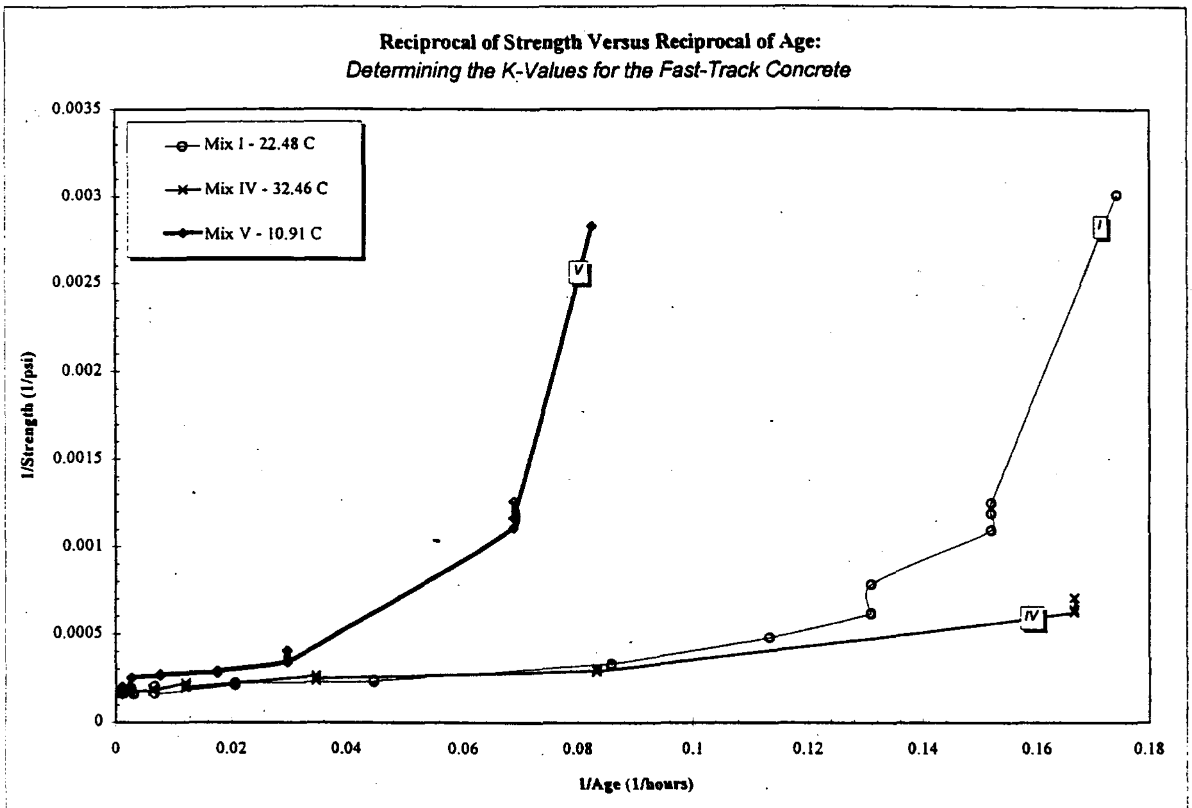


For clarity, mixes II and III are not shown

Comments: It is evident that the relationship between the reciprocal of strength and the reciprocal of age is non-linear, indicating that the K-values are not constant.

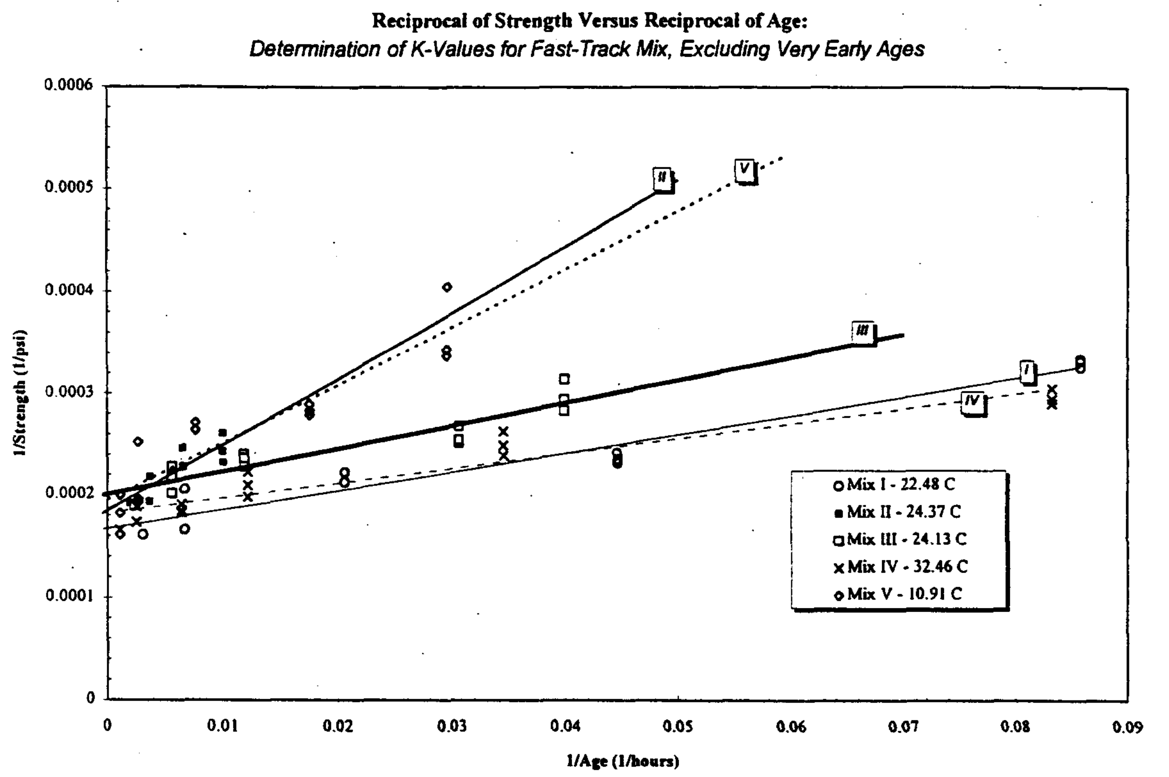
Figure 1.4 Reciprocal of Strength Versus Reciprocal of Age for the Fast-Track Concrete

From Figure 1.4, it is evident that the K-values are not constant for the fast-track concrete, over time; i.e., the curves are not straight lines. The curves only approach linearity for times exceeding 12 hours at high temperatures, and 48 hours at very lower temperatures.

The implication of K-values that are not constant is that the datum temperature is not constant over time. In fact, the datum temperature decreases over time. At a very early age it may be found that *hydration only proceeds if the temperature is quite high*. Over time, however, hydration will begin, at an *ever decreasing temperature*. Eventually, the decrease in the datum temperature becomes insignificant and a constant datum temperature is reached. This time coincides with the portions of Figure 1.4 that are straight lines.

Efforts were made to estimate the manner in which the datum temperature decreases over time, through use of the experimental data. Various functional forms were chosen for the K-values, including exponential and piece-wise linear functions of time. The results were maturity functions where the *datum temperature was expressed as a function of time*. However, these maturity functions were unnecessarily complex and could not be incorporated in standard maturity meters in any way. Consequently, the study of time-dependent datum temperatures was not considered further.

It was concluded that a single datum temperature for the first twelve hours could not be obtained using the ASTM standard.



Mix I - 22.48 °C Average Curing Temperature
Slope = 0.0018516
Intercept = 0.0001669
K = 0.090131
$R^2 = 0.9474$

Mix II - 24.37 °C Average Curing Temperature
Slope = 0.006495
Intercept = 0.000184
K = 0.028357
$R^2 = 0.7221$

Mix III - 24.13 °C Average Curing Temperature
Slope = 0.002264
Intercept = 0.000200
K = 0.088557
$R^2 = 0.9439$

Mix IV - 32.46 °C Average Curing Temperature
Slope = 0.0014667
Intercept = 0.0001821
K = 0.124135
$R^2 = 0.9124$

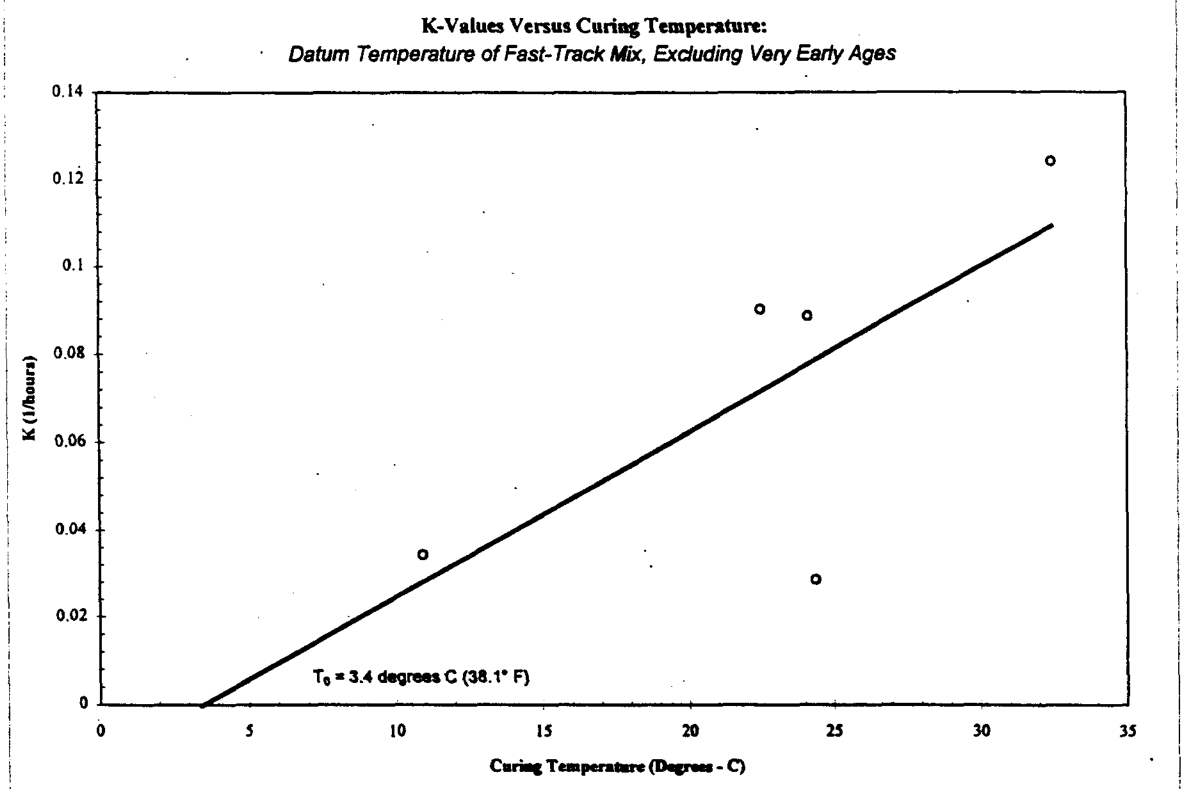
Mix V - 10.91 °C Average Curing Temperature
Slope = 0.0056927
Intercept = 0.0001945
K = 0.034161
$R^2 = 0.8546$

Figure 1.5 Determining the "Long-Term" K-Values for the Fast-Track Mix

Although the datum temperature cannot be determined for very early age, some estimation of the datum temperature may still be made. Examining Figure 1.4, the data approaches linearity when the reciprocal of age is low (later ages). Therefore, a "long-term" datum temperature could be obtained by considering only the linear portion of the curves found in Figure 1.4. This is done in Figure 1.5. From the K-values determined in Figure 1.5, the "long-term" datum temperature of 3.4° C (38.1° F) was determined from Figure 1.6.

The datum temperature is relatively high. Datum temperatures that are below 0° C (32.0°F) are more typical (-10° C is a typical assumed datum temperature). In addition, the use of admixtures generally lower the datum temperature, further. However, a concrete mixture that proceeds at a high rate with excessive temperatures can be expected to lose efficiency, in terms of reaction and crystallization, raising the activation energy, and the corresponding datum temperature. Considering this, a high datum temperature appears to be reasonable.

A high datum temperature implies that the initial concrete temperature must be high, for hydration to begin quickly. Maintaining high concrete temperatures, particularly in cold weather, is likely to be more important with the fast-track mix than with conventional mixes.



By excluding the very early age data points, the computed datum temperature reflects the datum at later ages, approaching infinity. This datum is only applicable after about 12 hours elapsed. With the K-values determined, the long-term datum temperature can be estimated. A best-fit line is made for the five K-values, previously computed. From the best-fit line, the datum temperature is 3.4° C (38.1° F)

Figure 1.6 Determining the "Long-Term" Datum Temperature for the Fast-Track Concrete

Estimating the Datum Temperature by Statistical Means

It was previously concluded that a single, temperature-independent datum temperature for very early ages cannot be obtained by using the ASTM standard; i.e., the chemical laws embodied in the ASTM standard do not appear to sufficiently explain the behavior of the fast-track mix at very early ages.

However, the practical use of the datum temperature is to facilitate accurate prediction of the strength of concrete based upon its maturity. Hence, for practical purposes, the datum temperature need not be scientifically correct; it is more important that it be statistically correct. The datum temperature that ought to be used is the one that provides the best statistical explanation of the strength-maturity correlation.

A simple statistical study was conducted for the purpose of identifying the datum temperature that results in the maximum R^2 for the strength-maturity function. The compressive strength data was analyzed for the strength range that was considered most relevant - greater than 1,900 psi. It was assumed that the relationship between strength and the temperature-time factor should be a reciprocal function (implying that strength reaches an upper limit with infinite maturity).

The statistical procedure consisted of

- Assuming a datum temperature
- Using a computer spreadsheet program to compute the temperature-time factors corresponding to each compressive test, for the assumed datum temperature.
- The spreadsheet program automatically recomputed the best-fit reciprocal function of strength versus temperature-time and its associated R^2.
- The procedure was repeated for datum temperatures ranging from -5° C to 6° C. The results are shown below in Table 1.5. The data is graphed in Figure 1.7.

By examining Figure 1.7, it may be concluded that a datum temperature of 3.2° C provides the best statistical fit.

Assumed Datum Temperature (°C)	R-Squared
-5	0.7451
-4	0.7490
-3	0.7531
-2	0.7571
-1	0.7612
0	0.7650
1	0.7685
2	0.7712
3	0.7725
3.2	0.7725
3.4	0.7725
3.6	0.7722
3.8	0.7718
4	0.7712
5	0.7649

Table 1.5

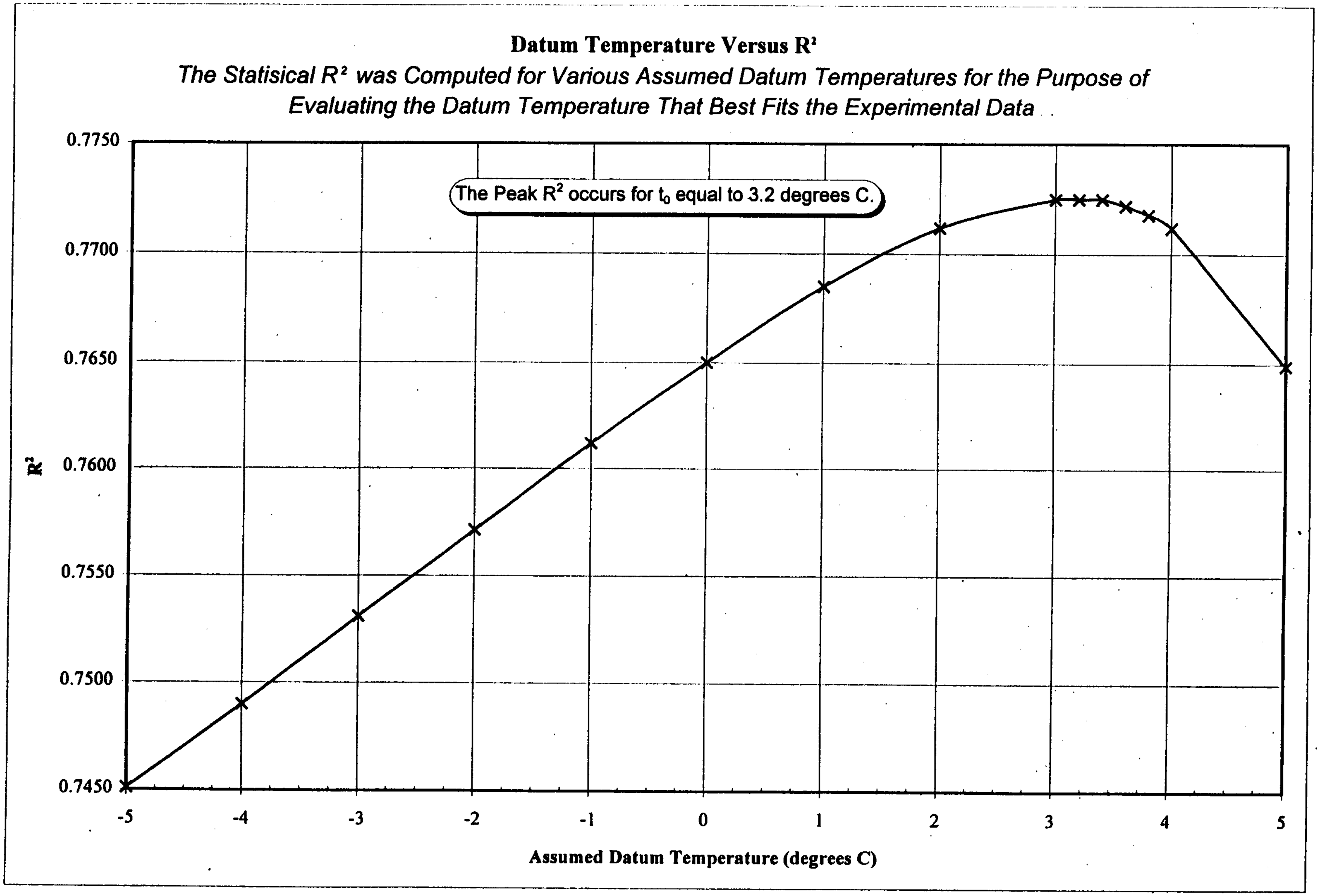

Datum Temperature Versus R²
The Statisical R² was Computed for Various Assumed Datum Temperatures for the Purpose of Evaluating the Datum Temperature That Best Fits the Experimental Data
The Peak R² occurs for t₀ equal to 3.2 degrees C.
R²
0.7750
0.7700
0.7650
0.7600
0.7550
0.7500
0.7450
-5
-4
-3
-2
-1
0
1
2
3
4
5
Assumed Datum Temperature (degrees C)

Figure 1.7

C. Strength - Maturity Correlation

The maturity function that was chosen was the *temperature-time factor*. From ASTM C1074, the temperature-time factor is:

$$M(t) = \Sigma (T_a - T_0) \Delta t$$

Where:

$M(t)$ = the temperature-time factor at age t, in degree C - hours

T_a = average concrete temperature during the time interval Δt, degrees C

T_0 = datum temperature, degrees C

Δt = a time interval, in decimal hours

The datum temperature T_0 was taken as 3.2° C (37.8° F), as determined on a statistical basis in Chapter 1B.

Compressive Strength - Temperature-Time Factor Correlation

A total of 161 compressive strength cylinders from seven mixes were available for strength-maturity correlation. These cylinders represent curing temperatures ranging from 10.9° C (51.6° F) to 68.0° C (154.4° F).

Using a datum temperature of 3.2° C (37.8°F), the maturity-compressive strength correlation is as shown in Figures 1.8 and 1.9. Although the spread of data is quite large for maturities above about 300, the data showed no correlation with temperature; i.e., manual inspection of the data showed that the residuals were randomly distributed, independent of temperature. This is particularly encouraging because, as previously stated, the curing conditions that were included represented all possible temperatures. It may be concluded that the maturity relationship is valid for all anticipated temperatures.

The compressive strength - temperature-time factor data was best-fit using least-squares regression. Linear functions were used for temperature-time factors less than 240 and or greater than 7,000 because the data in these ranges most closely resembled a linear function. For the 240 to 7,000 range, a reciprocal function was used because it is a realistic functional form for a chemical process (see Figure 1.10).

The best-fit equations for compressive strength versus the temperature-time factor are:

$$\text{For } M < 240: \quad f_c = 13.68007M - 987.374$$

$$\text{For } 240 < M < 7{,}000: \quad (1/f_c) = 0.057066\,(1/M) + 0.0001862$$

$$\text{for } M > 7{,}000: \quad f_c = 0.09636M + 4488.6$$

Based on the best-fit curve, the target compressive strength of 3,000 psi is reached at a temperature-time of 388° C-hours, on average (datum of 3.2° C).

Flexural Strength - Temperature-Time Correlation

A total of (35) 4" x 4" x 14" flexural specimens from six mixes were used. The specimens were tested in four-point flexure (loads at one-third points) using a universal test machine. Figures 1.11 and 1.12 show the flexural strength versus temperature-time relationship. The flexural strength -maturity data was best-fit using least-squares regression. A linear function was used for temperature-time factors less than 200 because the data most closely resembled a linear function. A reciprocal function was used for temperature-time factors greater than 200 because it is a realistic functional form for a chemical process (Figure 1.13).

The best-fit equations for flexural strength versus maturity are:

$$\text{For } M < 200: \quad f_r = 4.8522M - 581.8$$

$$\text{For } M > 200: \quad (1/f_r) = 0.305378(1/M) + 0.00161$$

Based on the best-fit curve, the target flexural strength of 350 psi is reached at a temperature-time of 245° C-hours, on average (datum of 3.2° C).

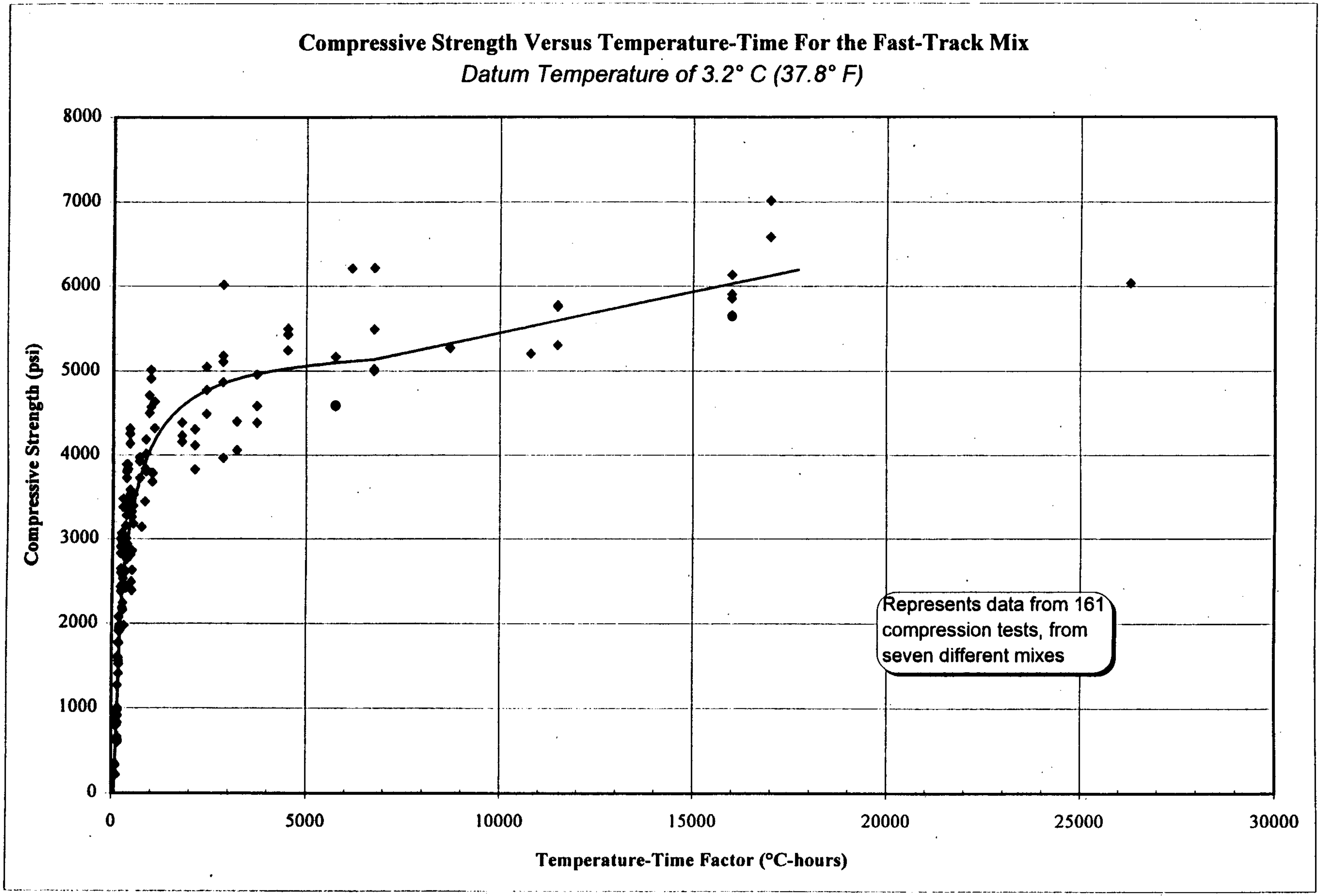

Compressive Strength Versus Temperature-Time For the Fast-Track Mix
Datum Temperature of 3.2° C (37.8° F)
Compressive Strength (psi)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
5000
10000
15000
20000
25000
30000
Temperature-Time Factor (°C-hours)
Represents data from 161 compression tests, from seven different mixes

Figure 1.8

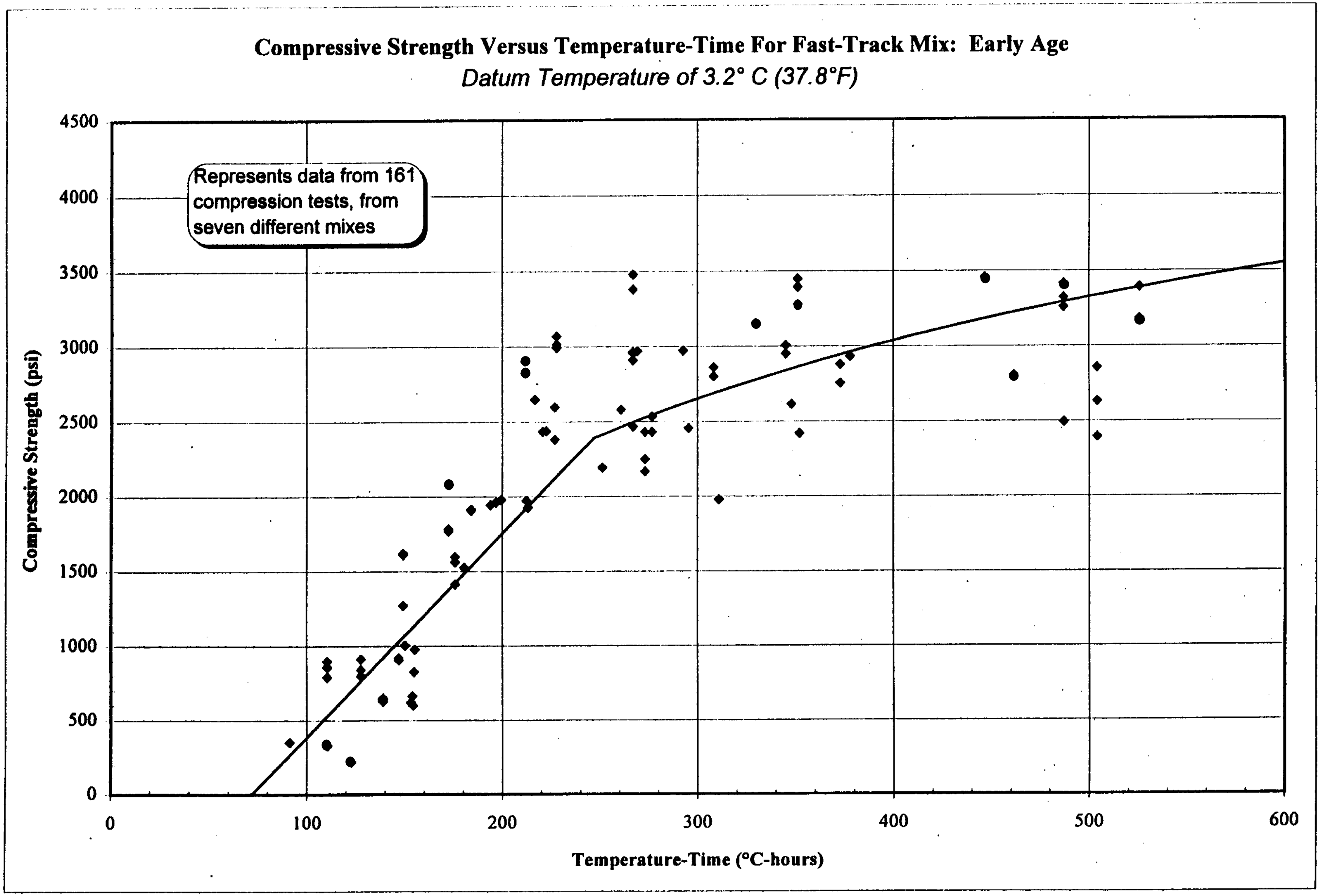

Compressive Strength Versus Temperature-Time For Fast-Track Mix: Early Age
Datum Temperature of 3.2° C (37.8°F)
Represents data from 161 compression tests, from seven different mixes
Compressive Strength (psi)
Temperature-Time (°C-hours)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400
500
600

Figure 1.9

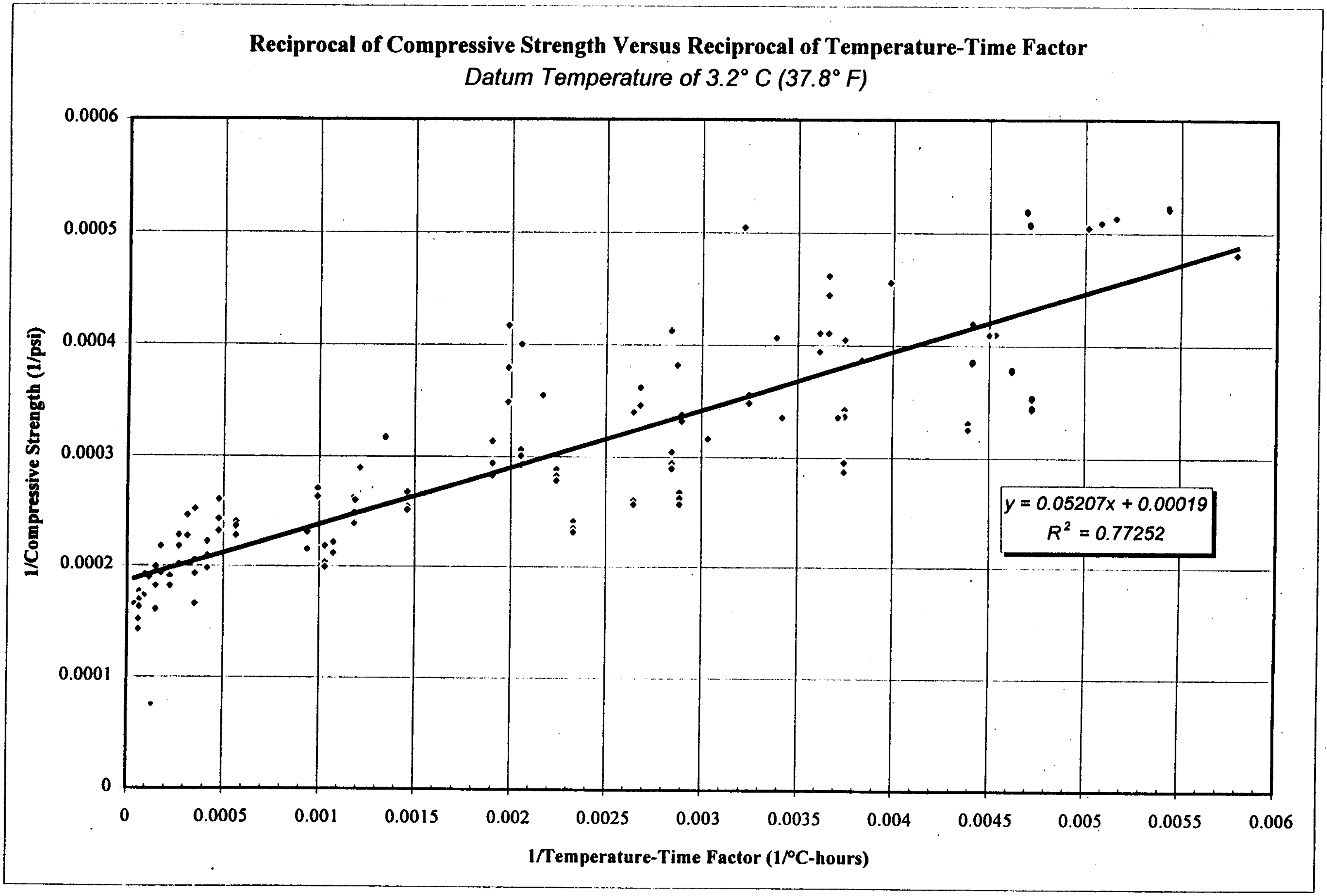

Reciprocal of Compressive Strength Versus Reciprocal of Temperature-Time Factor
Datum Temperature of 3.2° C (37.8° F)
1/Compressive Strength (1/psi)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
1/Temperature-Time Factor (1/°C-hours)
y = 0.05207x + 0.00019
R² = 0.77252

Figure 1.10

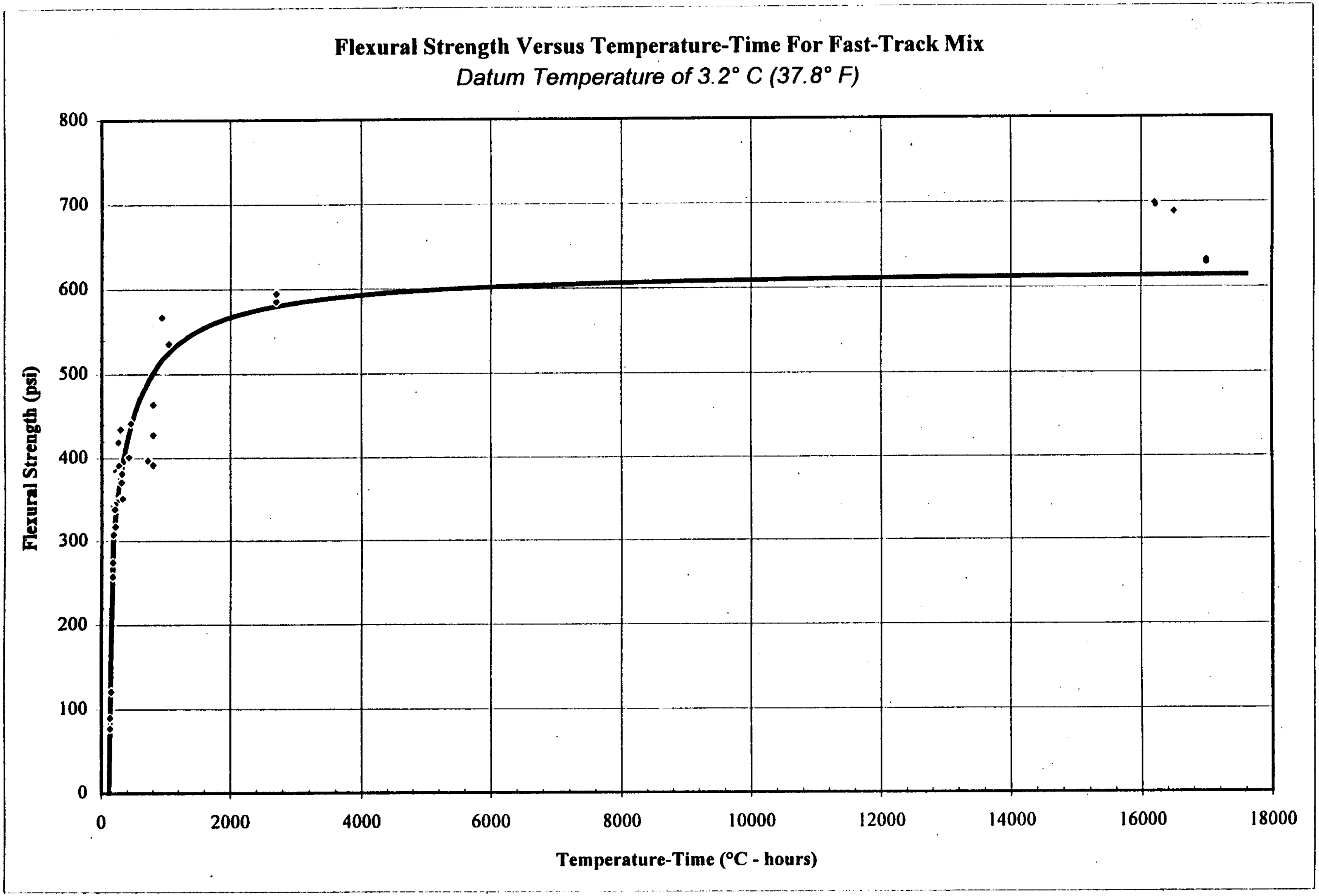

Flexural Strength Versus Temperature-Time For Fast-Track Mix
Datum Temperature of 3.2° C (37.8° F)
Flexural Strength (psi)
800
700
600
500
400
300
200
100
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Temperature-Time (°C - hours)

Figure 1.11

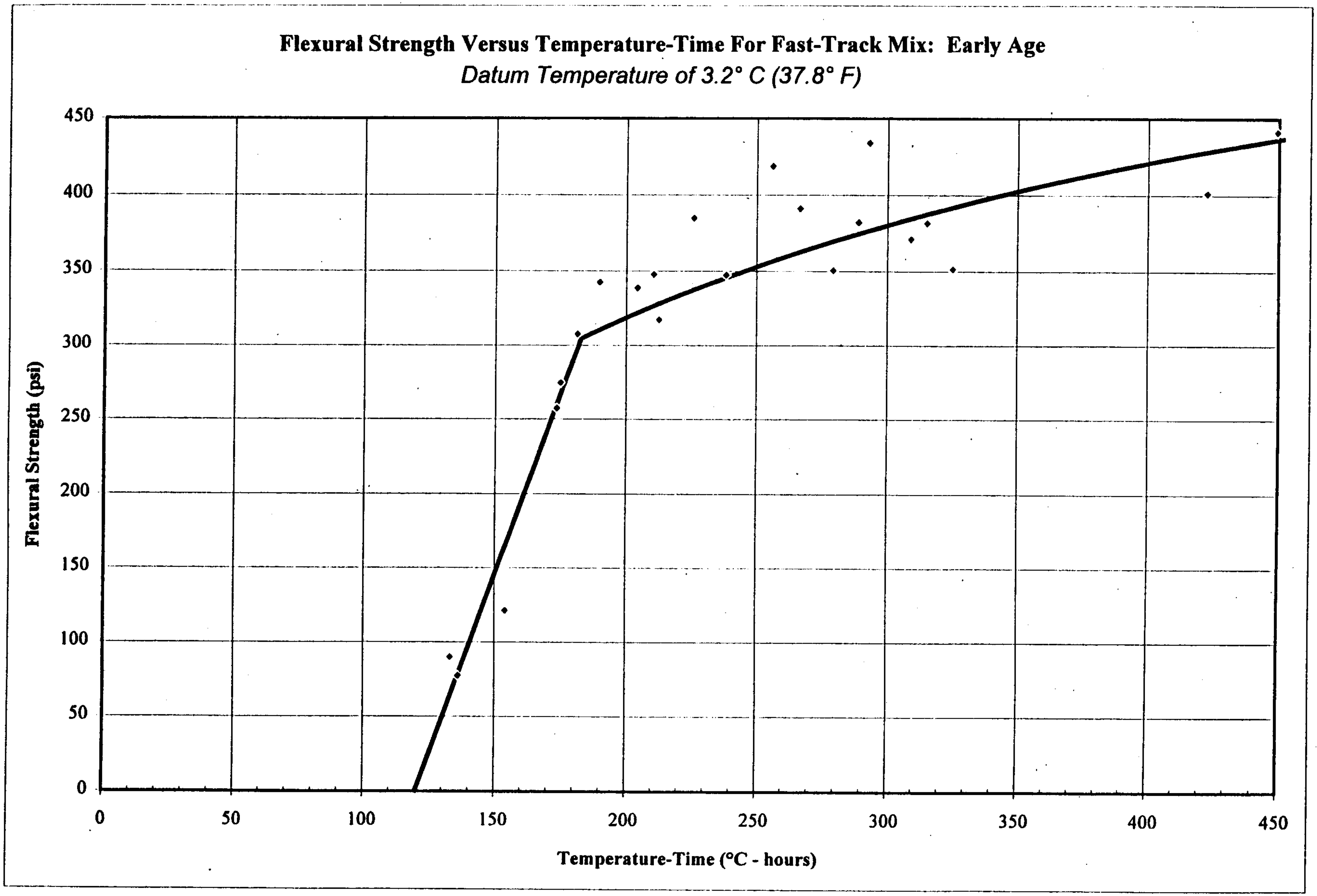

Flexural Strength Versus Temperature-Time For Fast-Track Mix: Early Age
Datum Temperature of 3.2° C (37.8° F)
Flexural Strength (psi)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
Temperature-Time (°C - hours)

Figure 1.12

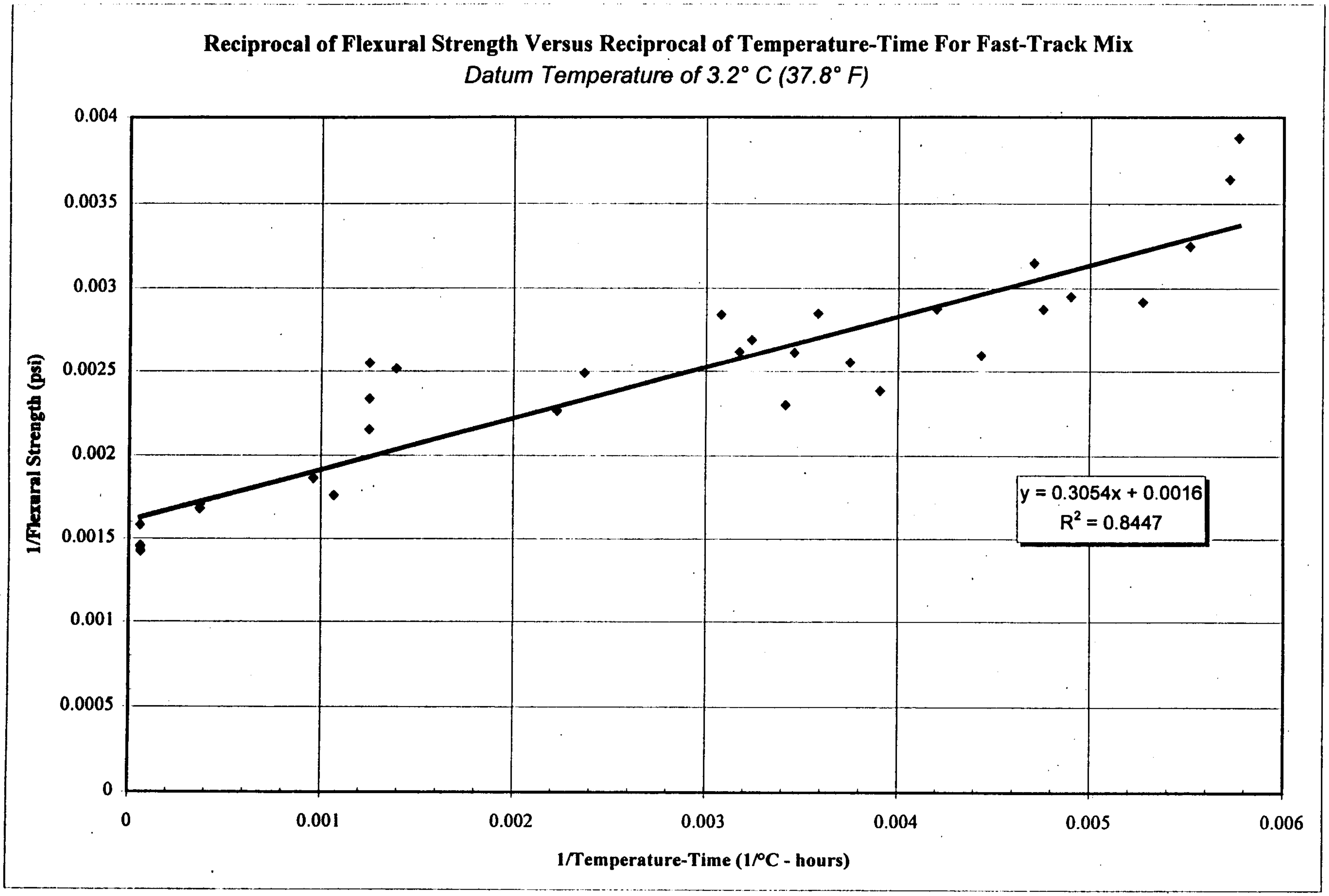

Reciprocal of Flexural Strength Versus Reciprocal of Temperature-Time For Fast-Track Mix
Datum Temperature of 3.2° C (37.8° F)
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
1/Flexural Strength (psi)
0
0.001
0.002
0.003
0.004
0.005
0.006
1/Temperature-Time (1/°C - hours)
y = 0.3054x + 0.0016
R2 = 0.8447

Figure 1.13

D. Factored Maturity

There are currently two maturity functions in use: ***equivalent age*** and ***temperature-time***. The temperature-time factor was the functional form that was used in Chapter 1.C for correlation with compressive and flexural strength.

In an effort to provide closer fit with the strength data, a new maturity function was used. This maturity function, termed *factored maturity*, combines aspects of both equivalent age and the temperature-time factor.

- Temperature-Time, as previously discussed.

$$M(t) = \Sigma (T_a - T_0) \Delta t$$

Where:
$M(t)$ = the temperature-time factor at age t, in degree C - hours
T_a = average concrete temperature during the time interval Δt , degrees C
T_0 = datum temperature, degrees C
Δt = a time interval, in decimal hours

- Equivalent age, defined as:

$$te = (\Sigma e \cdot \Delta t)^{-\left(Q\left(\frac{1}{Ta} - \frac{1}{Ts}\right)\right)}$$

Where:
t_e = equivalent age at a specified temperature T_s (typically 20° C), days or hours.
Q = activation energy divided by the gas constant, °K (determined experimentally by the same procedure as for datum temperature).
Ta = average temperature of concrete during time interval Δt, °K.
Ts = a specified temperature, °K (typically 20° C)
Δt = time interval, hours
e = base of the natural logarithm

Temperature-Time and equivalent age are related concepts. However, there are several key differences:

- The temperature-time factor, is the simple product of temperature and time. All temperatures are "the same". A temperature rise of one degree at 50° C results in the same temperature-time factor increase as a one degree rise at 20° C.
- All temperatures are not "the same" for the equivalent age number. A temperature rise of one degree at 50° C has a stronger impact on equivalent age than a one degree rise at 20° C (due to the exponential term).
- Whereas for maturity, hydration ceases at the datum temperature, for equivalent age, hydration never stops. The equivalent age exponential form supposes that hydration occurs at all temperatures, but the rate decreases exponentially as the temperature drops.

- Due to the difference in functional form, maturity and equivalent age are more likely to provide similar results if the prevalent temperatures are within a narrow range than if the temperatures are widely varying.

Factored Maturity combines aspects of temperature-time and equivalent age. The functional form was developed on the following basis:

- The exponentially increasing term used in computing equivalent age, is more realistic for a chemical process where temperatures vary widely, such as in the fast-track mix.
- The datum temperature concept that is used in the temperature-time factor realistically describes that the concrete will stop reacting if a minimum temperature is not maintained. Equivalent age does not make use of this concept.
- The hydration process at early ages may be characterized by:
    1. Initially, hydration proceeds very slowly, with a datum temperature, t_0', that is very high. Below this high datum temperature, very little activity occurs.
    2. After some temperature-time factor, M_t, is reached, datum temperature drops to its "long-term" level, t_0. Hydration rate rapidly increases and factored maturity rapidly accrues.
    3. High temperatures are more influential than low temperatures. This effect is reflected in an influence factor β.

The basic form of the factored maturity function is as follows:

$$M' = \Sigma (T_a - T_0)\beta \Delta t$$

Where:

M' = factored maturity, °C-hours

T_a = average concrete temperature during time interval Δt.

β = *influence factor*, increases the relative influence of high temperatures, decreases the relative influence of low temperatures. The factor is scaled to equal unity at 20° C (similar to equivalent age).

$$\beta = \frac{e^{\alpha(T_a - T_0)}}{e^{20\alpha}}$$

T_0 = *step-function datum temperature*. At low maturity, it is equal to a high datum temperature t_0'. Once a critical maturity M_t is reached, the datum temperature drops to the long-term datum temperature t_0.

$T_0 = t_0'$ for $M<M_t$

$T_0 = t_0$ for $M>M_t$

M = time-temperature factor with datum temperature of 0° C.

M_t = *a critical level of maturity*. At this level of maturity, the datum temperature drops to its long-term level.
t_0' = early period datum temperature
t_0 = later period or long term datum temperature

The factored maturity function consists of four constants that are determined by a multiple regression technique: the constants are α, M_t, t_0', t_0. The object of the multiple regression was to select the maturity function that results in the best correlation with strength. A reciprocal function was chosen as a logical expression of the relationship between strength and maturity. Plotting the reciprocal of strength versus the reciprocal of factored maturity, the best fit line is the one that minimizes the sum of the squared residuals (this is equivalent to maximizing R^2). Iterations were performed with a computer until the values of the four constants were selected that maximized R^2. The result was the set of values for the constants:

$\alpha = 0.0065$
M_t = 9 °C-hours
t_0' = 26° C (78.8° F)
t_0 = 3.43° C (38.2° F)

The resulting function describes the hydration process as being very slow, with a datum temperature of 26° C until a temperature-time of 9 °C-hours is reached (this typically occurs after about 20 minutes). Then, the datum drops to 3.43° C and hydration rate rapidly increases.

Figure 1.14 represents the same set of compression samples as Figure 1.10. Note that R^2 only increased slightly. It may be concluded that factored maturity offers a correlation with strength that is only marginally better than temperature-time. However, to obtain the best possible correlation, factored maturity was used in the subsequent development of the computer model.

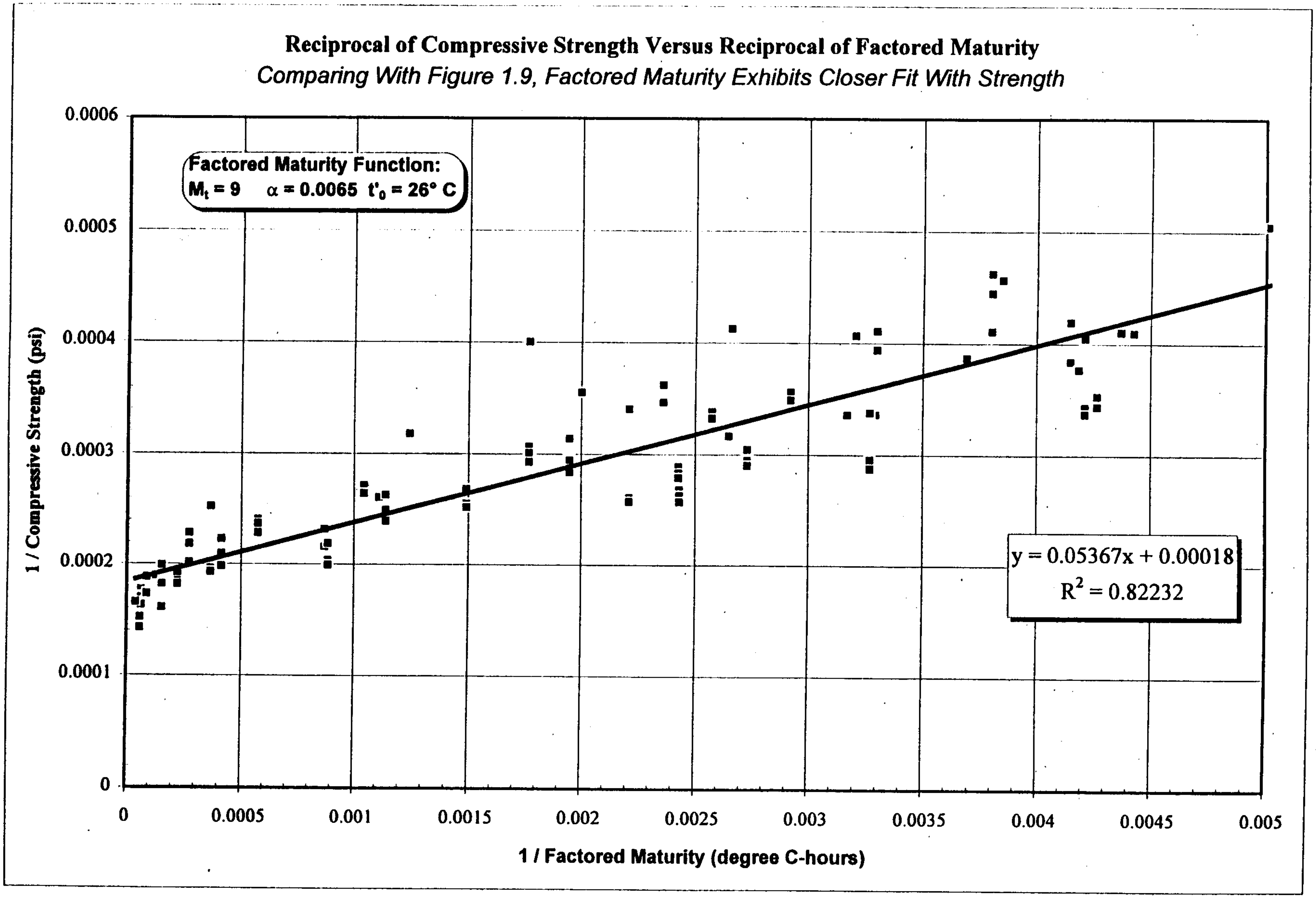

Reciprocal of Compressive Strength Versus Reciprocal of Factored Maturity
Comparing With Figure 1.9, Factored Maturity Exhibits Closer Fit With Strength
Factored Maturity Function:
Mt = 9 α = 0.0065 t'0 = 26° C
y = 0.05367x + 0.00018
R2 = 0.82232
1 / Compressive Strength (psi)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
1 / Factored Maturity (degree C-hours)

Figure 1.14

3. Determination of the Heat-Rate Function of the Fast-Track Concrete Mix

Five experiments were carried out for the purpose of obtaining a heat-rate function for the concrete. Heat-rate is the rate at which the internal heat of a concrete mass is increased due to cement hydration. It is well known that the heat-rate of concrete is not constant, but varies over time, typically with peaks associated with rheological changes such as at the time of setting [2]. The heat rate may be functionally related to either time or some measure of maturity. The factored maturity, as previously defined, provided the most consistent relationship over the tested temperature ranges.

Two test apparatus were specifically designed for the purpose of obtaining the heat-rate function.

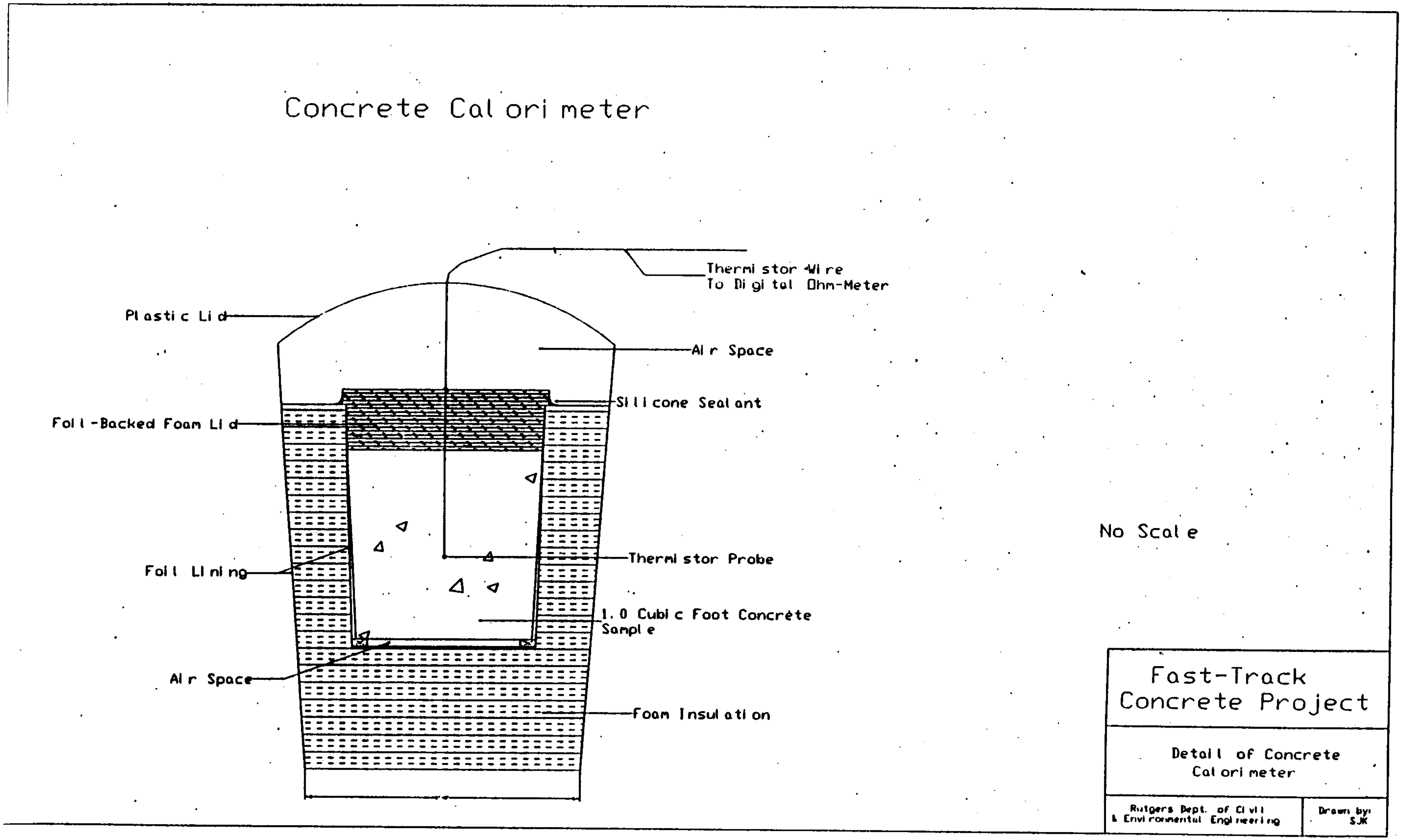
High-Precision Thermistor
Ordinary thermoprobes such as thermocouples provide a resolution and accuracy of about 1°C. For determining the heat-rate it was necessary to have higher resolution temperature measurement. Thermistors were chosen for this purpose. Using a digital ohm-meter, thermistors were individually calibrated. At room temperature, the thermistors used have a resolution of 0.01°C. Six thermistors were connected to a switching unit, wired to a digital ohm-meter. Temperature measurement was carried out manually by recording electrical resistance at time intervals of typically 3 to 10 minutes,

Concrete Calorimeter
A large calorimeter was built, a detail of which is found in Figure 2.1 A plastic drum was filled with 4" to 8" of foam insulation, surrounding a 1.0 $ft.^3$ core. In operation, the 1.0 $ft.^3$ core was filled with concrete, capped with its insulated lid, and sealed shut with silicone. The calorimeter was penetrated with a thermistor probe, embedded in the center of the concrete. The thermistor penetration was also sealed with silicone. This well-insulated vessel simulates the center of a large concrete mass. More importantly, the calorimeter's heat loss is easily calibrated, so that the heat generation caused by the concrete may be precisely known at any point in time.

The calorimeter was calibrated over a period of six days. It was calibrated using water because water is non-reactive, and its thermal properties may easily be related to the thermal properties of concrete, given only its mix proportions [2]. Hot water was placed in the calorimeter. The lid and thermistor penetration were sealed with silicone. Periodically, the temperature inside it was measured, along with the ambient temperature.

A calibration graph is found in Figure 2.2. A least-squares exponential function is fit to the data. To apply this calibration curve to concrete, the specific heat of the mix is assumed to be 0.28 times the specific heat of water (based on the mix proportions, and assuming the specific heat of aggregate and cement to be 22% of water). Heat loss is assumed to be the same for concrete and water (by conduction, only) so that the temperature loss rate constant for concrete is 3.2 times the rate constant determined for water; i.e., the temperature loss of concrete is about 3.2 times faster than for water.

Test Program
Five sets of calorimeter tests were performed. The only variable was initial temperature, varying from 16 to 35° C (60.8° F to 95° F). These mixes were designated III, IV, V, VI, VII and are the same mixes previously discussed. Temperatures were taken as previously described for a period of 24 hours following casting.


Concrete Calorimeter
Plastic Lid
Thermistor Wire
To Digital Ohm-Meter
Air Space
Silicone Sealant
Foil-Backed Foam Lid
Thermistor Probe
Foil Lining
1.0 Cubic Foot Concrete Sample
Air Space
Foam Insulation
No Scale
Fast-Track Concrete Project
Detail of Concrete Calorimeter
Rutgers Dept. of Civil & Environmental Engineering
Drawn by: SJK

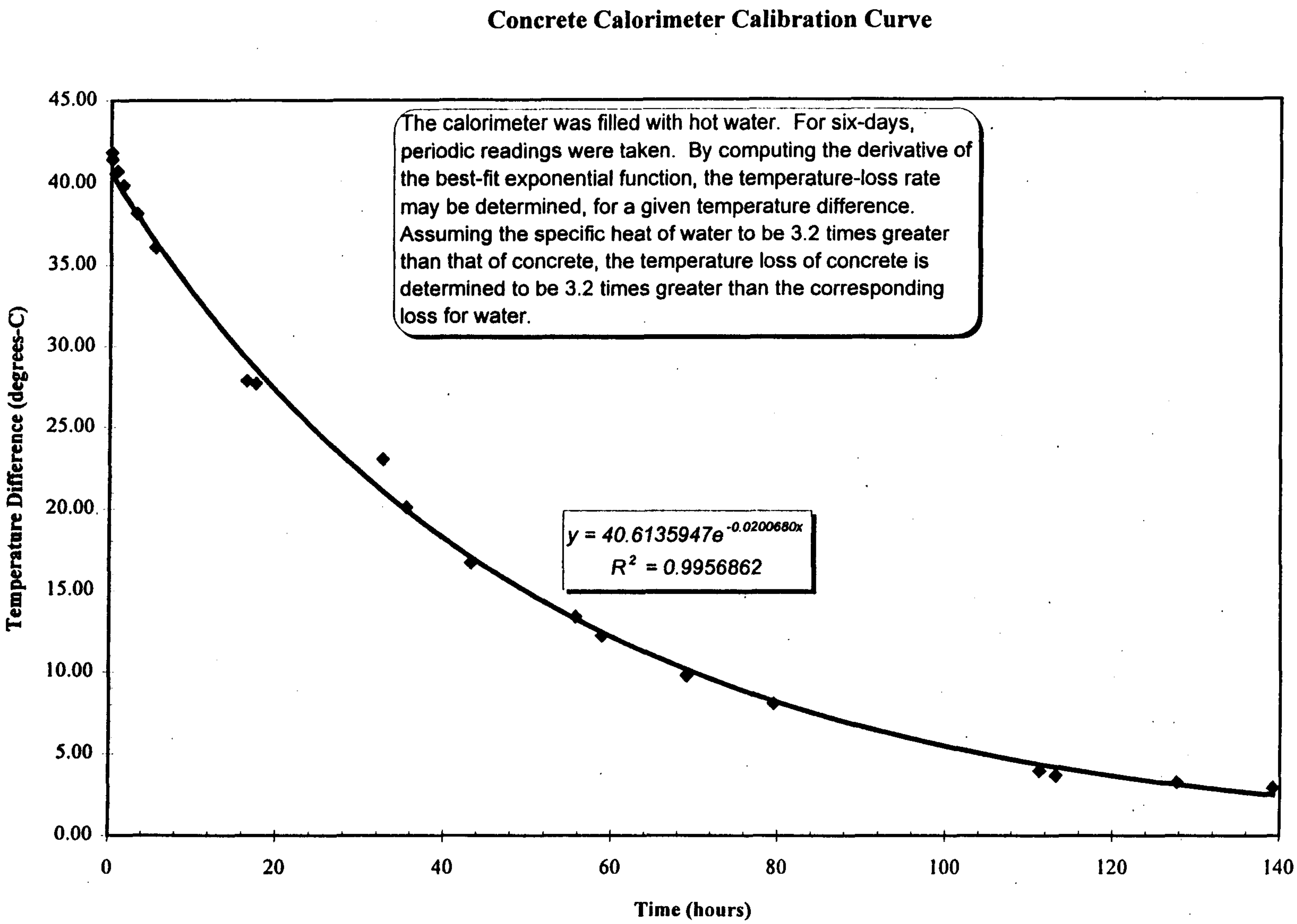

Concrete Calorimeter Calibration Curve
The calorimeter was filled with hot water. For six-days, periodic readings were taken. By computing the derivative of the best-fit exponential function, the temperature-loss rate may be determined, for a given temperature difference. Assuming the specific heat of water to be 3.2 times greater than that of concrete, the temperature loss of concrete is determined to be 3.2 times greater than the corresponding loss for water.
y = 40.6135947e^-0.0200680x
R² = 0.9956862
Temperature Difference (degrees-C)
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
20
40
60
80
100
120
140
Time (hours)

Figure 2.2

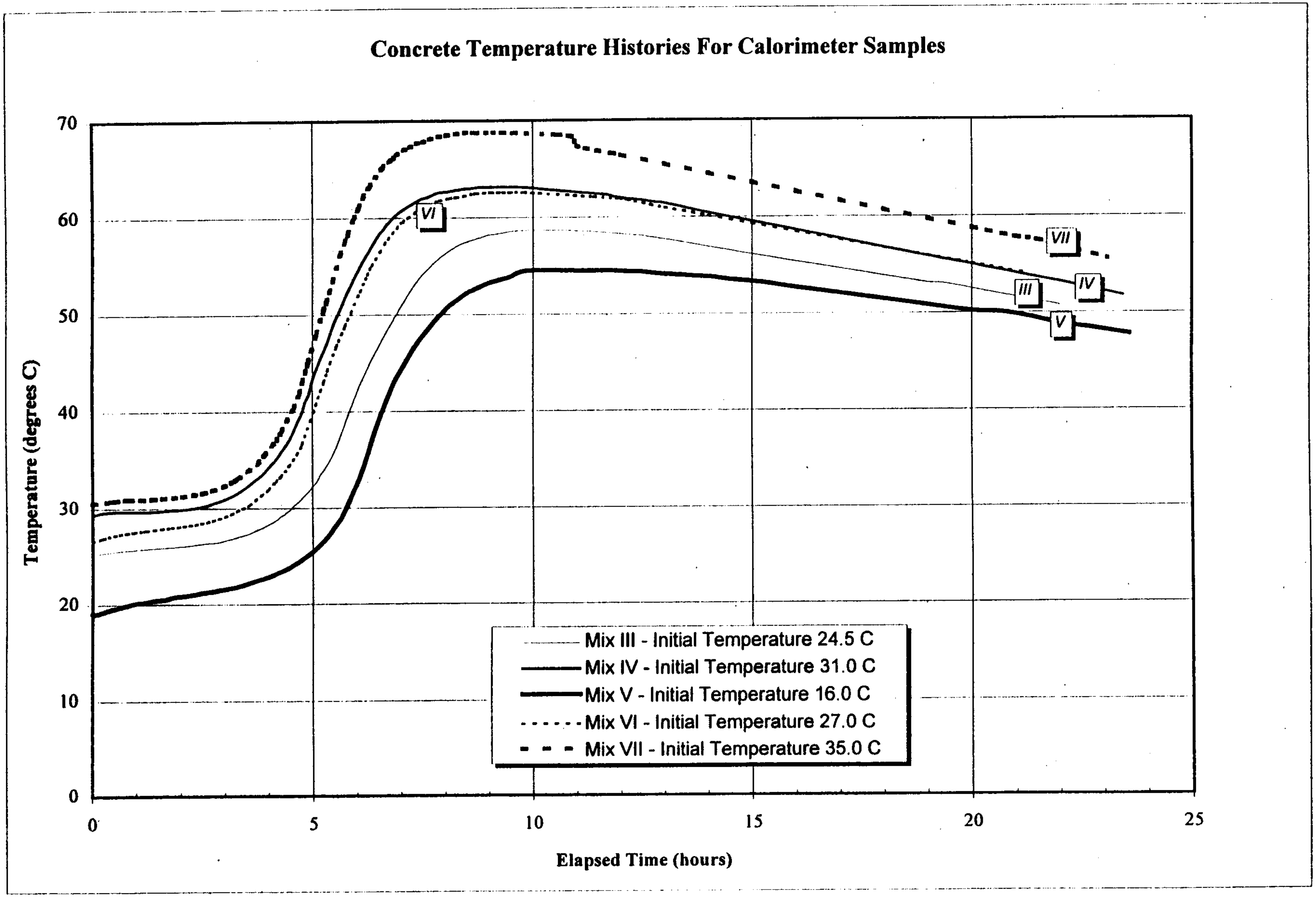

Concrete Temperature Histories For Calorimeter Samples
Temperature (degrees C)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
Elapsed Time (hours)
VI
VII
III
IV
V
Mix III - Initial Temperature 24.5 C
Mix IV - Initial Temperature 31.0 C
Mix V - Initial Temperature 16.0 C
Mix VI - Initial Temperature 27.0 C
Mix VII - Initial Temperature 35.0 C

Figure 2.3

Temperature Rate Data Reduction

The temperature-time history for each calorimeter test was obtained. A plot of these temperature-time histories is found in Figure 2.3. At any point on these curves, the slope represents the temperature rate for that instant of time. The slopes of these curves were computed numerically for each data points as the average of the forward and backward tangents. A graphical example of these calculations are given below in Figure 2.4

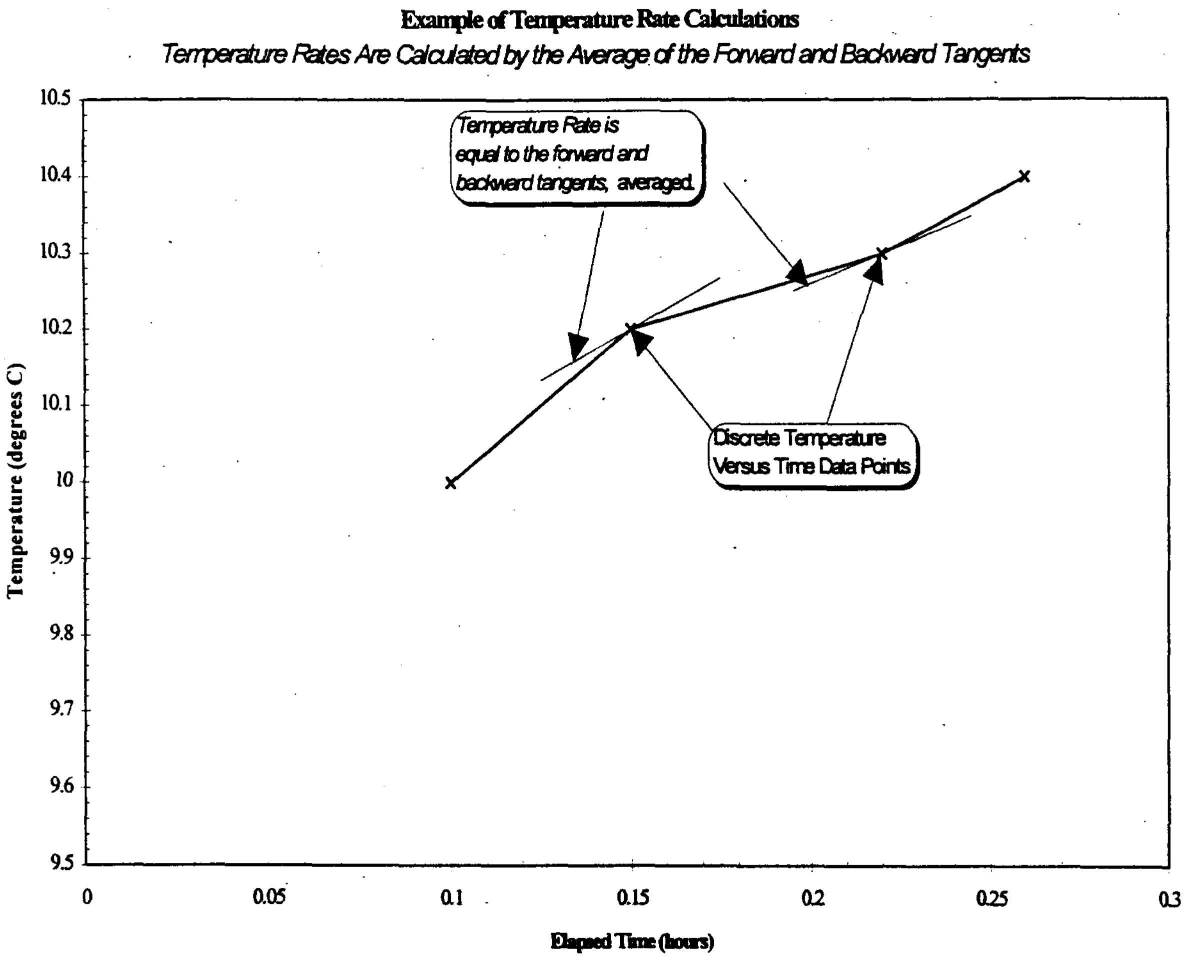


Figure 2.4 Example of Temperature Rate Calculations From Typical Temperature-Time Plots

The temperature rates were computed numerically as described in Figure 2.4 and plotted versus the factored maturity (refer to section 1D for the discussion of factored maturity). A temperature rate plot for Mix III is given in Figure 2.5.

The temperature rate plot in Figure 2.5 shows two curves: an adjusted curve and an unadjusted curve. The unadjusted curve does not reflect the temperature losses of the calorimeter (note that the temperature rate drops below zero, for this curve). The adjusted curve reflects the calorimeter losses and includes the addition of a loss term. The temperature loss term, as previously described, is based on the temperature *difference* between the outside air and the calorimeter. Knowing the average temperature difference between the calorimeter and the outside air, along with the corresponding time duration, the temperature change due to losses are easily computed. Generally, the adjustment for temperature losses is reflected by an *increased* temperature rate (a decrease occurs if the concrete is below room temperature). After making the temperature loss adjustments for all time intervals, the adjusted temperature rate versus factored maturity plots are obtained and presented in Figures 2.6, 2.7, 2.8, 2.9, 2.10.

Best-Fit Equations for the Heat Function

The computer model requires the temperature rate in the form of continuous functions. While fitting curves to the temperature rate versus factored maturity data, the following items were considered:
For a single chemical reaction, the reaction rate is expected to take the following form:

$$\text{rate} \propto [\text{concentration level}] \times [e^{\alpha T}]$$

where:

The exponential term reflects a simplified expression of the Arrhenius Law

And,

α = some constant, dependent on the specific chemical reaction
T = the temperature

- The inverse of the factored maturity (1/M') is a rough estimate of the concentration level; e.g., the concentration level is zero at an infinite maturity.
- Although cement hydration is not a single reaction, the functional relationship for reaction rate may be expected to contain the product of (1/M') and ($e^{\alpha T}$), for at least part of its history.
- Because cement hydration is not a single reaction, the rate may be expected to undergo several distinct phases.

Upon examining the curves of Figures 2.6 through 2.10, it was determined that *four distinct phases* are present:

1. Factored Maturity M' less than 70° C-hours - hydration rate dips into a "well". In the factored maturity domain, the data takes the approximate shape of a second-order parabola. Using multiple regression, it was also found that temperature explained a significant portion of the data. The multiple regression functional form that was chosen for this region was:

$$\text{rate} = (AM'^2 + BM' + C)(e^{\alpha T})$$

From least-squares regression the constants A, B, C, and α were found to be:
A = 0.000342734
B = -0.017511043
C = 0.626669857
α = 0.021730119
R^2 = 0.63027

2. Factored Maturity M' between 70° C-hours and peak - hydration rate reaches its peak. The multiple regression functional form that was chosen for this region was:

$$\text{rate} = A + (BM')(e^{\alpha T})$$

From least-squares regression the constants A, B, and α were found to be:
A = -5.534535632
B = 0.051846421
α = 0.023953257
R^2 = 0.88701

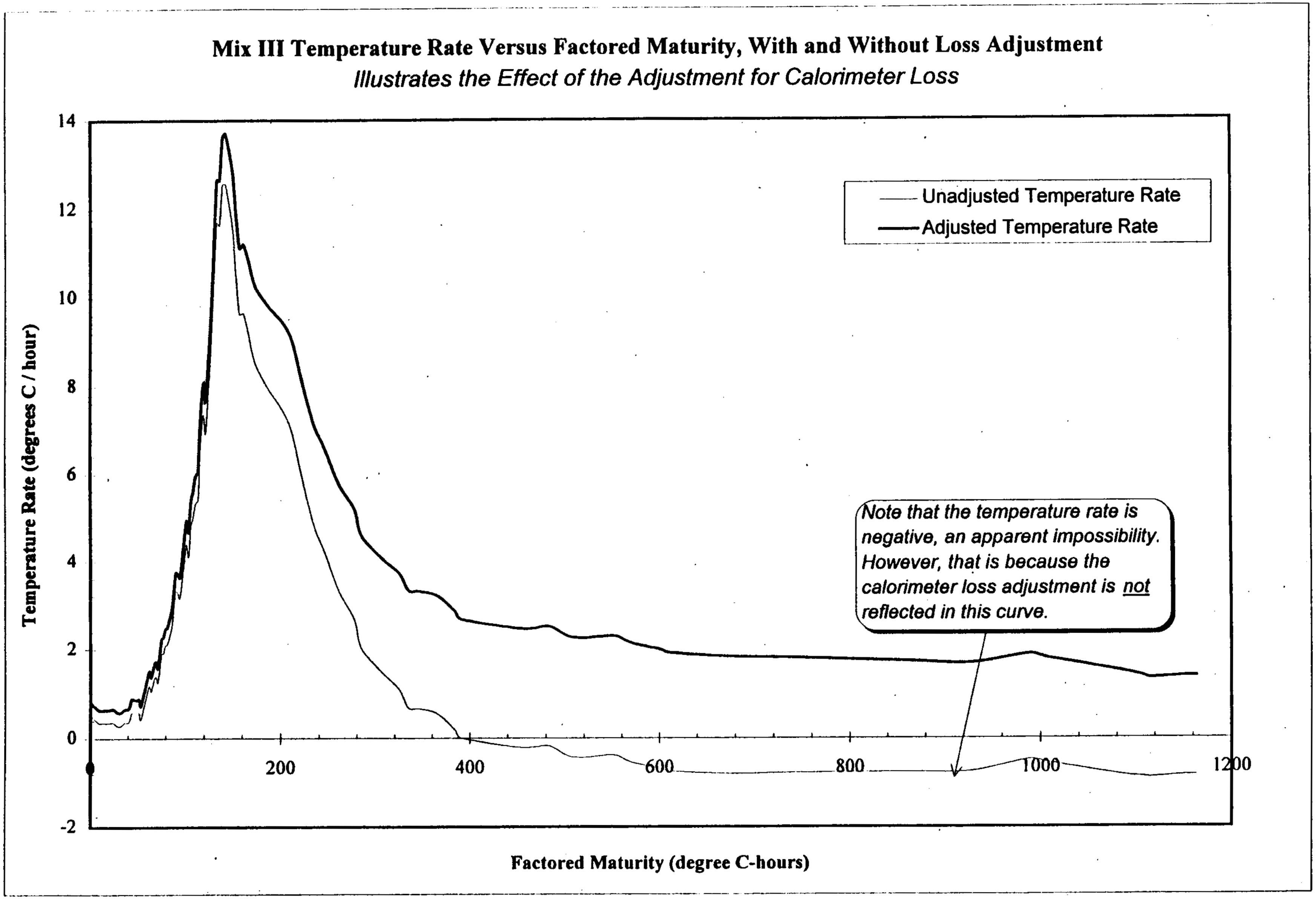

Mix III Temperature Rate Versus Factored Maturity, With and Without Loss Adjustment
Illustrates the Effect of the Adjustment for Calorimeter Loss
Unadjusted Temperature Rate
Adjusted Temperature Rate
Note that the temperature rate is negative, an apparent impossibility. However, that is because the calorimeter loss adjustment is not reflected in this curve.
Temperature Rate (degrees C / hour)
Factored Maturity (degree C-hours)
14
12
10
8
6
4
2
0
-2
200
400
600
800
1000
1200

Figure 2.5

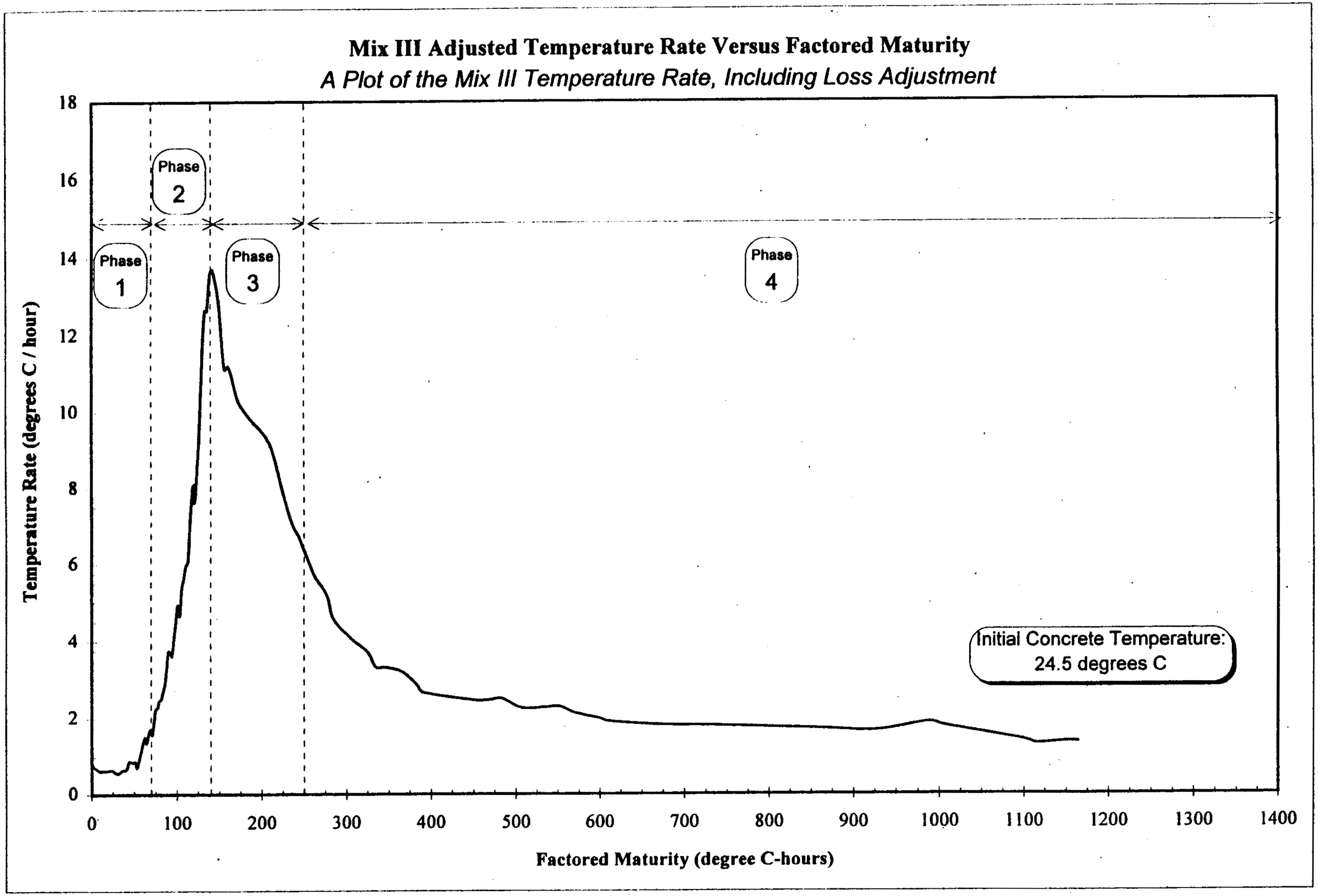

Mix III Adjusted Temperature Rate Versus Factored Maturity
A Plot of the Mix III Temperature Rate, Including Loss Adjustment
Phase 1
Phase 2
Phase 3
Phase 4
Initial Concrete Temperature: 24.5 degrees C
Temperature Rate (degrees C / hour)
Factored Maturity (degree C-hours)
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

Figure 2.6

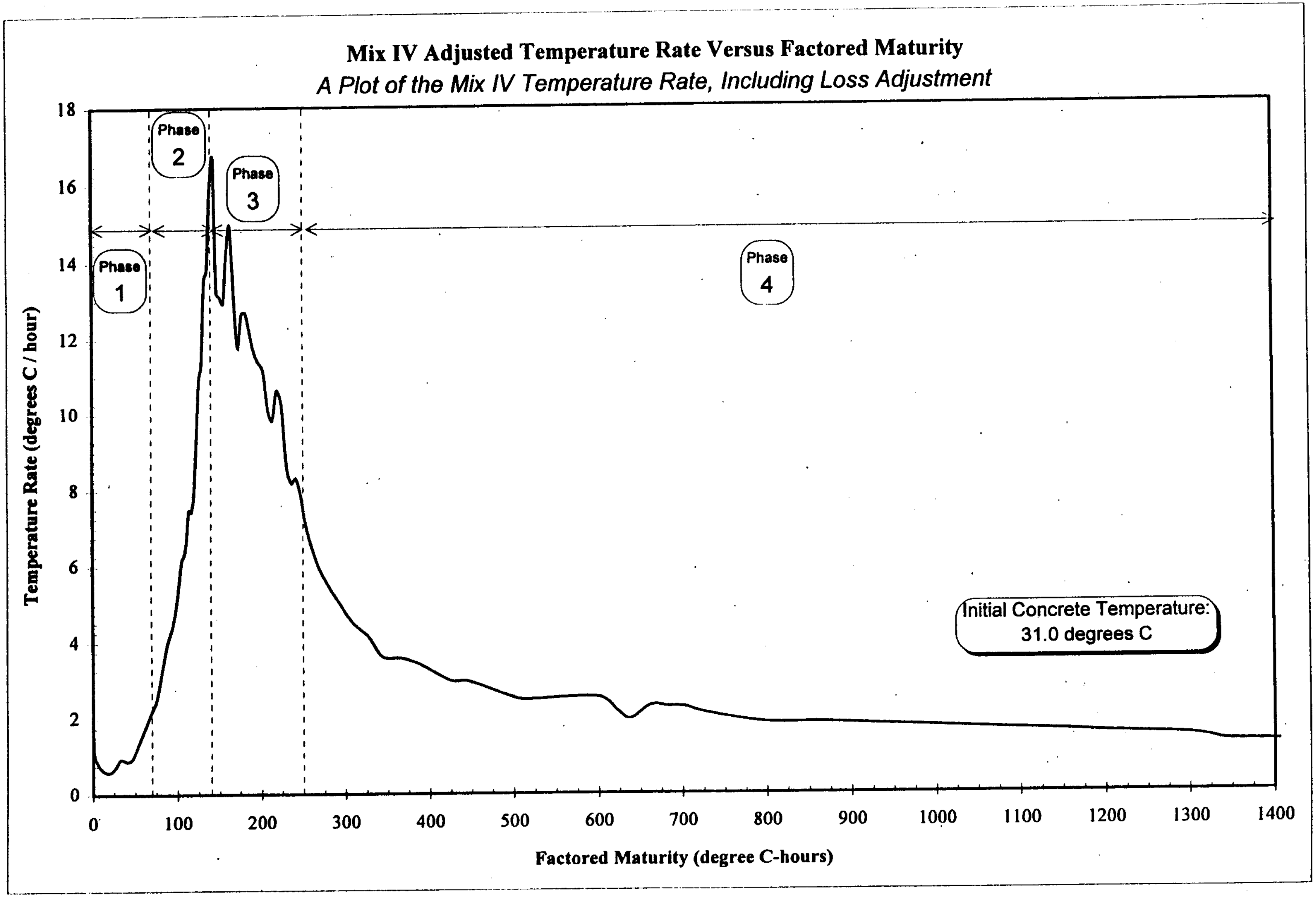

Mix IV Adjusted Temperature Rate Versus Factored Maturity
A Plot of the Mix IV Temperature Rate, Including Loss Adjustment
Phase 1
Phase 2
Phase 3
Phase 4
Initial Concrete Temperature: 31.0 degrees C
Temperature Rate (degrees C / hour)
Factored Maturity (degree C-hours)
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

Figure 2.7

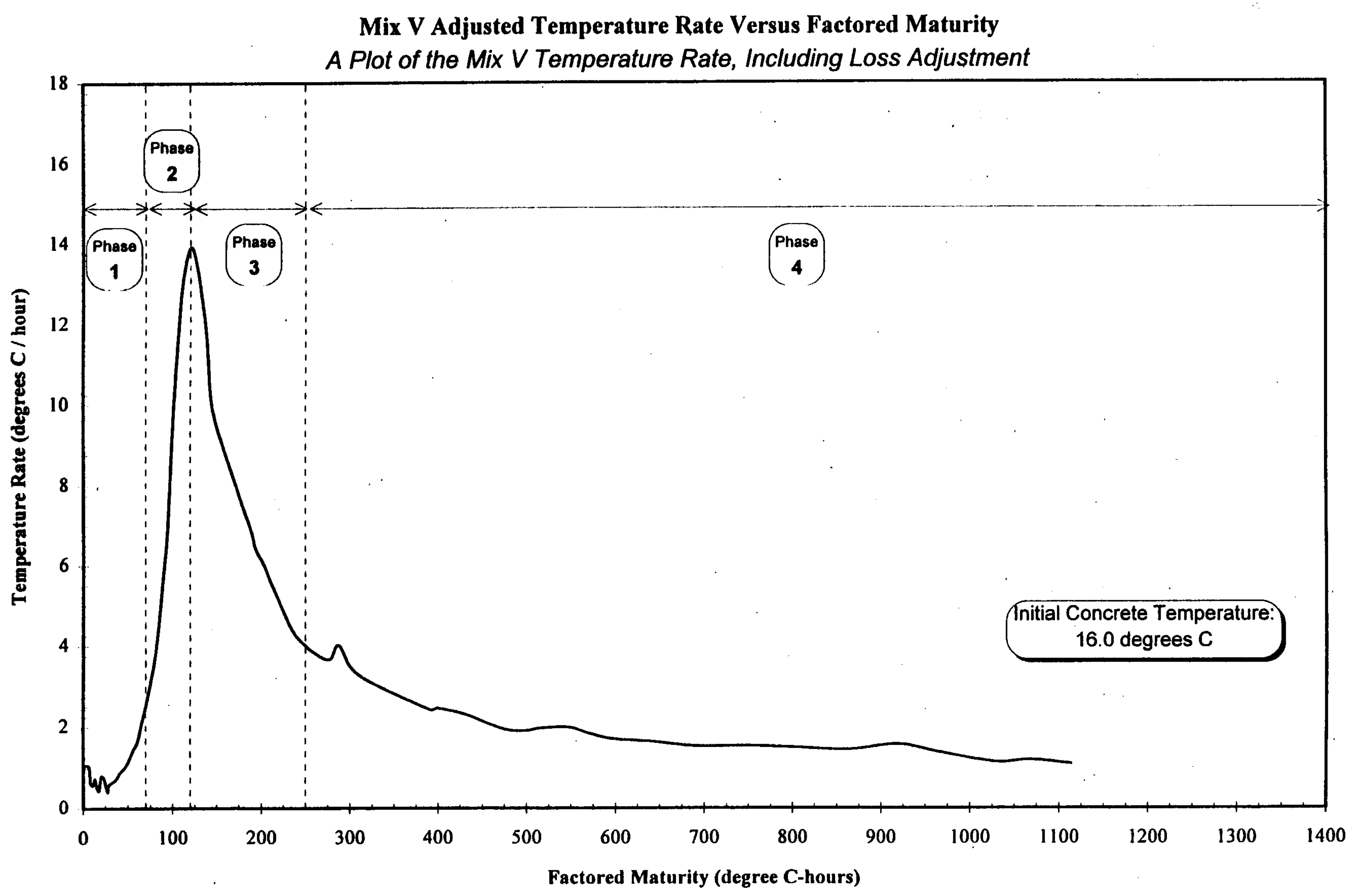

Mix V Adjusted Temperature Rate Versus Factored Maturity
A Plot of the Mix V Temperature Rate, Including Loss Adjustment
Temperature Rate (degrees C / hour)
18
16
14
12
10
8
6
4
2
0
Phase 1
Phase 2
Phase 3
Phase 4
Initial Concrete Temperature:
16.0 degrees C
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Factored Maturity (degree C-hours)

Figure 2.8

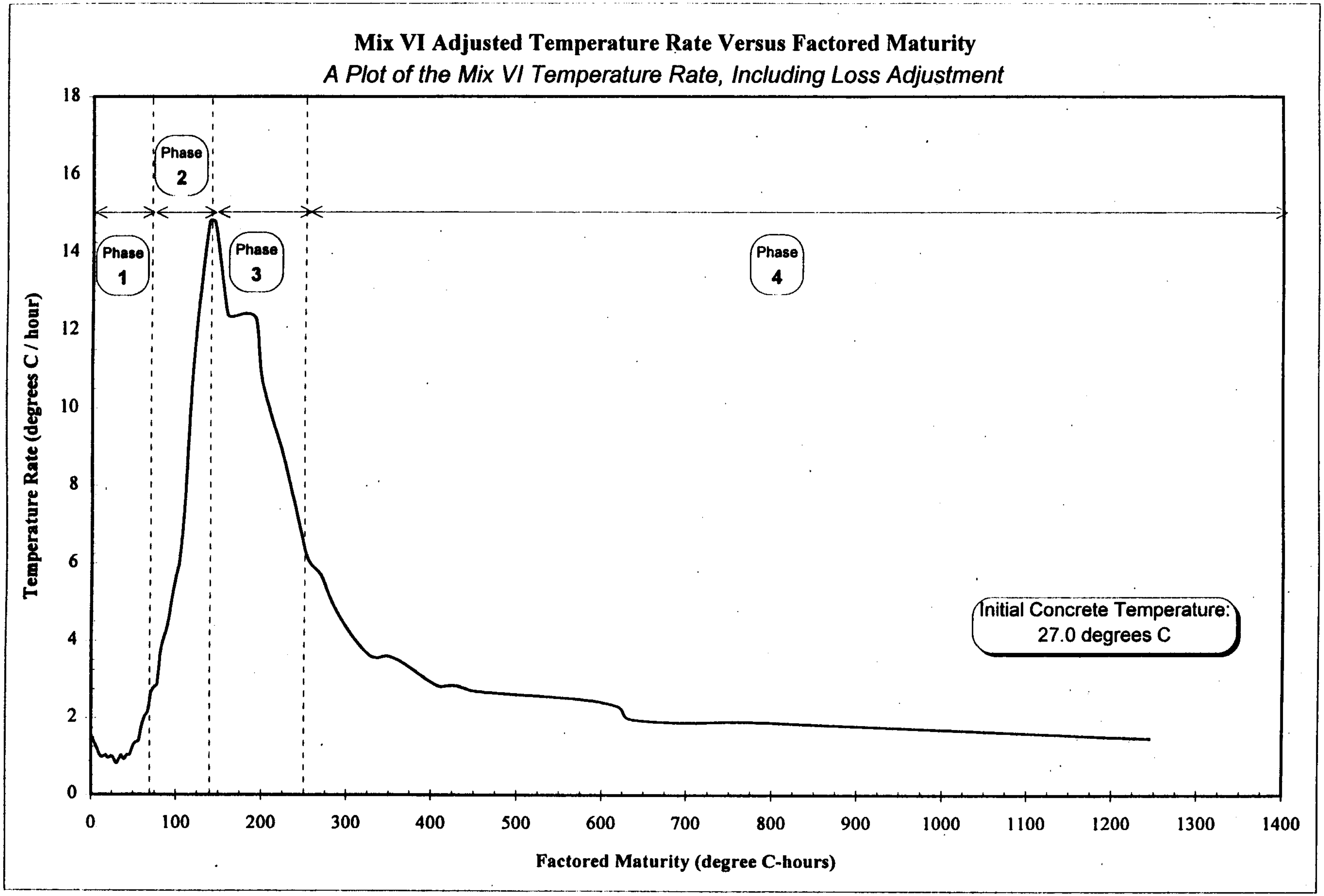

Mix VI Adjusted Temperature Rate Versus Factored Maturity
A Plot of the Mix VI Temperature Rate, Including Loss Adjustment
Temperature Rate (degrees C / hour)
0
2
4
6
8
10
12
14
16
18
Factored Maturity (degree C-hours)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Phase 1
Phase 2
Phase 3
Phase 4
Initial Concrete Temperature:
27.0 degrees C

Figure 2.9

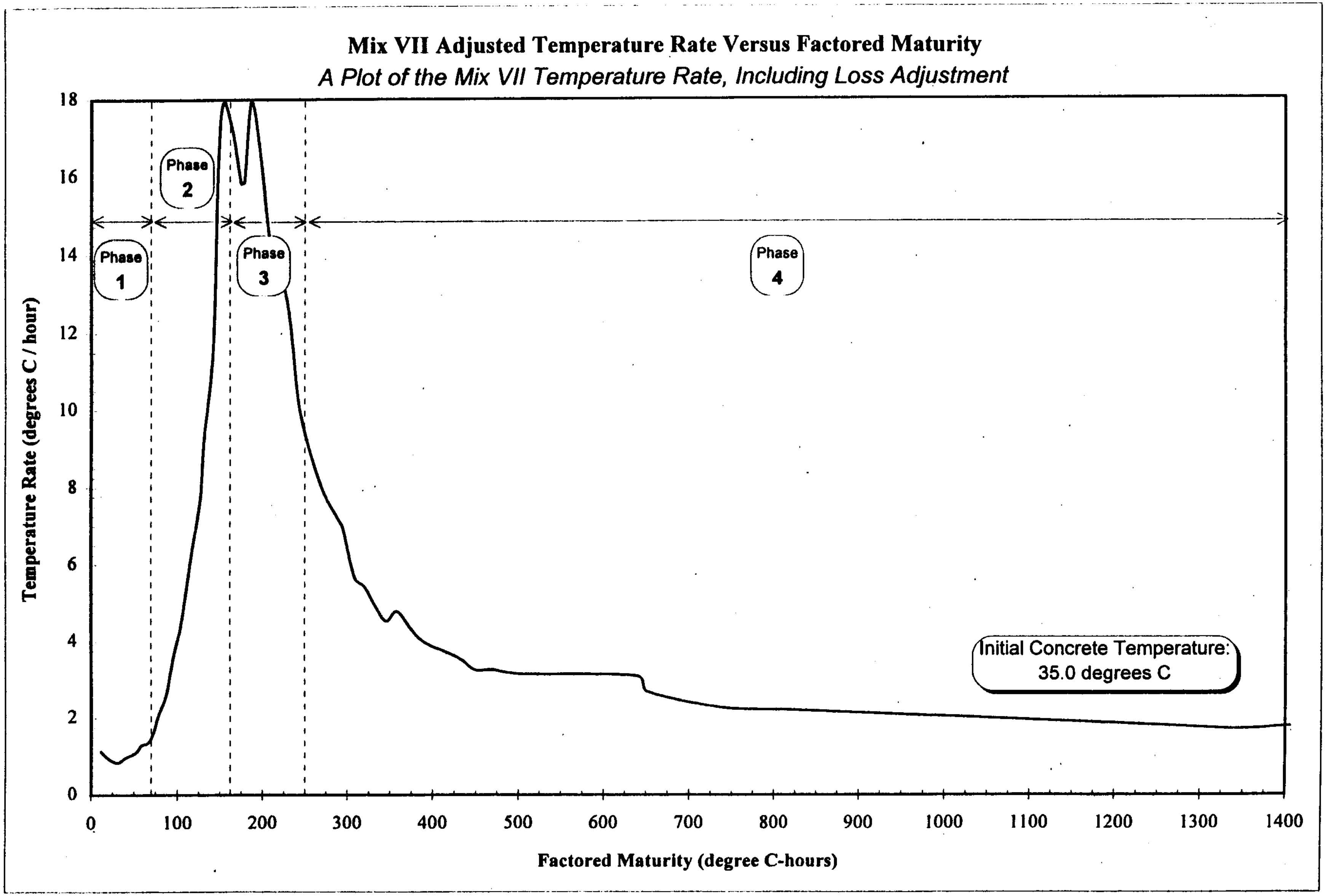

Mix VII Adjusted Temperature Rate Versus Factored Maturity
A Plot of the Mix VII Temperature Rate, Including Loss Adjustment
Temperature Rate (degrees C / hour)
Factored Maturity (degree C-hours)
Phase 1
Phase 2
Phase 3
Phase 4
Initial Concrete Temperature: 35.0 degrees C
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

Figure 2.10

3. Factored Maturity M' between peak and 250° C-hours - In this phase, the rate appears nearly linear in the factored maturity domain. Multiple regression analysis revealed that the data was more influenced by the temperatures of previous periods then current temperature. The resulting expression was:

$$rate = AM' + (BT_I + C)$$

T_I = initial concrete temperature
A = -0.0651
B = 0.2
C = 17.66

4. Factored Maturity M' greater than 250° C-hours - The multiple regression model is:

$$rate = AM'^B$$

From least-squares regression the constants A, B, and α were found to be:
A = 375.79
B = -0.7901
R^2 = 0.8065

The actual temperature and factored maturity data was inserted into the predictive equations so that they may be compared with the actual temperature rate data. Figures 2.11 to 2.15 show that the predictive equations provide a satisfactory estimation of the temperature rate curves.

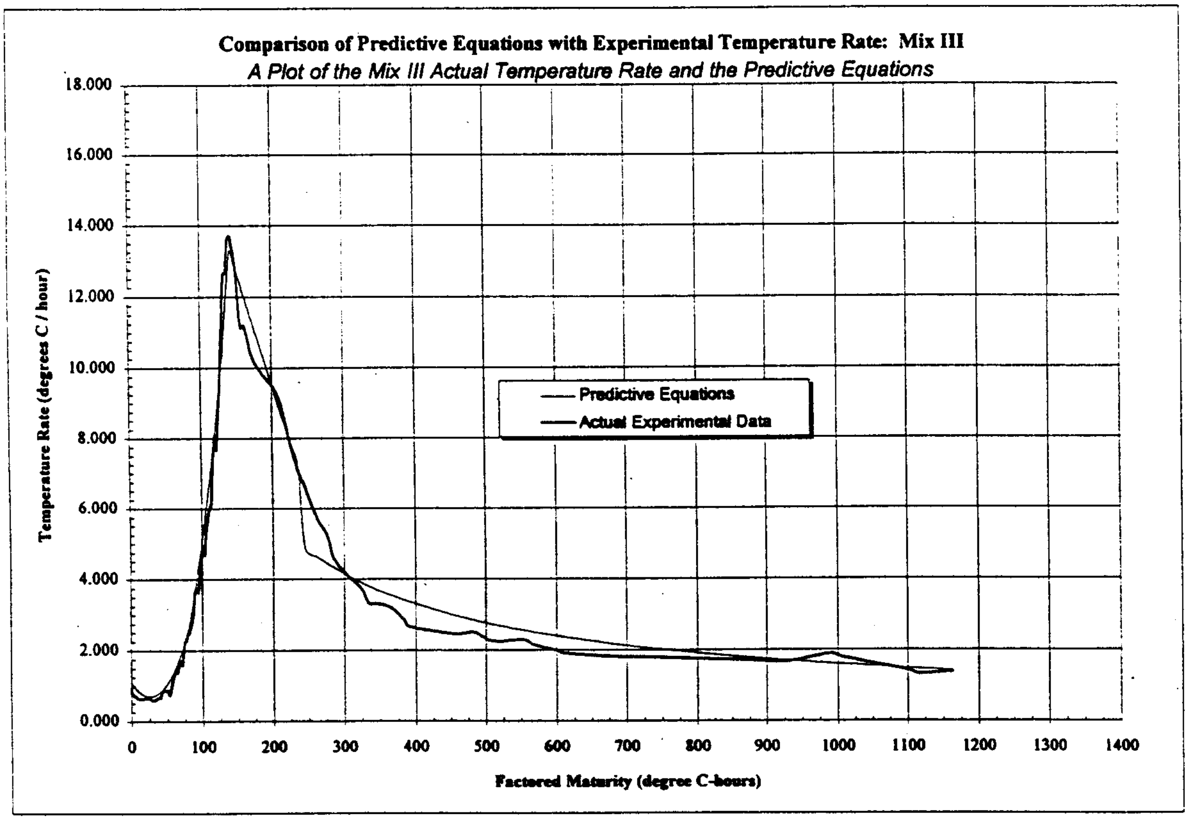


Figure 2.11 Comparison of Predictive Equations with Experimental Temperature Rate: Mix III

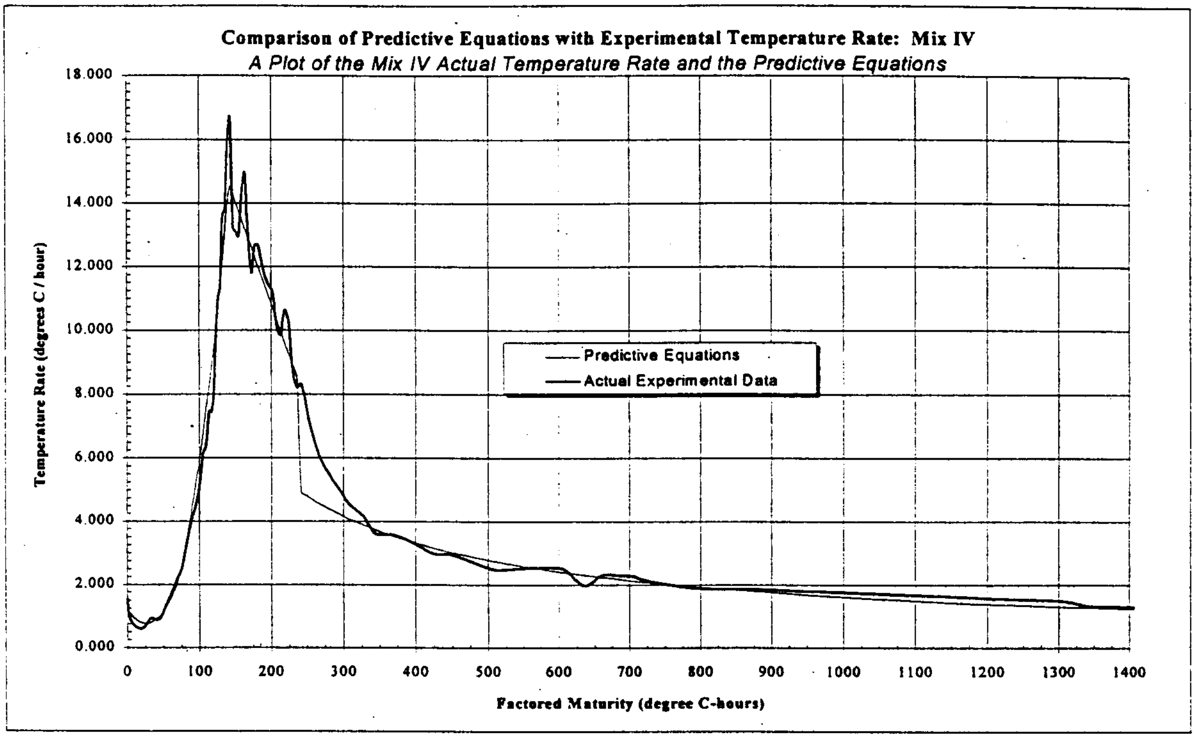


Figure 2.12 Comparison of Predictive Equations with Experimental Temperature Rate: Mix IV

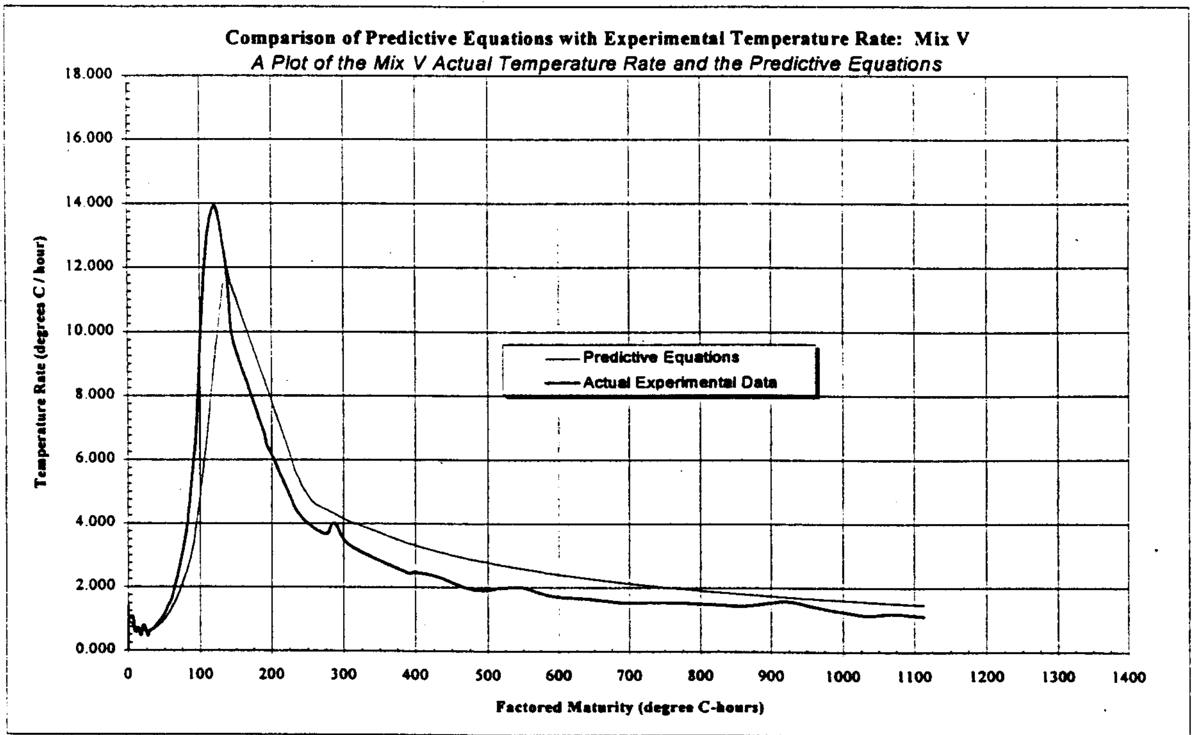


Figure 2.13 Comparison of Predictive Equations with Experimental Temperature Rate: Mix V

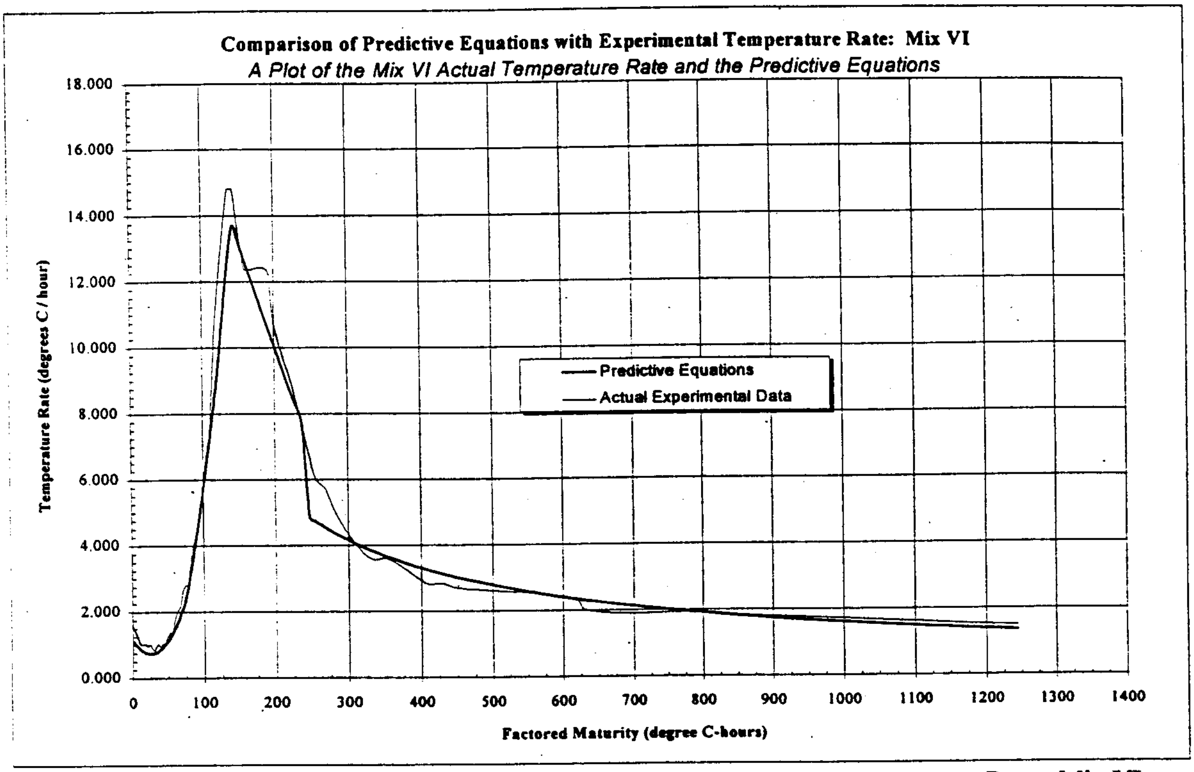


Figure 2.14 Comparison of Predictive Equations with Experimental Temperature Rate: Mix VI

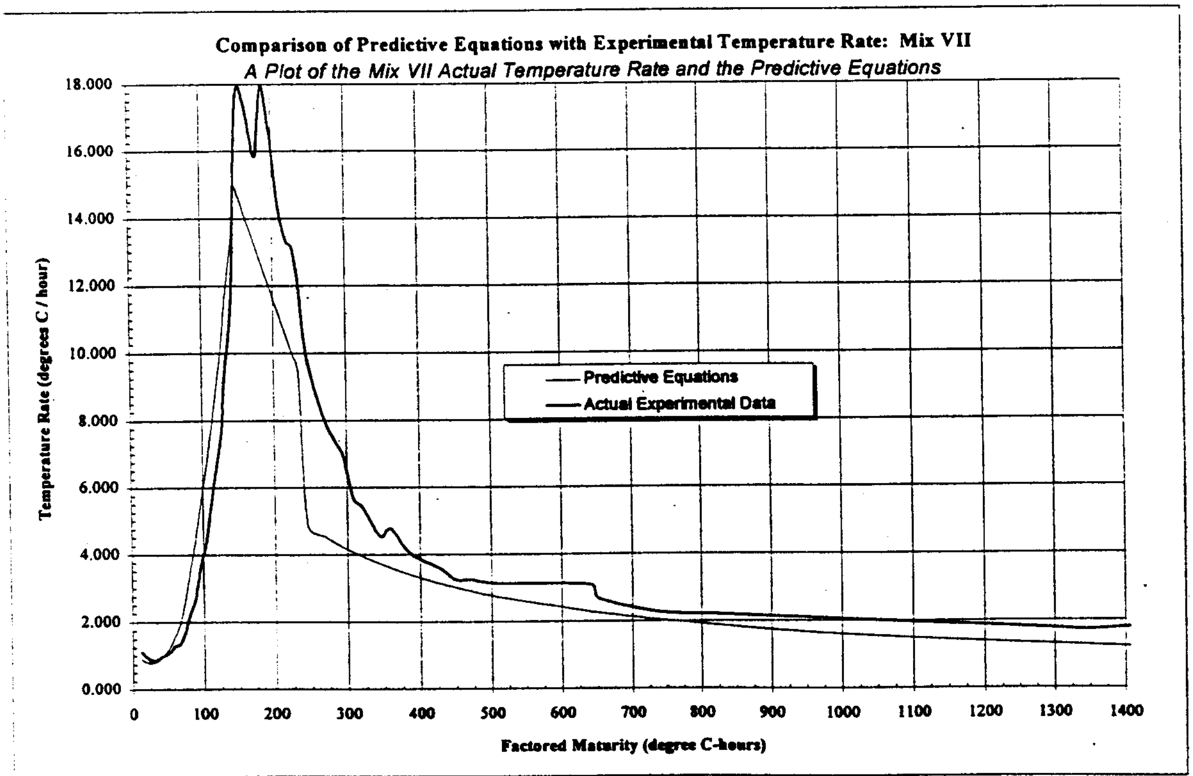


Figure 2.15 Comparison of Predictive Equations with Experimental Temperature Rate: Mix VII

Hydration Heat Rate

The predictive equations satisfactorily estimate the temperature rate of the fast-track mix. To convert this information to the heat of hydration rate, all that is needed is the thermal properties of concrete. Given the mass density of the concrete and an assumed specific heat, c = 880 J/kg -°C [3], the heat of hydration is computed by:

$$q = m\,c\,\Delta t$$

Where

q = heat of hydration rate (W)

m = mass of concrete (kg)

c = specific heat (J/kg - °C)

Δt = temperature rate (°C/s)

4. Development of a Computer Simulation to Predict the Temperature History of the Fast-Track Concrete Mix

Specifications and Model Assumptions

- The computer model is a one-dimensional simulation of the temperature history of the middle of a concrete slab. Field tests have verified that edge-effects are very small. Hence two or three-dimensional simulations are not warranted.
- The heat transferred within the slab is modeled by the finite-difference approximation to the governing differential equation for one-dimensional transient flow.
- The heat generated by the concrete is based on the predictive equations, developed in chapter 2.
- The thermal resistance and capacitance of concrete and the soil are assumed, based on handbook values [3].
- The heat generated by the slab influences ground temperature to a maximum depth of 40 inches (the computer, itself, has been used to verify that this assumption is reasonable).
- A constant temperature "heat sink" is located at a depth of 40 inches.
- The computer model permits the following parameters to be changed and/or studied:

  Primary, or studied parameters
  - ♦ Initial concrete temperature
  - ♦ Outside temperature
  - ♦ Insulated covering (R-value)
  - ♦ Slab thickness

  Secondary, or option parameters - generally fixed at default values, but may easily be changed if warranted
  - ♦ Thermal resistance and capacitance of concrete
  - ♦ Thermal resistance and capacitance of the subbase
  - ♦ Depth to heat sink (default = 40")
  - ♦ Temperature of heat sink (default = 8° C = 46.4° F)

Theoretical Background

The heat transfer model is based on the finite difference approximation to the governing differential equation for one-dimensional transient heat flow in a solid. For further details regarding heat transfer through a solid, see reference [3]. Referring to Figure 3.1:

$$T_{ij} = (\Delta\tau / C_i)\,(q_{ij} + ((T_{i-1,j-1} - T_{i,j-1})(1/R_{ib}) + (T_{i+1,j-1} - T_{i,j-1})(1/R_{if})) + T_{i,j-1}$$

Where

T_{ij} = temperature of node *i*, at time period *j*.

$\Delta\tau$ = duration of the time interval

C_i = the capacitance associated with node *i*

q_{ij} = heat (of hydration) rate of node *i*, for time *j*.

R_{ib} = the total resistance associated with node *i*, either in the forward (*f*) or backward (*b*) direction.

The default time period $\Delta\tau$ is five minutes. The heat transfer solution proceeds in five minute intervals, each temperature T_{ij} is computed based on the temperatures of the adjacent nodes from the previous time period. The heat of hydration rate q_{ij} is re-computed at each interval, based on the equations presented in Chapter 2.

Characteristics of Ground Temperatures

The initial ground temperature is modeled as a parabolic temperature distribution bounded by a constant temperature heat sink (default setting of 8° C) and the specified surface temperature. Figure 3.2 illustrates this feature. The advantages of this method are:

- The exact temperature distribution of the ground need not be known.
- A reasonable approximation of the initial ground temperature distribution is made by knowing the ambient (air) temperature.
- Ground temperature need not be considered as a separate variable
- Once the simulation begins, heat transfer laws take over, determining the actual temperature distribution through the soil (see Figures 4.4 through 4.6). Therefore, initial errors made in assuming the ground temperature profile are short lived.
- Field experiments at Rutgers have verified that the temperature at a (default) depth of 40" is very stable and may be reasonably assumed to be about 8° C (46.4° F), during the spring months.

Overview of the Operation of the Computer Simulation

The simulation consists of seven blocks, or modules:

1. Input - This allows the user to change the studied parameters, or opt to change default settings.
2. Element Properties - Based on the user input, this module computes the thermal (resistance and capacitance) and geometric properties of each element - concrete, soil, or insulation.
3. Initial Ground Temperature Profile - Based on the input ambient temperature, a heat sink temperature (default setting = 8° C), a depth to the heat sink (default setting = 40"), and assuming a parabolic temperature distribution, this module computes the *starting* temperature of each soil element (subsequently, the soil temperature is determined by heat transfer).
4. Heat Generation & Factored Maturity - This module continually computes the heat rate of the concrete, based on its factored maturity and temperature. These are typically re-computed at five minute intervals of simulation time. All of this information is stored, for easy recovery, graphical output, etc.
5. Temperature - Time - This is the core of the simulation. Based on the finite difference approximation to the differential equation for one-dimensional transient heat flow, the temperature of each of twelve nodes, representing either concrete or soil, are updated at time intervals (typically five minutes). All of this information is stored.
6. Summary Statistics - This is a database search. It searches the stored information in the Temperature - Time and Heat Generation & Factored Maturity modules, identifying the time at which the target temperature-time product is reached (default = 245° C-hours). This also identifies the peak temperature, and the time at which the peak was reached.
7. Graphical Output - Graphs of the temperature-time history, maturity versus time, and temperature cross-sections of the slab-soil system are automatically generated every time the simulation is run.

Finite Difference Heat Transfer Model for Soil-Slab

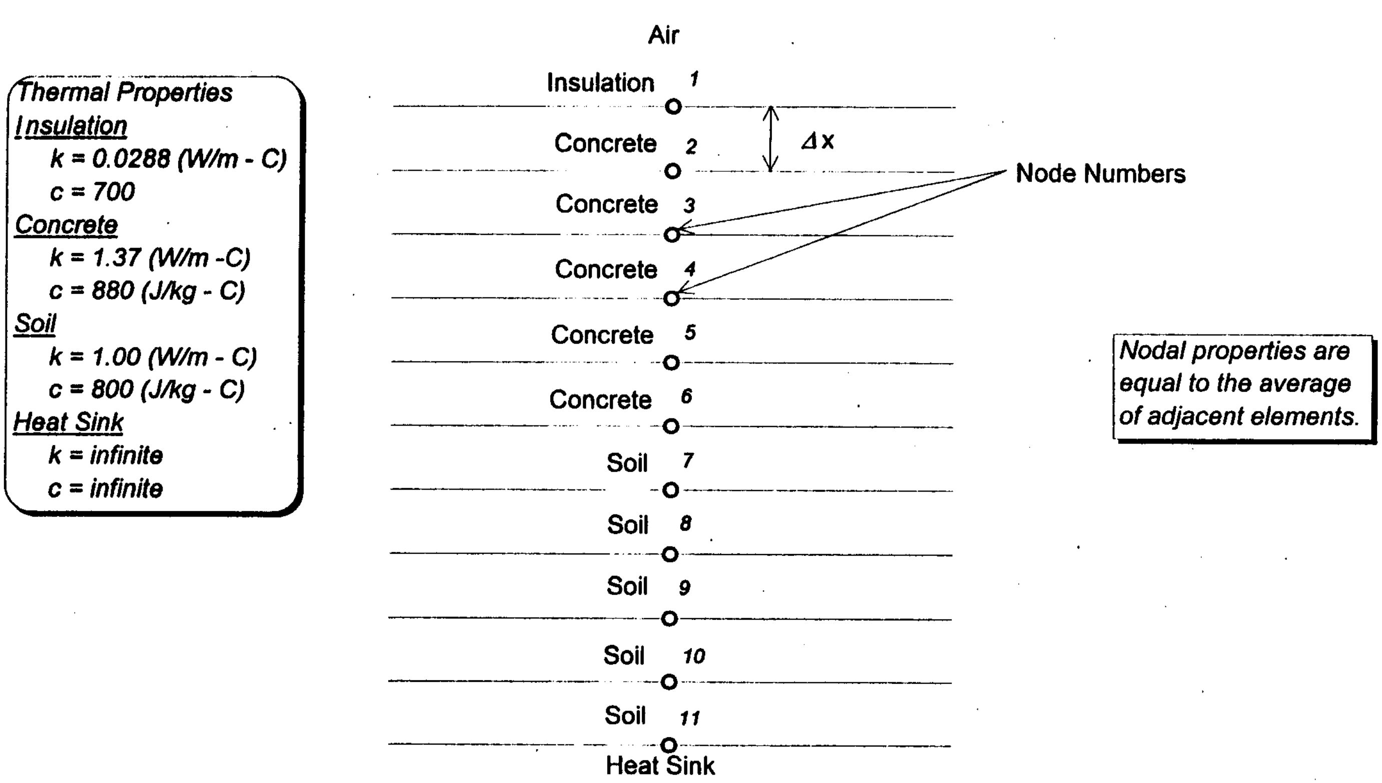
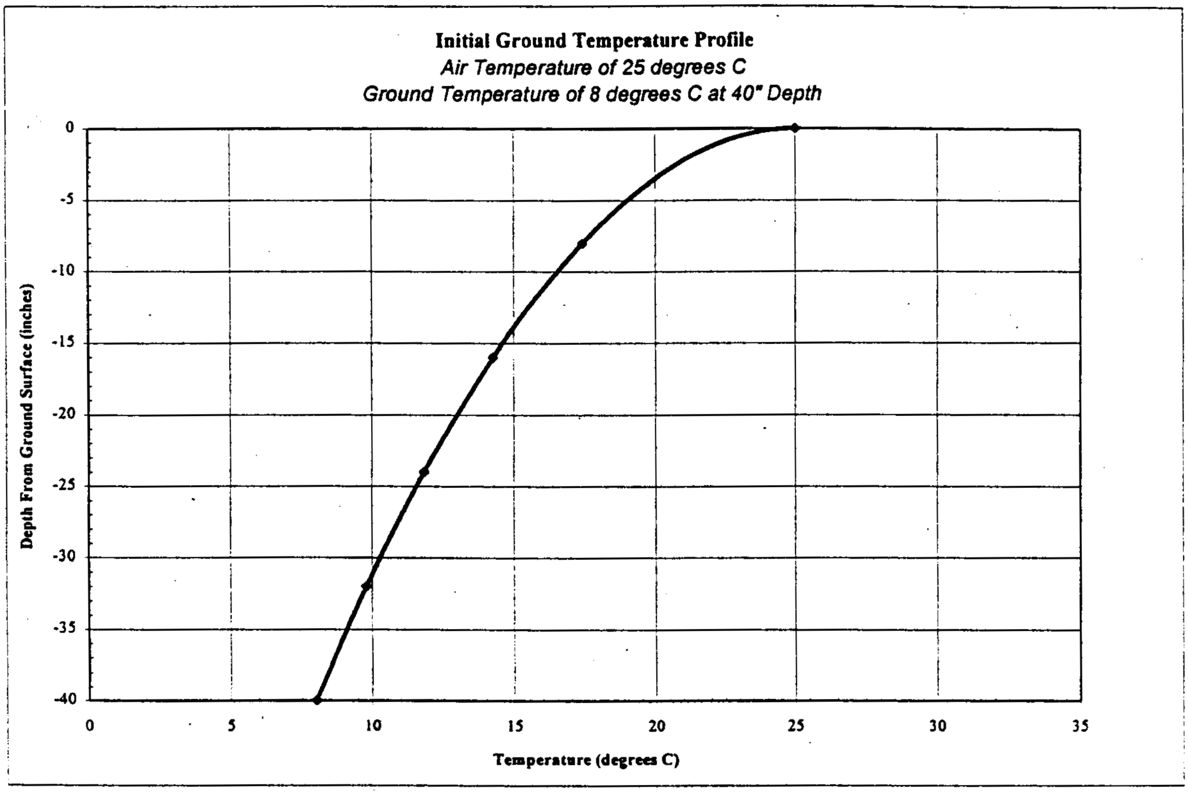


Figure 3.1



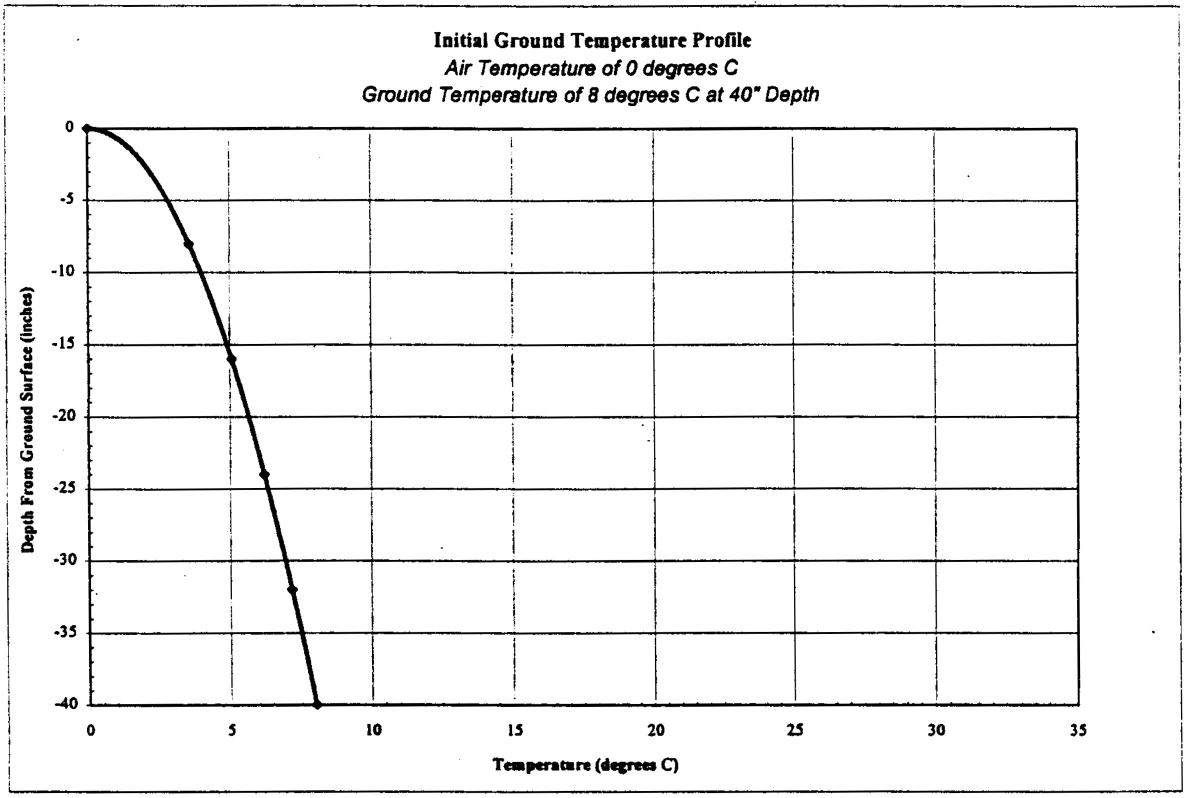


Figure 3.2 - Computer Simulation's Initial Ground Temperature Profile

Input Options

- Primary, or Studied Parameters
  - Initial concrete temperature - studied for temperatures ranging from 5 to 35° C (41 to 95° F).
  - Outside temperature - studied for temperatures ranging from 0 to 35° C (32 to 95° F)
  - Insulated covering (R-value) - studied for R-values ranging from 0.1 to 20.
  - Slab thickness - studied for thickness' ranging from 4 to 18 inches
- Secondary, or option parameters - generally fixed at default values, but may easily be changed
  - Thermal properties of materials may be changed, if justified. Handbook properties were used as default settings:

    Concrete
    k (W/m - °C): 1.37
    c (J/kg - °C): 880
    ρ (kg/m^3): 2350
    Soil (properties of compacted trap rock were approximated)
    k (W/m - °C): 1.00
    c (J/kg - °C): 800
    ρ (kg/m^3): 1900
    Insulation
    k (W/m - °C): 0.0288
    c (J/kg - °C): 700
    ρ (kg/m^3): 15
  - Depth to heat sink may be changed. However, the default setting of 40" is a reasonable value because field tests and the heat transfer simulation, itself, verify that negligible influence results at this depth.
  - Temperature of heat sink may be changed. However, the default setting of 8° C is quite reasonable for the spring months.
  - The time increment, $\Delta\tau$, may also be changed.

5. Use of the Computer Simulation

By changing the input parameters, studies of slab performance may be conducted. Four types of output may be generated:

1. Temperature Rate Histories - The computer simulation automatically plots the temperature rate function that was used to simulate the heat of hydration. This plot is an important method of verifying that the simulation is realistic; i.e., for all conditions, the temperature rate function should still closely resemble the temperature rate functions determined experimentally. The simulation has been run for over 200 different sets of initial conditions and in all cases, the temperature rate functions have closely resembled the experimental results.
2. Temperature History and Temperature-Time vs. Time - The computer simulation automatically plots the temperature history of the slab and a plot of Temperature-Time vs. Time.
3. Temperature Cross-Sections - The temperature distribution of the soil-slab system is automatically plotted as a function of depth for several points in time. Typically, the temperature cross-sections are generated for two hours elapsed and six hours elapsed.
4. Parametric Study - The performance of the slab is most simply evaluated in terms of the time required to reach some target temperature-time. A parametric study was conducted with a target of 245° C-hours. This target was chosen because it reflects the average temperature-time that corresponds with 350 psi flexural strength. The sensitivity of slab performance was evaluated with respect to changes in four parameters:
   - Slab Thickness
   - Initial Concrete Temperature
   - Ambient (air) Temperature
   - Insulation R-value

Example Simulation

This example illustrates the performance of a slab for a case where ambient conditions are relatively cold. Consequently, the mixing water is heated to produce the highest possible initial concrete temperature.

Input:

Slab Thickness: 12 inches

Initial Concrete Temperature: 25° C (77° F)

Ambient Temperature: 10° C (50° F)

Insulation: R = 3.2 (standard insulating blanket for concrete) [4]

Output:

- *Temperature Rate History* is found in Figure 4.1. Its peak values and general shape closely resemble the temperature rate curves developed experimentally in chapter 2.
- *Temperature Versus Time* is found in Figure 4.2. A graph of the *Temperature-Time Factor versus time* is found in Figure 4.3. Note that the target of 245° C-hours is reached in 7.75 hours.
- *A Temperature Cross-Section* is shown in Figure 4.4, representing the temperature distribution after two hours elapsed time. Note that the concrete temperature at the ground surface is only about 21° C (69.8° F) and has actually dropped from its initial temperature. The cross-section shows a variation of about 4° C (7.2 ° F) across the depth of the slab.
- Another temperature cross-section is shown in Figure 4.5, representing the temperature distribution after six hours elapsed. At this time, the temperature variation across the slab varies by as much as 12° C (21.6° F), with a peak of about 51° C (123.8°F).
- Figure 4.6 is included for the purpose of *comparing R-values*. It represents the same time period as Figure 4.5, but the insulation R-value has been increased from 3.2 to 20. Now, the peak temperature occurs near the surface of the slab. Also, note that the peak temperature has increased to about 57° C (134.6° F). However, much of the improved performance that results from the additional insulation is lost by increased heat flow to the ground, as evidenced by a flatter curve near the ground surface.

Parametric Study

A parametric study of four variables was conducted.

- Slab Thickness
- Initial Concrete Temperature
- Ambient (air) Temperature
- Insulation R-value

Slab Thickness

- Figure 4.7 plots slab thickness versus the elapsed time required to reach the target (245 °C-hours). The ambient temperature was 20° C (68° F). The insulation was R = 3.2, which represents a conventional thermal blanket. Iso-curves are plotted for three initial concrete temperatures, 25, 30, and 35° C, each showing similar trends.
- The effect of slab thickness is non-linear. For slabs of about 12" thickness, an additional inch of thickness results in only about 4 ½ minutes reduction in time requirement. However, for 6" thick slabs, an additional inch of thickness results in about a 20 minute reduction.

Initial Concrete Temperature

- Figure 4.8 plots the initial concrete temperature versus the time required to reach the target. For this parameter study, the slab thickness was fixed at 12". The insulation was a conventional thermal blanket. Iso-curves are plotted for seven different ambient temperatures:
- The initial concrete temperature is extremely influential. For average conditions, a one degree increase in concrete temperature results in about 7 ½ minutes reduction in time requirement. For lower temperatures, the effect is even more pronounced. The increase from 10 to 11 degrees impacts the time requirement by nearly 25 minutes.

Ambient Temperature

- Figure 4.9 plots the ambient temperature versus the time required to reach the target, showing five iso-curves for different concrete temperatures. The slab thickness is 12" and the insulation is a conventional thermal blanket.
- Ambient temperature directly effects the outcome far less than concrete temperature. Figure 4.9 illustrates that, at average temperatures, an increase in ambient temperature reduces the time required by about 5 minutes. However, as discussed earlier and shown in Tables 4.1 and 4.2, ambient temperature has significant indirect effects by lowering the maximum attainable concrete temperature. Therefore, when combining direct and indirect effects, ambient temperature has the greatest impact of any parameter.

Insulation R-Value

- Figure 4.10 shows the effect of insulation R-Value on the time required. For ambient temperature of 20° C, and a 12" thick slab, insulation has a very significant effect for R-values below about 3. Higher R's have negligible impact, for this case.
- Whereas Figure 4.10 shows the effect of R-Value for a somewhat average case, Figure 4.11 shows the effect for an exceptional case. In Figure 4.11, the slab is thinner (8 inches), the ambient temperature is colder (5° C), and the concrete is heated as much as possible. Figure 4.11 illustrates that an increase in insulation above that of a conventional thermal blanket may be warranted when slabs are thinner, temperatures are colder, or concrete is significantly warmer than the outside air. An increase in R from 3.2 to 10 can reduce the time required by as much as 40 minutes.

Maximum Attainable Initial Concrete Temperatures

The ambient temperature limits the maximum attainable concrete temperature because aggregates and cement cannot normally be heated. Consequently, ambient temperature has both indirect and direct effects on the performance of the concrete: low air temperatures lower the initial concrete temperature and results in higher heat loss to the ground and to the air. Both effects reduce the performance of the concrete. The maximum attainable concrete temperature may be estimated [2] based on the mix proportions, assuming the specific heat of aggregates and cement to be 22% of the specific heat of water. Based on these assumptions, Tables 4.1 and 4.2 provide the maximum attainable concrete temperatures.

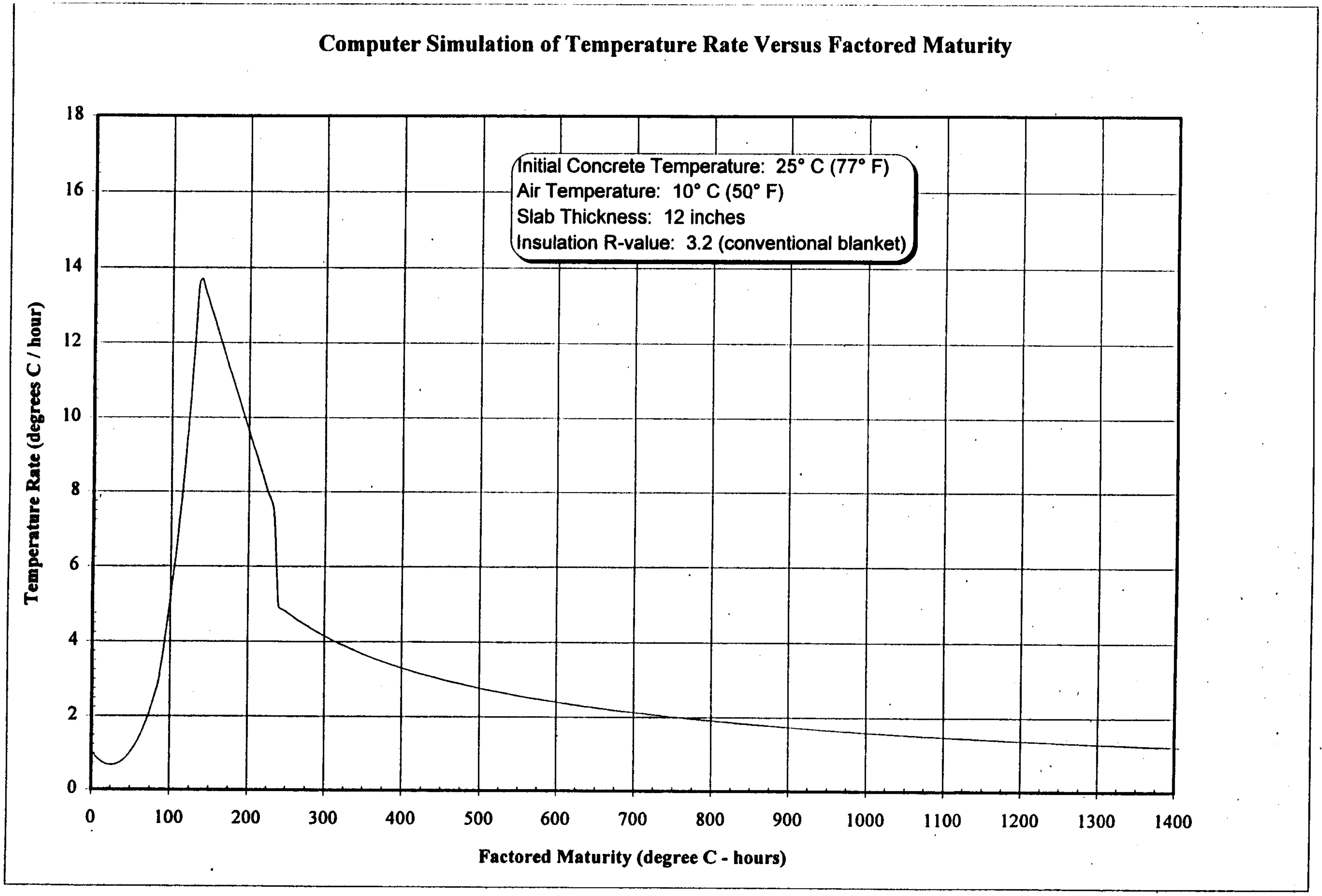

Computer Simulation of Temperature Rate Versus Factored Maturity
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)
Temperature Rate (degrees C / hour)
Factored Maturity (degree C - hours)
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

Figure 4.1

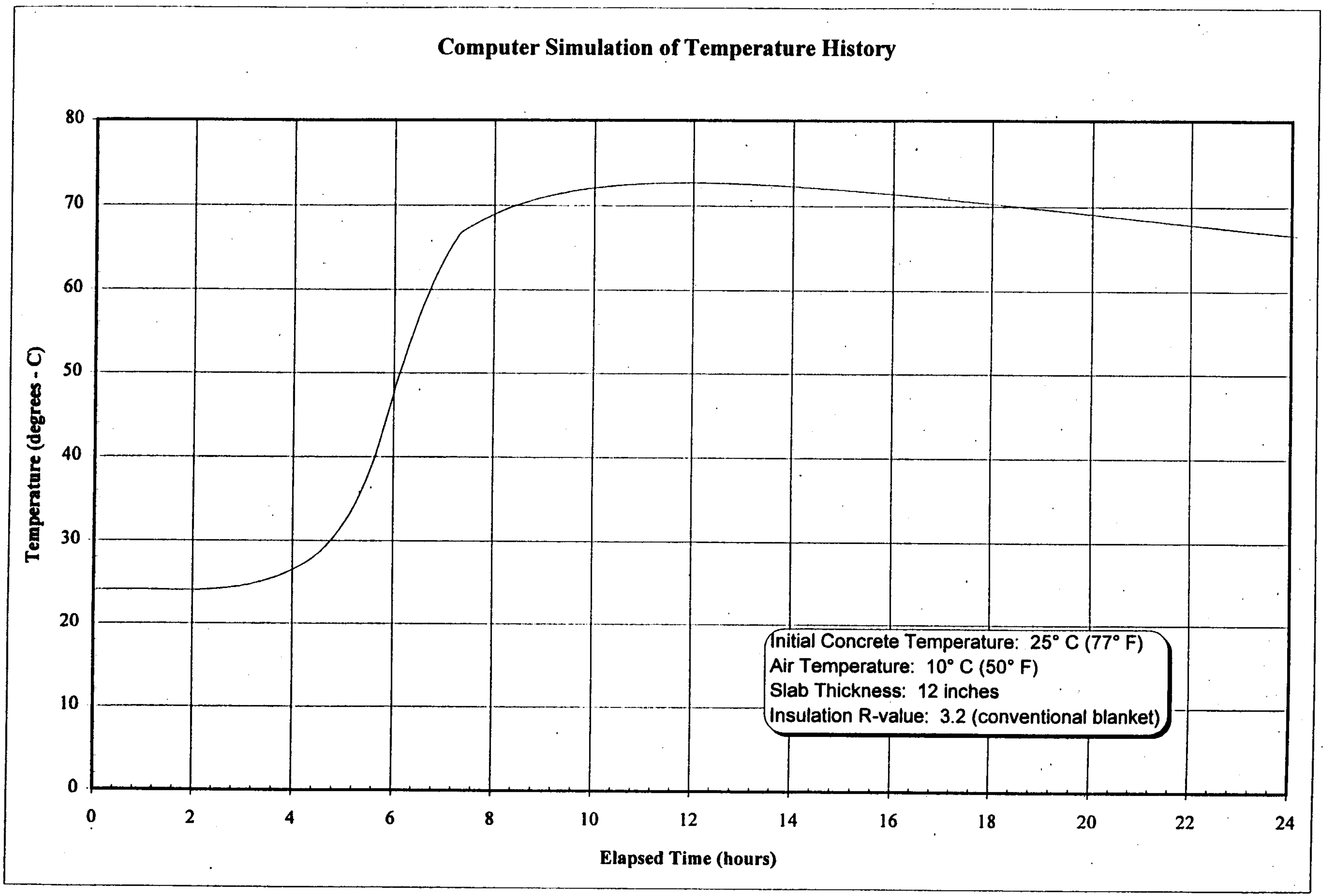

Computer Simulation of Temperature History
Temperature (degrees - C)
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Elapsed Time (hours)
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)

Figure 4.2

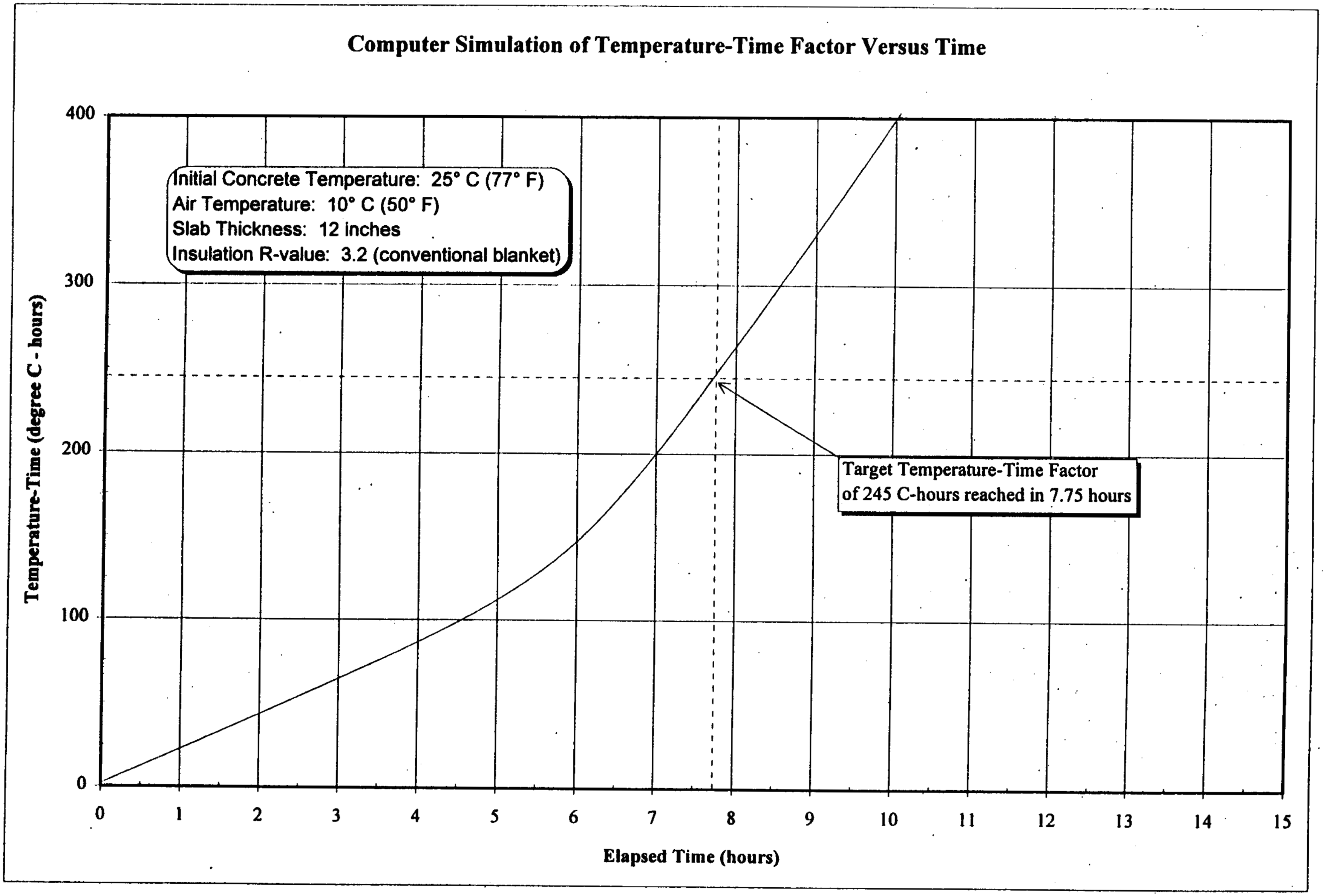

Computer Simulation of Temperature-Time Factor Versus Time
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)
Target Temperature-Time Factor
of 245 C-hours reached in 7.75 hours
Temperature-Time (degree C - hours)
0
100
200
300
400
Elapsed Time (hours)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Figure 4.3

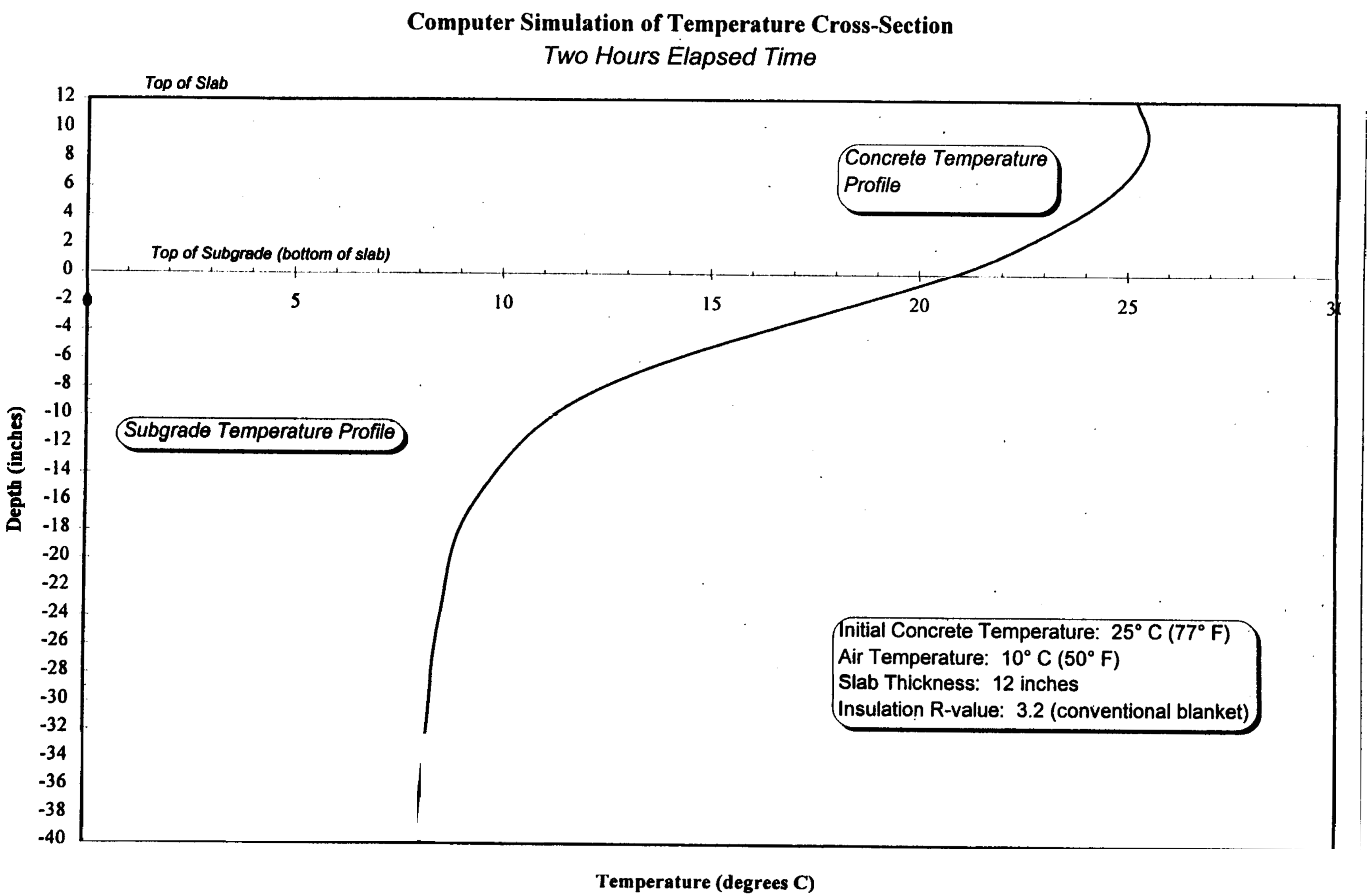
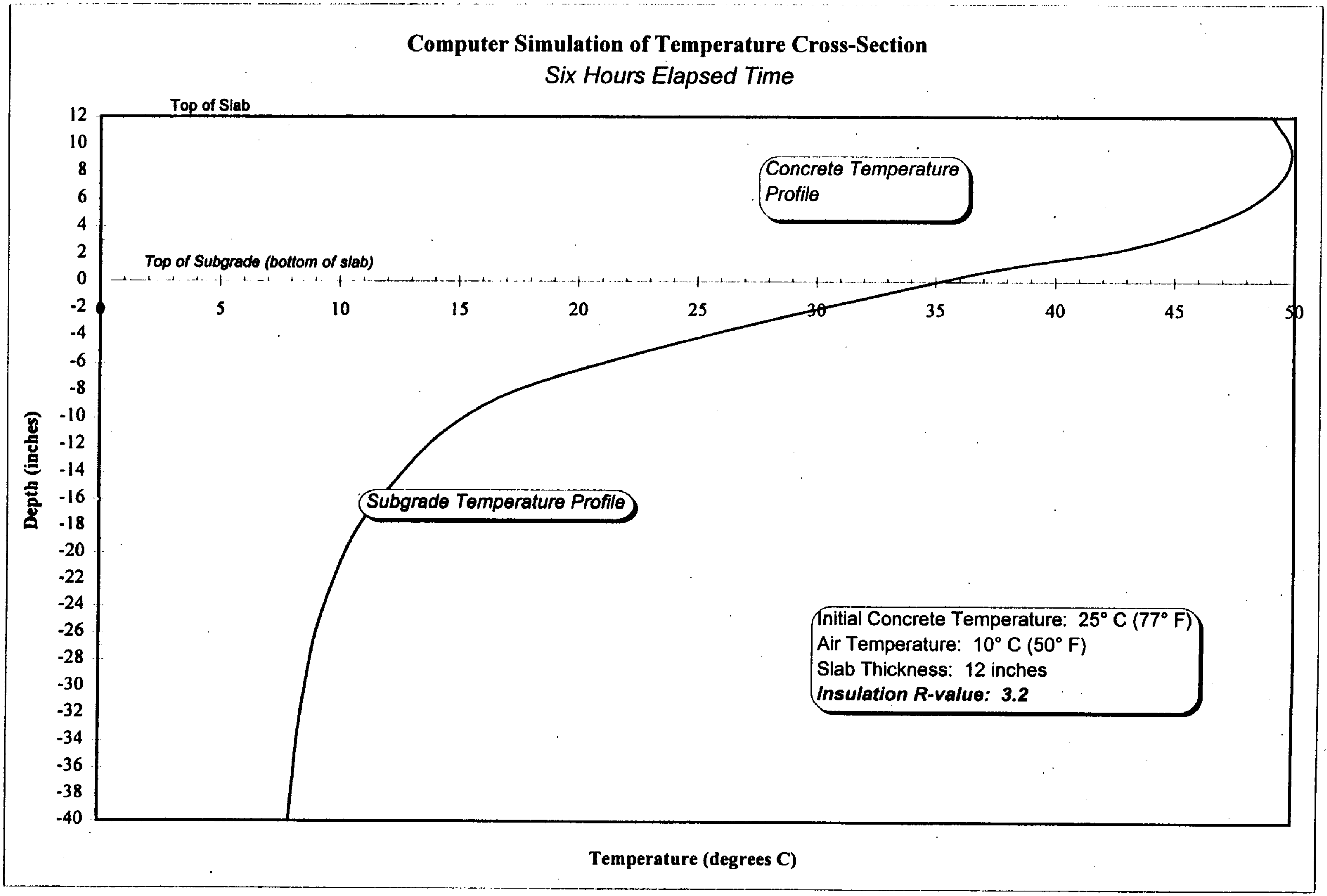

Computer Simulation of Temperature Cross-Section
Two Hours Elapsed Time
Top of Slab
Top of Subgrade (bottom of slab)
Concrete Temperature Profile
Subgrade Temperature Profile
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)
Depth (inches)
Temperature (degrees C)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
5
10
15
20
25

Figure 4.4



Computer Simulation of Temperature Cross-Section
Six Hours Elapsed Time
Top of Slab
Concrete Temperature Profile
Top of Subgrade (bottom of slab)
Subgrade Temperature Profile
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 3.2
Depth (inches)
Temperature (degrees C)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
5
10
15
20
25
30
35
40
45
50

Figure 4.5

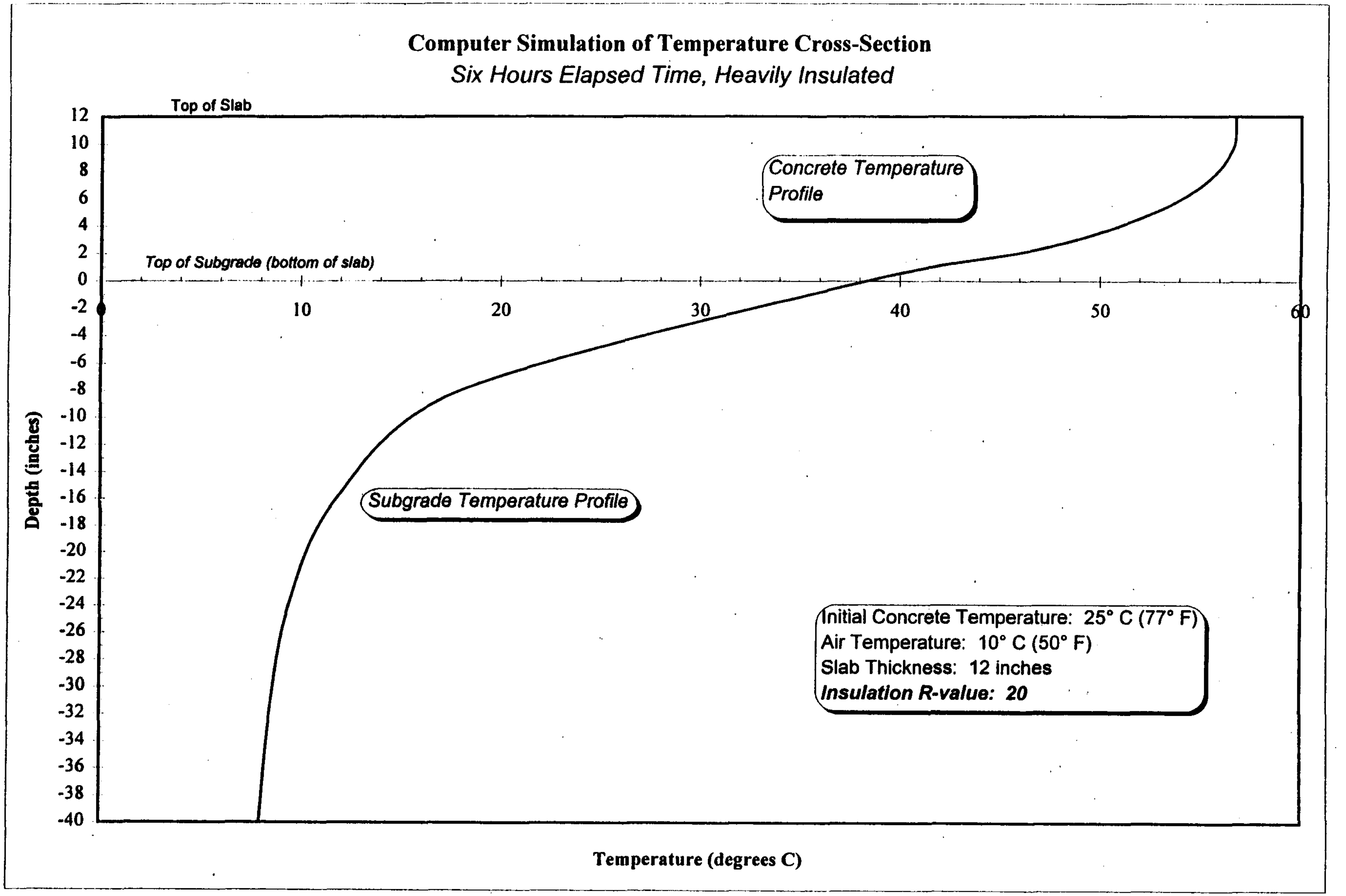

Computer Simulation of Temperature Cross-Section
Six Hours Elapsed Time, Heavily Insulated
Top of Slab
Top of Subgrade (bottom of slab)
Concrete Temperature Profile
Subgrade Temperature Profile
Initial Concrete Temperature: 25° C (77° F)
Air Temperature: 10° C (50° F)
Slab Thickness: 12 inches
Insulation R-value: 20
Depth (inches)
Temperature (degrees C)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
10
20
30
40
50
60

Figure 4.6

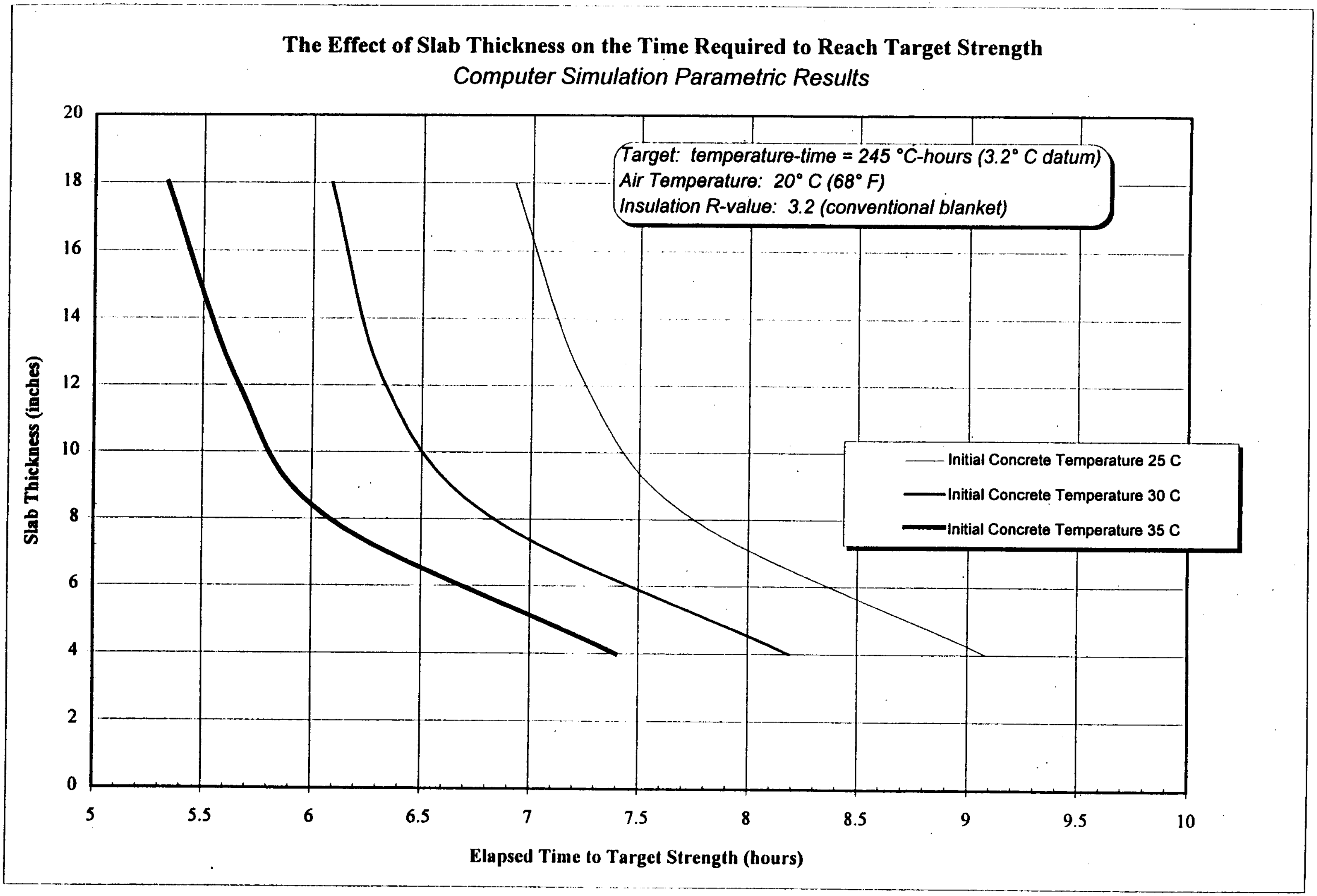

The Effect of Slab Thickness on the Time Required to Reach Target Strength
Computer Simulation Parametric Results
Target: temperature-time = 245 °C-hours (3.2° C datum)
Air Temperature: 20° C (68° F)
Insulation R-value: 3.2 (conventional blanket)
Initial Concrete Temperature 25 C
Initial Concrete Temperature 30 C
Initial Concrete Temperature 35 C
Slab Thickness (inches)
0
2
4
6
8
10
12
14
16
18
20
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
Elapsed Time to Target Strength (hours)

Figure 4.7

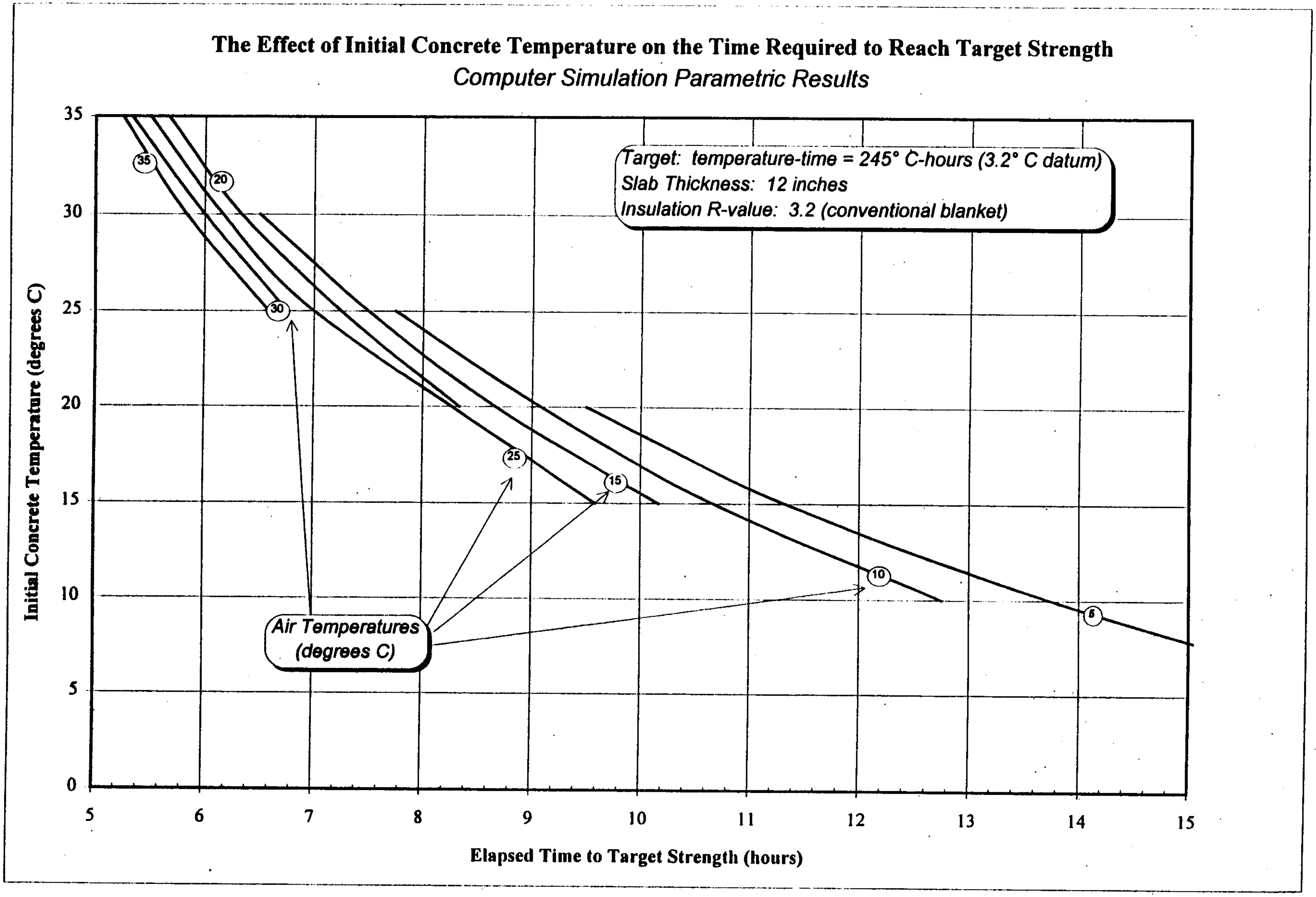

The Effect of Initial Concrete Temperature on the Time Required to Reach Target Strength
Computer Simulation Parametric Results
Target: temperature-time = 245° C-hours (3.2° C datum)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)
Air Temperatures (degrees C)
35
20
30
25
15
10
5
Initial Concrete Temperature (degrees C)
Elapsed Time to Target Strength (hours)
0
5
10
15
20
25
30
35
5
6
7
8
9
10
11
12
13
14
15

Figure 4.8

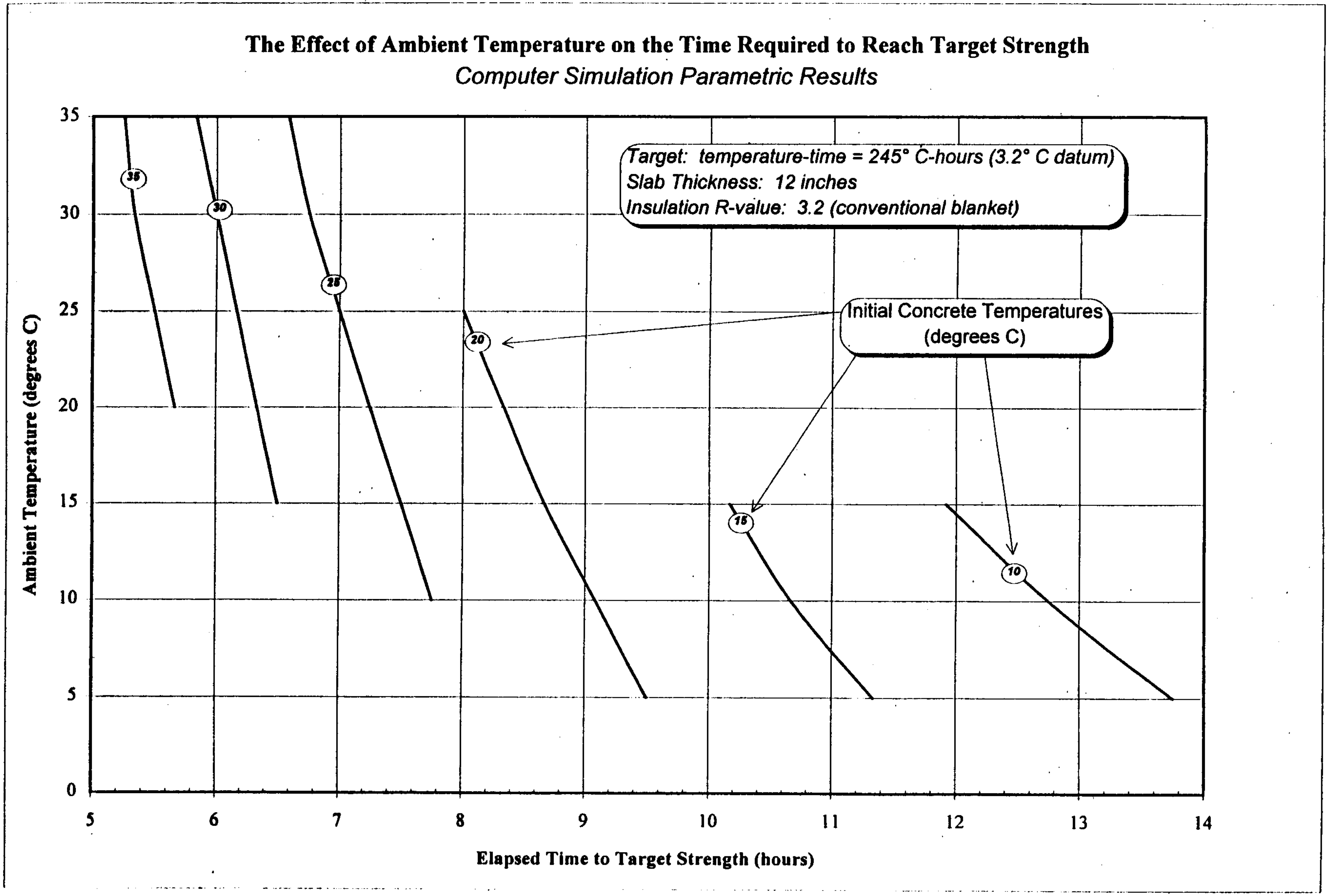

The Effect of Ambient Temperature on the Time Required to Reach Target Strength
Computer Simulation Parametric Results
Target: temperature-time = 245° C-hours (3.2° C datum)
Slab Thickness: 12 inches
Insulation R-value: 3.2 (conventional blanket)
Initial Concrete Temperatures (degrees C)
35
30
25
20
15
10
Ambient Temperature (degrees C)
0
5
10
15
20
25
30
35
5
6
7
8
9
10
11
12
13
14
Elapsed Time to Target Strength (hours)

Figure 4.9

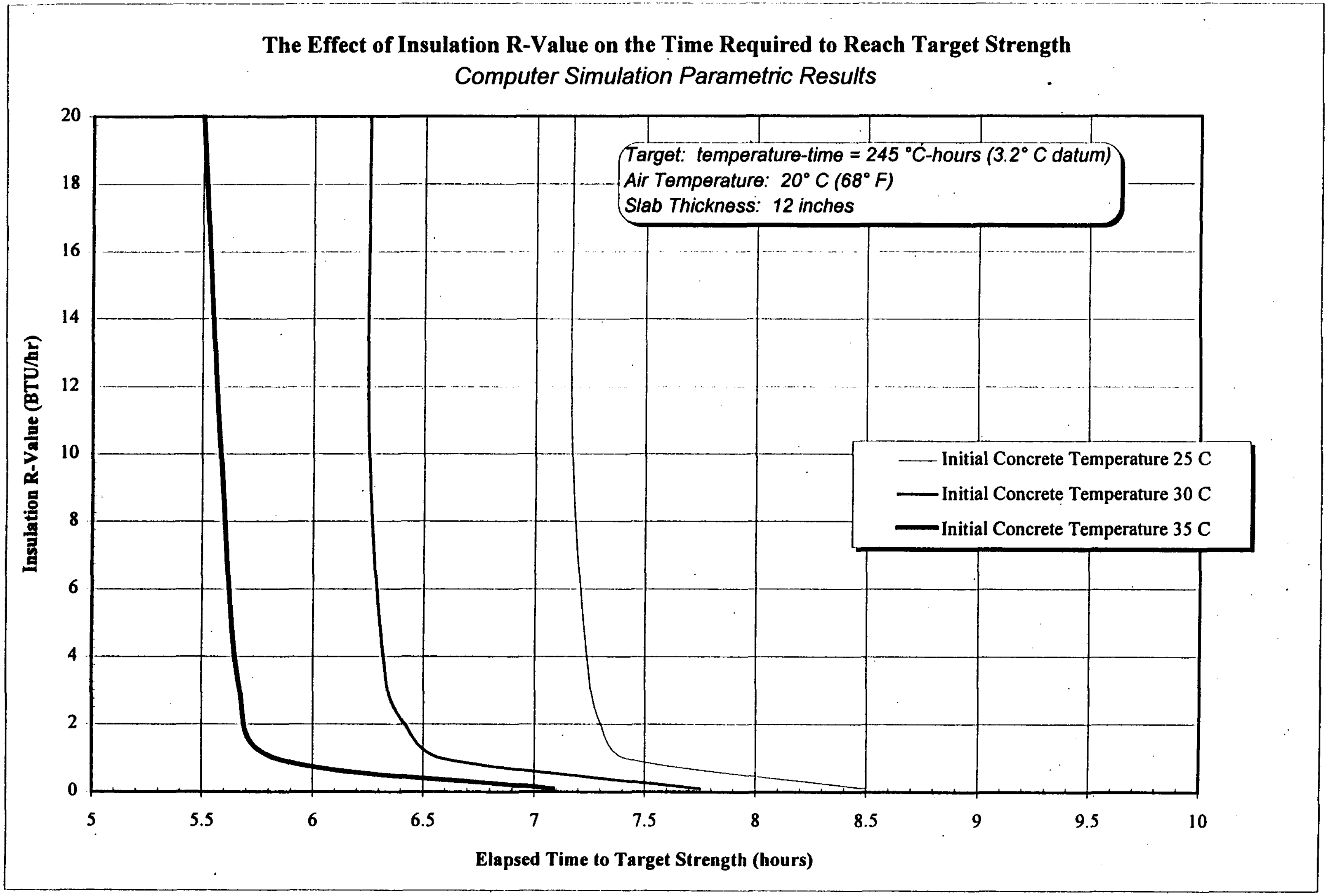

The Effect of Insulation R-Value on the Time Required to Reach Target Strength
Computer Simulation Parametric Results
Target: temperature-time = 245 °C-hours (3.2° C datum)
Air Temperature: 20° C (68° F)
Slab Thickness: 12 inches
Initial Concrete Temperature 25 C
Initial Concrete Temperature 30 C
Initial Concrete Temperature 35 C
Insulation R-Value (BTU/hr)
Elapsed Time to Target Strength (hours)
0
2
4
6
8
10
12
14
16
18
20
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10

Figure 4.10

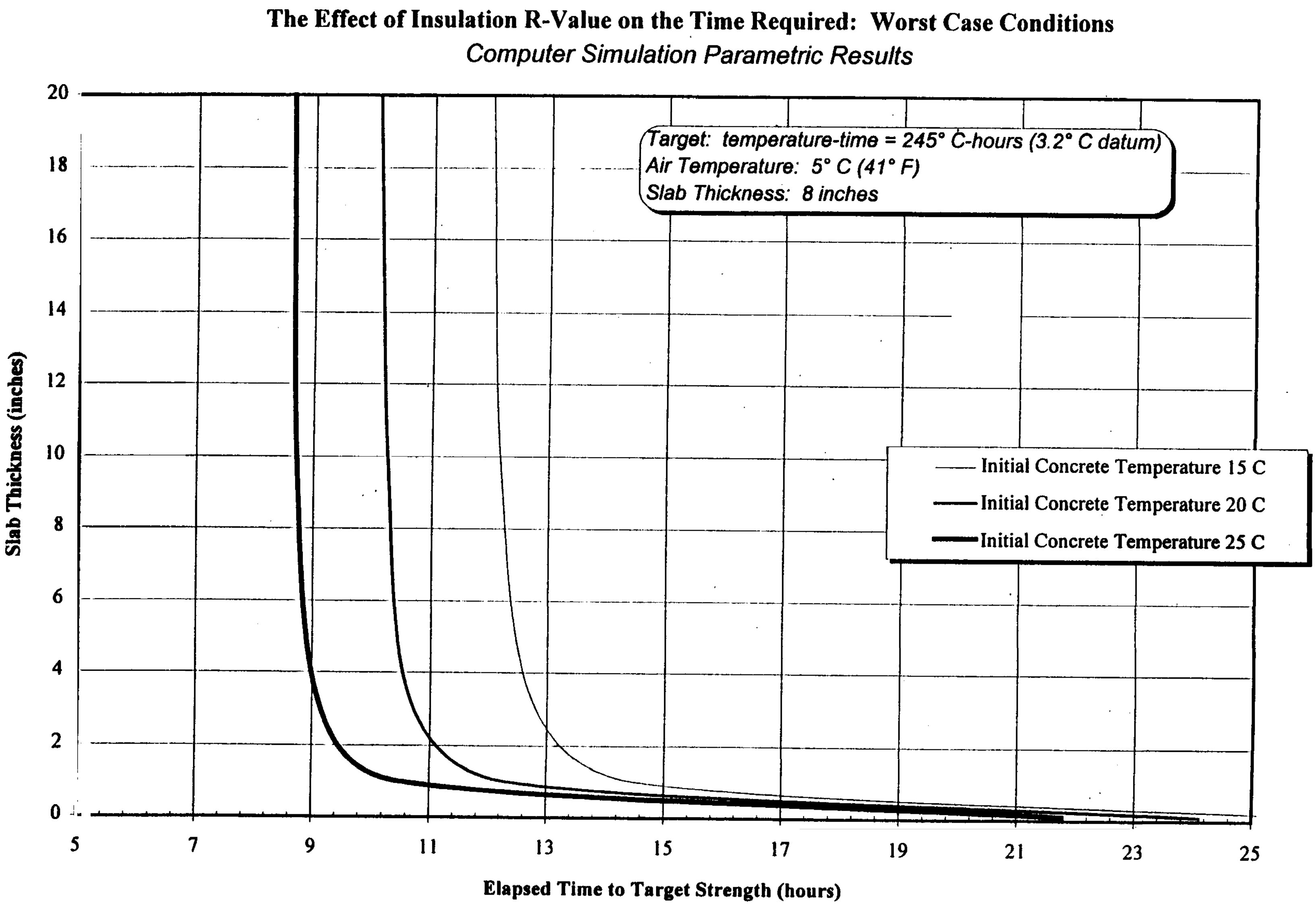

The Effect of Insulation R-Value on the Time Required: Worst Case Conditions
Computer Simulation Parametric Results
Target: temperature-time = 245° C-hours (3.2° C datum)
Air Temperature: 5° C (41° F)
Slab Thickness: 8 inches
Initial Concrete Temperature 15 C
Initial Concrete Temperature 20 C
Initial Concrete Temperature 25 C
Slab Thickness (inches)
0
2
4
6
8
10
12
14
16
18
20
5
7
9
11
13
15
17
19
21
23
25
Elapsed Time to Target Strength (hours)

Figure 4.11

Maximum Attainable Concrete Temperatures, for Given Ambient Temperatures
Assuming Water Heated to 60° C (140° F)
Assuming Aggregates and Cement are not Heated

Ambient Temperature, degrees C	*Ambient Temperature, degrees F*	*Maximum Concrete Temperature, degrees C*	*Maximum Concrete Temperature, degrees F*
0	32	16	61
5	41	20	68
10	50	23	74
15	59	27	81
20	68	31	87
25	77	34	94

Table 4.1

Maximum Attainable Concrete Temperatures, for Given Ambient Temperatures

Assuming Water Heated to 80° C (176° F)

Assuming Aggregates and Cement are not Heated

Ambient Temperature, degrees C	*Ambient Temperature, degrees F*	*Maximum Concrete Temperature, degrees C*	*Maximum Concrete Temperature, degrees F*
0	32	22	71
5	41	25	77
10	50	29	84
15	59	33	91
20	68	36	97
25	77	40	104

Table 4.2

6. Conclusions

Mix Design and Strength Correlation

The mix described in this report was based on the mixes researched at NJIT and its design varies very little from those mixes. Several minor modifications were made to the basic NJIT design, none of which are likely to result in significant difference in performance. However, the mixes at the two universities *did* perform differently and it is believed this is best explained by the differences in cements used. While generally using Essroc cement, NJIT mixes were observed to reach the target strengths at a temperature-time of between 150 and 250 °C-hours. While using Hercules Type I cement, this report finds that the target strengths are reached between 245 (for 350 psi in flexure) and 388 °C-hours (for 3,000 psi in compression) for a datum temperature of 3.2° C (37.8° F). It may be concluded that the Hercules cement requires higher temperatures to reach comparable strengths (whether or not Hercules cement *results* in higher temperatures has not been addressed).

Despite the different performance of the mixes using Hercules cement, it was found that they still meet the performance goals of the project. Using a computer simulation, it was found that the fast-track mix using Hercules cement achieves the target temperature-time of 245 °C-hours (datum of 3.2° C) for a wide range of temperatures and conditions.

Some other results:

- A single datum temperature could not be determined using the ASTM method. The datum temperature was selected as 3.2° C, on a statistical basis; i.e., a datum temperature of 3.2° C provides the best strength-maturity correlation.
- The correlation of strength with the temperature-time product is valid for all temperatures, exhibiting no apparent bias related to initial or curing temperatures.
- In an effort to improve the strength correlation, a new functional form for maturity was defined and given the term factored maturity. This functional form showed only marginally better correlation then the temperature-time factor. However, it was used in the development of the computer simulation because the best possible correlation was required.

Determining the Heat Function

The variation of the heat of hydration with the factored maturity was determined experimentally. It was found that the rate of temperature increase is closely related to the factored maturity. This temperature rate exhibits four phases, characterized by distinct functional shapes. The temperature-rate curves were analyzed statistically to obtain four equations that describe the heat of hydration of the fast-track mix. By knowing the rate of heat generated, it became possible to develop a heat transfer computer simulation capable of predicting the temperature history of the slab.

Development of a Computer Simulation

A computer simulation was developed based on heat transfer principles. The simulation used the experimentally-obtained heat functions and the thermal properties of the soil, slab, and insulation, to calculate the change in temperature of a model slab, over time.

The computer simulation was used for the study of model slabs, varying the thickness, the initial concrete temperature, the air temperature, and the insulation R-value. The results of the parametric study enable recommendations to be made regarding the use of the fast-track mix.

Recommendations

The computer simulation enables rational recommendations to made regarding the effects of different slab thickness', the useful temperature ranges of the mix, and the required insulated covering(s).

Slab Thickness

Most of the recommendations are intended for 12 inch thick slabs. For slabs that are about 12" thick, a change in thickness of 1" results in only about 4 ½ minutes change in required time (to reach the target strength). However, for slabs as thin as 6", the effect of a 1" change is about 30 minutes. Slab thickness is critical at low temperatures. In some cases additional insulation may be warranted (see Figure 4.7)

Temperature

Table 5.1 summarizes recommendations for initial concrete temperature, given the ambient temperature. Some additional comments:

- For average conditions, an increase in concrete temperature of 1° C results in a reduction in required time of 7 ½ minutes. An increase of 1° F results in a reduction in required time of 4.2 minutes(see Figure 4.8).
- For average conditions, increase in air temperature of 1° C directly results in a reduction in required time of about 5 minutes (1° F reduces time requirement by 2.8 minutes). Increased air temperature has the additional indirect impact of raising the maximum attainable concrete temperature. Between direct and indirect effects, air temperature is the most influential variable. (see Figure 4.9)
- Rapid cooling of the slab may occur during finishing and must be considered in cold weather. It is not sufficient that the concrete be *poured* at a high temperature; it must *be* at the required temperature at the time the insulation is placed.
- It has been shown that insulation (up to about R = 10), above a conventional thermal blanket, may be beneficial for colder temperatures or for thin slabs. This may be obtained with foam insulation board or with additional blankets.
- Concrete temperatures above about 32° C (89.6° F) lose slump very quickly and should be used with caution (see Table 1.4)

Insulation

An insulated covering is a necessity in all temperature conditions. For average conditions, the use of conventional thermal blankets provides sufficient insulation; additional insulation is not required and has negligible impact. However, additional insulation is a beneficial option for the following cases:

- Thin slabs, thickness less than about 6"
- Cold temperatures (about 10 to 15° C, or 50° F to 59° F), all thickness'

Quality Control

It has been shown that the size of the concrete pour strongly influences the time requirement; thin slabs require significantly more time to reach the target, than thicker slabs. Size effect has a similar effect on test samples such as cylinders and prisms. Consequently, cylinders and prisms will tend to gain maturity much slower than the slab. For this reason evaluation of in-place strength should follow these procedures:

- Decisions regarding in-place strength, such as the re-opening of a roadway, should be based on the target temperature-time factor of 245° C-hours in the slab (at 3.2° C datum). Waiting until the target strength is reached in the test samples is overly conservative.
- Cylinders and prisms should be tested at or near the target temperature-time factor of 245° C-hours, to verify its correlation with the target strength. This will necessarily occur *after* the slab has reached its target.
- For subsequent pours, the target temperature-time factor may be modified (if justified) based on the performance of previous jobs.

Table 5.1: Temperature Recommendations
Assuming Slab Thickness of 12 inches
Assuming Conventional Insulating Blanket (R = 3.2)
Target Strength: 350 psi in Flexure (245° C-hours for 3.2° C datum)

Ambient Temperature, degrees C	*Minimum Concrete Temperature to Attain Strength in 6 hours*	*Minimum Concrete Temperature to Attain Strength in 8 hours*	*Minimum Concrete Temperature to Attain Strength in 9 hours*	*Comments*
<10	-	-	-	Pour not recommended
10	-	24	21	Heat as warm as possible. Additional insulation optional.
15	-	23	19	Heating required
20	33	22	18	Heating required
25	32	22	17	Heating optional
30	30	18	-	
35	29	-	-	

7. References

1. American Society for Testing and Materials, 1991 Annual Book of ASTM Standards, Construction, Vol. 4.02, 1991, C1074, pp. 544-540.
2. Mehta, P. Kumar, Concrete: Structure, Properties, and Materials, Prentice-Hall, First Edition, 1986.
3. Holman, J.P., Heat Transfer, McGraw-Hill, seventh edition, 1990.
4. American Concrete Institute, ACI Manual of Concrete Practice Part I, 1978, Committee 306, pp. 1-19.