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Maturity Model and Curing Technology

D.M. Roy, B.E. Scheetz, S. Sabol,
P.W. Brown, D. Shi, P.H. Licastro

Materials Research Laboratory
The Pennsylvania State University
University Park, PA

G.M. Idorn, P.J. Andersen, V. Johanson

G.M. Idorn Consult A/S
Blokken 44 Birkerod
Denmark

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Program Manager: *Don M. Harriott*
Project Manager: *Inam Jawed*
Production Editor: *Marsha Barrett*
Program Area Secretary: *Ann Saccomano*

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Strategic Highway Research Program
National Academy of Sciences
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

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Contents

Abstract

Concrete maturity which correlates with the strength of concrete, is based on its age and temperature history which require long-term data measurements. This report proposes a new method for determining concrete maturity based on kinetic models of cement hydration employing short-term measurements of heat generated during hydration using isothermal calorimetry. The method uses Computer Interactive Maturity System (CMIS) software. The interrelationship of heat generation, maturity and strength development can be used to predict thermal conditions and strength gain in concrete during curing. The results are presented in table form.

The work includes field studies of a bridge pier and highway slabs, and curing tables which include variants such as concrete thickness, weather conditions, and concrete temperature.

Executive Summary

It is well established that the strength development of concrete is a function of its age and temperature history. The combined effect of time and temperature on strength development may be expressed in terms of "maturity," which can also be defined as an equivalent age at a reference temperature. In this report, maturity is defined as an equivalent age at 20°C (68°F). As an equivalent age, the maturity can be derived using the classic Arrhenius equation, which involves an important factor called "activation energy." The conventional methods to determine the activation energy of cement hydration, such as the one included in ASTM C1074-87 require long-term data. Because the purpose of a maturity model is to predict long-term strength and heat development in concrete from short-term data, this requirement is not very efficient. This report proposes a new method based on the kinetic models of cement hydration and only needs relatively short-term measurement of the heat generated during hydration using isothermal calorimetry. Rates of heat evolution are measured at constant temperatures. The temperatures selected should cover the range of temperatures likely to be encountered when concrete containing the cement in question is field cured. In some cases, this range may be from 5 to 70°C. Isothermal calorimetric runs are carried out at temperature intervals within this range. In the present study 5°C intervals were used and the temperature range was 10 to 55°C. The rates of heat evolution are integrated to obtain the total amounts of heat evolved for the first 24 to 48 hours. The slopes of these curves are then obtained. A plot of the natural log of these slopes against the inverse temperature in Kelvin provides the Arrhenius activation energy. This is a true activation energy.

Results of the present study, while encouraging, must be regarded as preliminary. This is because of the limited number of cements investigated. The generality of the method should be demonstrated by using a variety of blended and portland cements.
This is because both composition and fineness of cements will affect the rates of hydration, and thereby the value for activation energy. It is also warranted to compare the results obtained using compressive strength tests with those obtained calorimetrically.

The activation energy obtained is the basis for the development of maturity models and, regardless of the particular model, an activation energy is used. Once the maturity has been determined, the heat development and the strength development in concrete can be calculated by using some empirical formulas. This report uses a commercial software, Computer Interactive Maturity System (CIMS) released by Digital Site Systems, to

calculate the heat and strength development. CIMS uses a lower value for the activation energy than was calculated by the isothermal method described above. The effects of these differences are illustrated.

An exponential relationship between the heat and maturity, and the strength and maturity has been assumed in CIMS. CIMS can also be used to predict the change of maximum temperature in concrete with time. Based on the predictions of both thermal conditions and strength gain in concrete, one can predict: the possibility of thermal cracking due to too large a temperature difference and low strength in concrete; or the possibility of permanent strength loss due to too high a temperature in concrete; or early freezing due to too low a temperature and strength in concrete.

To evaluate the CIMS model, two field studies were conducted, one involved a bridge pier, and another involved two highway slabs. CIMS HayBox calorimeter was used to obtain the calorimetric data which are required by CIMS. In contrast to the isothermal calorimetric studies carried out, the data obtained in the HayBox calorimeter is adiabatic. The field studies have shown that the predicted temperatures in concrete exhibit the same trend observed in the field. However, the predicted accuracy of the model needs further verification.

Because the graphical presentation output by CIMS may not be convenient for field use, curing tables have been generated for this report. The variants include: typical thickness of concrete section; typical and local weather conditions; and typical concrete temperature at placement. A list of input parameters includes the following:

1. wind speed
2. air temperature
3. base temperature
4. concrete temperature
5. base materials
6. insulation
7. cement type
8. cement content
9. thickness
10. mix design

These curing tables may be used to predict conditions in which there is a risk of early freezing, where there is a risk of excessive thermal gradients in the concrete, or where there is a risk of excessive temperature rise within the slab.

Potential applications of the maturity/curing model and the curing tables are discussed in this report. Some precaution or preventions, as examples, have been suggested to achieve desirable curing domain.

In summary, the maturity/curing model is valuable in construction practice. Further investigation is needed to verify the method of activation energy determination, and the predicted accuracy of the maturity model.

Introduction

In concrete engineering and construction practice, the prediction of strength and heat development in concrete has economic significance. Accelerated yet safe construction schedules can be derived based on the combined consideration of heat and strength development in concretes.

It has been long recognized that the strength of a given concrete mixture is a function of its age and temperature history.[1-3] The term "maturity" has been used to account for the combined effect of time and temperature on strength development.[3] Maturity can also be considered as an equivalent age at a reference temperature.[4] ASTM C1074-87 is the standard practice for estimated concrete strength by the maturity method. It also includes the method for determining the activation energy which is used to calculate maturity. However, this method requires long-term strength data to determine the activation energy. Because the purpose of a maturity model is to predict long-term strength from short-term data, this requirement is not very efficient. In this report a new model is proposed, which is based on the kinetic models of cement hydration and needs only relatively short-term measurement of the heat generated during hydration using isothermal calorimetry.

Once the maturity, or the equivalent age at a reference temperature, is determined, the strength development and heat development with the equivalent ages can be determined. Conventional compressive strength testing (ASTM C39) is used to obtain the strength data. Adiabatic calorimetry is used to obtain the maximum temperature change in a concrete mixture with time. A commercial software, Computer Interactive Maturity System (CIMS) released by Digital Site Systems, is tested in this study.

Maturity Model

Maturity is here defined as the equivalent age at a reference temperature. If the reference temperature is chosen as 20°C, the maturity, or equivalent age at 20°C, can be calculated as

$$M_{20} = \int_0^t H(T)\,dt$$

where H(T) is defined as temperature function, or affinity ratio,[4] and T is the curing temperature in Celsius. H(T) is actually the relative rate of hardening at temperature T compared to the rate at 20°C.

An expression of H(T) for portland cement has been found to have the form of the Arrhenius equation: [4,5]

$$H(T) = \mathrm{Exp}\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+T}\right)\right]$$

where E is the activation energy for the cement hydration in Joules/mol, and R is the gas constant, 8.314 Joule/mole°C.

Determination of Activation Energy

In the CIMS model, the activation energy for the hydration of portland cement is expressed as a function of temperature:[6]

$$E = 33500 \text{ J/mol for } T >= 20^\circ\text{C and}$$
$$33500 \text{ J/mol} + 1470\,(20 - T) \text{ J/mol for } T < 20^\circ\text{C.}$$

However, the method recommended by ASTM C1074-87 for determining the activation energy is based on a model as follows:[4]

$$S = S_\infty \frac{K_T(t-t_0)}{1+K_T(t-t_0)}$$

where K_T is the rate constant at temperature T, t_o is defined as the age beyond the time of final setting, and S_∞ is the "infinite" strength. The inverse of the rate constant was also found to be proportional to equal the time beyond t_o for strength to reach 50% of the infinite strength.[7] From the plot of 1/S versus $1/(t-t_o)$, (or, 1/S vs. 1/t if t_o is much smaller than t), one can determine the infinite strength as the reciprocal of the intercept at infinite time, and the rate constant as the intercept divided by the slope.

It is worth noting that the statement in ASTM C 1074-87, "determine the slope and intercept of the best fitting straight line through the data ...," appears to be incorrect. Figure 1 is such a plot of 1/S vs. 1/t, (assuming that $t - t_o = t$) based on the data shown in Ref. 4, Table 1, the strength of portland cement mortar hydrated at w/c = 0.43 and temperature 32°C for 0.38 day to 25.79 days. Obviously, an overall linear regression will result in an incorrect slope and intercept. It is very likely that the early-stage data need to be ignored in many cases. The values of S_∞ and K_T must be determined by extrapolating sufficient available data, instead of by regression on the whole range of data. On the other hand, if only very short-term data are available, it is very likely to have misleading results. The intercept may turn to negative, which is absolutely meaningless. Figure 1 shows the possible misleading extrapolation if only short-term data are available. Because one of the objectives of using the maturity model is to predict long-term behavior of cement/concrete, it is not efficient that one must use long-term data to determine activation energy in the first place.

An alternative is based on hydration kinetic models. A generally accepted hydration kinetic model for the acceleration period of cement hydration is:[8,9]

$$1 - (1 - \alpha)^{1/3} = Kt$$

where ‡ is the degree of hydration. This model assumes that the growth or dissolution is controlled by diffusion through a liquid mass transfer layer.[8] Because complete or near complete hydration will take very long, actually infinite time, the term $(1 - \alpha)$ is impossible to determine based only on short-term data. However, the kinetic equation can be approximated by:

$$1 - (1 - \alpha/3) = Kt$$

$$\alpha = K't$$

$$d\alpha/dt = K'$$

if $\alpha << 1$.

Another widely accepted model is

$$-\ln(1 - \alpha) = k(t-t_o)$$

which assumes that hydration occurs by processes involving nucleation and growth.[8,9] If $\alpha << 1$, then $\ln(1 - \alpha)$ can be approximated by $-\alpha$. The kinetic model becomes

$$\alpha = k(t-t_o)$$

$$d\alpha/dt = K$$

It follows that the rate constant can be obtained from the slope of the curve of the degree of hydration vs. time, as long as α is small enough. Simple calculation shows that when $\alpha <= 0.2$, the approximations that $(1 - \alpha)^{1/3} = 1 - \alpha/3$ and $\ln(1 - \alpha) = -\alpha$ are reasonable, as shown in Figures 2 and 3.

The degree of hydration can be represented by the heat of hydration. Figure 4 is a typical reaction rate curve from the isothermal calorimetry measurement (T = 40°C). Figure 5 is the integral derived from Fig. 4. Assuming that the hydration is completed in one day, it appears that the acceleration peak occurs near or before the point where 20% of hydration is completed. Because the complete hydration takes a much longer time, the acceleration peak must occur when less than 20% of hydration has been completed. We have measured the reaction rate of cements at temperatures from 10°C to 55°C. In this temperature range the acceleration period will normally be completed within a few hours to, at most, one day. Figure 5 shows that a linear section can be found between about 5 and 7 hours. Figure 4 shows that the acceleration peak is within this period. Therefore, the rate constant, K, for the acceleration period in hydration of this cement at 40°C can be obtained from the slope of the curve shown in Fig. 5. Similarly, the rate constants for hydration at other temperatures can be determined.

Once the rate constants have been determined for different temperatures, the activation energy can be determined from the plot of ln(K) versus $1/T_k$, T_k being temperature in Kelvin, based on the relationship:

$$\ln(k) \propto \exp\left[-\frac{E}{RT_k}\right]$$

Figure 6 is the plot of ln(k) vs. $1/T_k$, based on the proposed method, from which an activation energy for Type I portland cement is determined to have a value of 48 KJ/mole. It is worth noting that using the ASTM method and the data from Ref. 4, Table 1, the same value is obtained. This value is significantly different from the value used in CIMS, 33.5 KJ/mol.

The composition and fineness of cements will affect the reactivity, and thereby the value for activation energy. Therefore, it will in general not be valid to compare the E values from different sources without knowing the size distribution and fineness, in addition to their chemistry.

Determination of Maturity

Once the activation energy is determined, the temperature function and the maturity in terms of the equivalent age at a reference temperature can be readily calculated. For example, if the activation energy is 48 KJ/mol, and the reference temperature is 20°C,

$$H(25^\circ C) = \exp\left[\frac{48000}{8.314}\left(\frac{1}{293} - \frac{1}{298}\right)\right]$$
$$= 1.39$$

it indicates that the rate of hardening at temperature T (298°K = 25°C) is 1.39 times that at 20°C. A given concrete mixture cured at 25°C for 1 day has the same maturity as that cured at 20°C for 1.39 day. Or, it only needs 1/1.39 = 0.72 day to cure a given concrete at 25°C to the same degree of hydration as it would be obtained for this concrete cured at 20°C for 1 day. However, if the value of 33.5 KJ/mol is used as in CIMS, the value for H(25°C) will be 1.26. The effects of the value for activation energy will be discussed later.

Prediction of Heat Development in Concrete

The prediction of heat development in concrete is based on the model:

$$Q_M = Q_\infty \exp[-(t_c/M)^\alpha]$$

where

Q_M = heat development at maturity M

Q_∞ = total heat development

M = maturity

t_c = characteristic time constant, roughly the maturity time at the inflection point on the heat development curve.

α = curvature factor, dimensionless, a measure of the slope of the steep portion of the curve.

The three curve parameters have some physical significance. The meaning of the total heat, Q_∞ is obvious. The characteristic time constant, t_c is a measure of degree of retardation or acceleration. Addition of a retarder results in an increase in t_c, while an accelerator will decrease it. The curvature factor, α, is a measure of the rate of heat release. Higher values of α represent higher reactivity of cement, or lower activation energy of cement.

The CIMS program takes adiabatic calorimetry data as input and transforms the temperature rise into heat development, once the composition and the heat capacity of the concrete in question are known. For demonstration, Figures 7 and 8 show typical heat development curves, plots of heat vs. the maturity (equivalent ages). A value of 33.5 KJ/mol is used as activation energy in Fig. 7, and 48 KJ/mol in Fig. 8. Comparing the two sets of curve parameters shows that higher activation energy results in a retardation effect, i.e., higher value for t_c; lower rate of heat release, or less reactivity, i.e., lower value for α. However, the total heat generated ultimately approaches almost the same value.

Prediction of Strength Development in Concrete

The prediction of strength development is based on the model

$$\sigma_M = \sigma_\infty \exp[-(t_c/M)^\alpha]$$

where:

σ_M = strength at maturity M

σ_∞ = potential final strength

M = maturity

t_c = characteristic time constant, roughly the maturity time at the inflection point on the strength development curve.

α = curvature factor, dimensionless, a measure of the slope of the steep portion of the curve.

The three curve parameters have similar physical significance to those described in the previous section. CIMS takes compressive strength data as input and outputs the strength development curve. For demonstration, Figures 9 and 10 show the strength development curves, plots of strength vs. the maturity (equivalent ages). A value of 33.5 KJ/mole is used as activation energy in Fig. 9, and 48 KJ/mole in Fig. 10.

CIMS (Computer Interactive Maturity System)

Inputs needed for the CIMS Program are as follows:

1) Climatic conditions
   Wind Speed (mph):
   Air Temp. (°F):
2) Concrete
   Temp. (°F):
   Slump (inch):

Air Content (% volume):
W/C (pound/pound):
Specific heat (calculated by CIMS, Btu/lb/dF)
Thermal conductivity (Btu/ft/h/dF):
Unit weight (lb/ft^3):
Thickness (inch):

3) Cement
   Type:
   Content (pound):
   Density (lb/ft^3):
4) Coarse aggregate
   Type:
   Density (lb/ft^3):
   Content (pound):
5) Fine aggregate
   Type:
   Density (lb/ft^3):
   Content (pound):
6) Water
   Type:
   Content (pound):
   Density (lb/ft^3):
7) Chemical admixtures
   Type:
   Density (lb/ft^3):
   Content (pound):
8) Mineral admixtures
   Type:
   Density (lb/ft^3):
   Content (pound):
9) Base conditions
   Type:
   Specific heat (Btu/lb/dF):
   Thermal conductivity (Btu/ft/h/dF):
   Density (lb/ft^3):
10) Formwork/insulation
   Type:
11) Simulation information
   Total process (simulation) time (hrs):
   Time step (hrs):
   Cast time (hrs):
   Interval between casts (hrs):
   Number of casts
12) Adiabatic calorimetry data for heat development simulation
13) Compressive strength data for strength development simulation

Outputs from CIMS are as follows:

1. The heat development simulation, such as Fig. 7 or 8.
2. The strength development simulation, such as Fig. 9 or 10.
3. The changes with time in the maximum temperature of concrete, such as Figures 11 and 12, the curve labeled "max."
4. The changes with time in the minimum temperature of concrete, such as Figures 11 and 12, the curve labeled "min."
5. The changes with time between maximum and minimum temperatures of concrete, such as Figures 11 and 12, the curve labeled "ΔT."
6. The temperature profile, bottom of Figures 11 and 12, the curves labeled "temperature profiles."

It is worth noting that the current version of CIMS can only be used for a one-dimensional concrete member such as a slab, and that the maximum thickness of the slab to be modeled is 5 feet.

Field studies were conducted to evaluate the accuracy of the computer program predictions. Two scenarios were chosen which had widely differing slab geometries and environmental conditions.

A bridge pier was selected since it is an extremely thick member and should be susceptible to attaining extremely high temperatures at the center of the pier. This allowed for verification of the computer program predictions of possible high thermal gradients or excessive temperatures. A highway slab was also selected as it represents the typical concrete slab geometry for which the computer model is recommended. The use of the curing technology computer program in construction practice for highway slab projects could greatly increase the quality and efficiency of large-scale roadway operations.

Thermocouples were placed strategically within each of these structures, and the actual temperature profiles within the structures over several days were recorded. The actual environmental conditions were also noted so that these same environmental conditions could be input to the computer model.

Comparisons between the actual temperature profiles and those predicted by the CIMS computer program were then made.

Field Studies I—Bridge Pier

<u>Site Location</u>

The location of this field experiment was in central Pennsylvania near the town of Faunce. The structure studied is the central bridge pier which was placed on a foundation in the middle of Clearfield Creek. The placement of the foundation was in the middle of this 200' wide stream and at a depth of approximately 6-8' below the water surface. The stream is polluted as a result of acid mine drainage from nearby coal strip mining operations and was running at 69.8°F and a pH of 3.5.

The pier was situated on the site in a north-south orientation with the north end of the pier facing down stream. The width of the east facing side of the pier received substantial exposure to the day time sun as did the south-facing ballister. Figures 13a and 13b provide an oversight of the construction location looking east to west and west to east, respectively.

Sensor Placement

As the photographs in Fig. 13 indicate, the formwork for this structure was steel and was erected around a rebar cage. Rebar was kept 5" from the surface of the formwork. The pier was 34' long, 17' high and 4' thick. Five type W (copper/constantan) thermocouples were placed on the rebar reinforcement of the pier in locations that were chosen to represent major points of symmetry in the structure. Figure 14 details the locations of the thermocouple placements. Each sensor was a grounded, stainless steel, sheathed type W thermocouple. To minimize thermal conduction to and along the rebar onto which they were attached, the 3/16" diameter sheath was covered with heat shrink tubing to within 1" of the end of the sensor. The active end of the thermocouple was then bent at an approximate 30° angle from the rebar. Figure 15 is a photograph of the installation of the thermal sensors. The sensors were securely attached to the underside of the rebar by the application of multiple nylon wire wraps. Approximately 60' of compensated thermocouple lead wire was attached to each sensor and secured to the rebar cage. These leads were run from the top of the down stream facing ballister to the data collection equipment. Readings were taken every 15 minutes on a battery-powered Doric 250 data logger with linearized inputs for type W thermocouples. The readings were both printed out for a hard copy and magnetically imprinted on a 5-1/4" floppy disc in standard text file format.

Concrete Placement

The concrete for this construction met PA DOT type A specification and was supplied by E.M. Brown, Inc. of Clearfield, PA. The concrete was transported approximately 12 miles to the construction site in 10 yard trucks. The composition and properties specified are listed in Table 1.

Four ready mix trucks delivered 96 yards of concrete to the construction site over the course of 6 hours. This represented 12 trucks arriving and dispatching their loads approximately every half hour. The concrete was transferred to a bucket and placed in the formwork. Two construction workers remained in the formwork with vibrators consolidating the concrete and two additional workers remained on the outside of the formwork assisting the consolidation, also with vibrators.

Curing of the Concrete Structure

The structure was allowed to remain in the formwork for approximately 14 hours after the final placement had occurred in order to develop initial strength. The formwork was removed ballister ends first. The holes left by the retaining rods from the formwork were caulked. Hands-on examination of the surface of the structure revealed that the east side and the up stream ballister were noticeably warmer to the touch than the west side and the down stream ballister. The latter part of the pier in fact was "cool" to the touch.

The pier was allowed to stand for approximately 22 hours and the pumps that controlled the water level in the hole were turned off and the pier was allowed to flood to a depth of approximately 6 to 8 feet around the base. Water contacted the base of the pier at approximately 23.5 hours after the pour was completed. The water temperature was recorded at 69.8°F.

Figures 16 and 17 represent the data collected from the five thermocouples embedded in the pier (labeled 1–5) and the thermocouple which recorded the ambient air temperature (labeled 6). The data are presented for the 72 hour duration of the experiment. Relative humidity at the data collection station was recorded on a clock-driven Honeywell Recorder. The humidity at the site ranged from 90 to 100% and the ambient temperature ranged from 55°F to 95°F in the 72-hour period.

Field Studies II—Highway Slab

Site Location

The test sections for this field experiment were located in the Williamsport District of PA DOT along State Route 15 approximately 22 miles north of Williamsport, PA near the crest of the mountain in Steam Valley. Two 6' x 12' slabs in the uphill passing lane were instrumented [969-97 and 970-60]. The two slabs, located approximately 40 feet from one another, will be referred to as the "up hill" and "down hill" slabs, respectively.

Sensor Placement

In total, eight type W thermocouples were placed in each slab. In addition, the "up hill" slab had one thermocouple placed in the base beneath the slab and one thermocouple monitored the air temperature. Prewired thermocouple supports were prepared in the laboratory and transported to the construction site where they were bolted together and placed in the hole. The rigs were designed with five thermocouples running down the 12' length of the slab at a nominal height of 5" above the base. At the mid-point of the rig three additional thermocouples were placed. At the two extremes, thermocouples were located at a nominal height of 2" and at the extreme right hand side another was placed at nominally 8". Figure 18 summarizes these locations. The rig was constructed of 1" angle iron for strength and the thermocouples supported in 1/2" thick, low thermal conduction, density polypropylene. To maximize the protection for the thermocouples, a one-inch diameter hole was drilled in the polypropylene and the active sensing portion of the thermocouple cemented into the center of the hole, Fig. 19. The single thermocouple support with two probes in it is illustrated in Fig. 20. Figure 21 is a photograph of one of these sensors in the field. All thermocouples were stainless steel sheathed, 3/16" type W. The contacts were protected from the concrete by overlapping rubber boots. Approximately 70' of compensated thermocouple lead wife was attached to each sensor and secured to the support. These leads ran from the berm side of the slabs to the data collection equipment. Readings were initially taken every 10 minutes for 2 hours after which readings were collected every 15 minutes on a battery powered Doric 250 data logger with linearized inputs for type W thermocouples. The readings were both printed out for a hard copy and magnetically imprinted on a 5-1/4" floppy disc in standard file format.

Figure 22 details the installed sensor network in a slab just before placement of the concrete. All locations were recorded from the bottom of the hole, in the nominally 10 inch thick slab. Figures 23 and 24 show the exact locations of all of the thermocouples.

Concrete Placement

The concrete for this road patch repair met PA DOT type AA specification and was supplied by Centre Concrete operating out of Montoursville, PA. The concrete was transported approximately 25 miles to the repair site in 10 yard trucks. The composition and properties of concrete mix specified are listed in Table 2.

Placement and densification of the concrete into the patch took approximately 20 minutes. Densification was achieved with the aid of vibrators. Following the initial leveling of the concrete, a motorized screed was used to level the patch. Hand troweling of the joints was followed by grooving of the prepared surfaces with a wire rake.

Curing of the Concrete Pavement Patches

Approximately 1 to 2 hours after the final surface preparation of the patch was completed, the entire patch was covered with a water dampened burlene covering which remained in place for several days to aid in curing of the concrete.

Figures 25 and 26 represent the data collected from the 16 thermocouples embedded in the road patch and the thermocouples which recorded the subsurface temperature and the ambient air temperature. The data are presented for the 72 hour duration of the experiment. Relative humidity at the data collection station was recorded on a clock-driven Honeywell Recorder. The humidity at the site ranged from 90 to 100% and the ambient temperature ranged from 53°F to 85°F in the period of 72 hours.

Maturity Model Verification

Bridge Pier

The concrete formulation is given in Table 1. The activation energy used is 48 KJ/mol as described in the section "Determination of activation energy." The field test data and

CIMS HayBox calorimetry data have been used in CIMS to predict the heat and strength development and possible thermal cracking in the bridge pier. The inputs are as follows.

1) Climatic conditions
   Wind Speed (mph): 3
   Air Temp. (°F):

Time (hrs)	Temp (°F)
0.0	77.0
3.5	95.0
10.0	72.0
20.0	64.0
30.0	90.0
40.0	66.0
54.0	81.0
60.0	63.0
70.0	55.0
77.0	78.0

2) Concrete
   Temp. (°F): 77
   Slump (inch): 2.63
   Air Content (% volume): 6.4
   W/C (pound/pound): 0.46
   Specific heat (calculated by CIMS): 0.225
   Thermal conductivity (Btu/ft/h/dF): 1.29
   Unit weight (lb/ft^3): 142.4
   Thickness (inch): 48
3) Cement
   Type: I (I-28)
   Content (pound): 588
   Density (lb/ft^3): 196.7
4) Coarse aggregate
   Type: crushed limestone #57 (SSD)
   Density (lb/ft^3): 168.6
   Content (pound): 1877
5) Fine aggregate
   Type: Lycoming sand (SSD)
   Density (lb/ft^3): 162.3
   Content (pound): 1239
6) Water
   Type: tap
   Content (pound): 271.5
   Density (lb/ft^3): 62.4
7) Chemical admixtures
   Type: water reducer (Master Builders, 122N)
      Density (lb/ft^3): 79.2
      Content (pound): 3.5
   Type: air entrainer (Master Builders, MBVA)

Density (lb/ft^3): 64.3
Content (pound): 0.9

8) Formwork/insulation
Steel formwork for the first 20 hours (including 6 hours of pouring)
9) Simulation information
Total process (simulation) time (hrs): 96
Time step (hrs): 2
10) CIMS HayBox Calorimetry data
(Note: The HayBox data are directly fed into CIMS program, and cannot be displayed.)
11) Compressive strength data for strength development simulation

days	strength (ksi)
1	2.628±0.141
3	5.189±0.081
7	6.280±0.158
14	6.561±0.334

The CIMS produces outputs as follows.

1) The heat development simulation, Fig. 27.
2) The strength development simulation, Fig. 28
3) The change with time in the maximum temperature of concrete, Fig. 29.
4) The changes with time in the minimum temperature of concrete, Fig. 29.
5) The changes with time in the difference between maximum and minimum temperatures of concrete, Fig. 29.
6) The temperature profile, Fig. 29.

In Fig. 16, the curve labeled "1" represents the temperature rise in the middle of the bridge pier. In Fig. 29, the curves labeled "max" should predict the temperature change in the middle of the bridge pier. Comparing two curves shows that they are reasonably close. At about 20 hours after the start of pouring, the temperature of the innermost concrete reached the peak. This was also true of the difference between the maximum and minimum temperatures in concrete. At about 20 hours, the steel formwork was removed, and the inside temperature began to drop. Eventually the temperature in the concrete reached the ambient temperature, Fig. 29. The minimum temperature in the concrete is definitely affected by the ambient temperature, Fig. 17.

Highway Slab

The concrete formulation is shown in Table 2. The activation energy used is 48 KJ/mol as described in the section "Determination of activation energy." The field test data and CIMS HayBox calorimetry data have been used in CIMS to predict the heat and strength development and possible thermal cracking in the highway slab. The inputs are as follows.

1) Climatic conditions
Wind Speed (mph): 3
Air Temp. (°F):

Time (hrs)	Temp (°F)
0.0	63.0
1.5	72.0
10.0	53.0
18.0	53.0
24.0	83.0
35.0	58.0
48.0	85.0
60.0	63.0
67.0	61.0
70.0	72.0

2) Concrete
Temp. (°F): 66
Slump (inch): 2.75
Air Content (% volume): 6.0
W/C (pound/pound): 0.45
Specific heat (calculated by CIMS): 0.225
Thermal conductivity (Btu/ft/h/dF): 1.29
Unit weight (lb/ft^3): 144
Thickness (inch): 10

3) Cement
Type: I (I - 29)
Content (pound): 588
Density (lb/ft^3): 196.7

4) Coarse aggregate
Type: crushed limestone, #57 (SSD)
Density (lb/ft^3): 168.6
Content (pound): 1878

5) Fine aggregate
Type: Lycoming sand (SSD)
Density (lb/ft^3): 162.3
Content (pound): 1132

6) Water
Type: tap
Content (pound): 262.7
Density (lb/ft^3): 62.4

7) Chemical admixtures
Type: water reducer (Master Builders, 122N)
Density (lb/ft^3): 79.2
Content (pound): 2.7
Type: air entrainer (Master Builders, MBVR)
Density (lb/ft^3): 64.3
Content (pound): 1.1

8) Formwork/insulation
Water dampened burlene

9) Simulation information
Total process (simulation) time (hrs): 96
Time step (hrs): 2
10) CIMS HayBox Calorimetry data
(Note: The HayBox data are directly fed into CIMS program, and can not be displayed.)
11) Compressive strength data for strength development simulation

days	strength (ksi)
2	3.649 ± 0.139
14	4.958 ± 0.212
28	5.554 ± 0.348

The CIMS produces outputs as follows.

1) The heat development simulation, Fig. 30.
2) The strength development simulation, Fig. 31
3) The change with time in the maximum temperature of concrete, Fig. 32.
4) The changes with time in the minimum temperature of concrete, Fig. 32.
5) The changes with time in the difference between maximum and minimum temperatures of concrete, Fig. 32.
6) The temperature profile, Fig. 32.

In Fig. 25, the upmost curve represents the temperature rise in the middle of the slab. In Fig. 32, the curve labeled "max" should predict the temperature change in the middle of the slab. Because the slab is much thinner than the bridge pier, both maximum and minimum temperatures in the concrete slab are affected significantly by the ambient temperature. The simulation seems insensitive to the effect of ambient temperature on the thinner sections. There are three peak temperatures observed in the field that occur at about 10, 26 and 50 hours, Figure 25. The first and third peaks are missed in the simulation. The predicted peak temperature is about 5°F higher than the second peak temperature observed in the field, both occurring at about 26 hours after pouring. However, the predicted temperatures and the observed ones have the same trend. The temperature difference is within 10°F. The maximum temperature and the minimum temperature become very close after about 72 hours. Because the slab is much thinner than the bridge pier, both its maximum and minimum concrete temperatures are more significantly affected by the ambient temperature. However, the CIMS simulation of the slab seems insensitive to the effect of ambient temperature. Specifically, the actual field data show three temperature peaks at 10, 26, and 50 hours, yet the first and third peaks are missed in the simulation.

The predicted peak temperature is about 5°F higher than the second peak temperature observed in the field, both occurring at about 26 hours after pouring. This 5°F difference indicates a fairly good ability of CIMS to predict peak temperatures.

Curing Tables

Because the graphical presentation may not be convenient for field use, curing tables have been generated. The variants include:

1) thickness: 48", 24" and 16" for bridge pier or wall (CIMS treats them as symmetrical section); 16", 12", 10", 8" and 6" for highway slab; those thicknesses were chosen as representative of common design thicknesses;
2) typical, local weather conditions: lowest temperature 30°F and highest temperature 50°F, and wind speed 10 mph which would be a "cold" pouring/curing scenario; lowest temperature 59.5°F and highest temperature 88.5°F, and wind speed 2 mph (close to the field test conditions); lowest temperature 80°F and highest temperature 100°F, and wind speed 7 mph which would be a "hot" curing/pouring scenario;
3) concrete temperatures: 100, 77 (field test temperature) and 50°F for bridge pier; 90, 66 (field test temperature), and 40 for the highway slab;
4) formwork/insulation: steel formwork for bridge pier; no insulation and 19 mm hardform for highway slab.

The total number of simulations is $3 \times 3 \times 3 = 27$ for bridge pier; and $5 \times 3 \times 3 \times 2 = 90$ for highway slab.

Tables 3–5 show the temperature and strength changes in a rectangular bridge pier or a wall. Tables 6–10 show the temperature and strength changes in highway slab with insulation. Tables 11–15 show the temperature and strength changes in the slab without insulation.

Each of these tables corresponds to one thickness, and has nine (9) combinations of weather conditions and concrete temperatures. For each combination, there are three (3) records (rows), representing three critical points observed on the simulated temperature/strength curves, such as Figures 29 and 32. These three records correspond to the earliest possible cracking predicted by the CIMS program, the largest temperature difference and the peak temperature. The first two records contain the time, the strength, the difference between the maximum and minimum temperatures. The third records contains the time, the strength, the largest temperature difference and the maximum temperature. For example, in Table 3 (48" thick bridge pier), for concrete temperature 50°F and air temperature 30°-50°F and wind speed 10 mph, the earliest possible cracking occurs at 38 hours after placement according to CIMS prediction, when the strength has reached 0.9 ksi, the maximum temperature difference in concrete is 36°F. At 45 hours after placement, the maximum temperature difference becomes 57°F and the strength 1.3 ksi. At 48 hours, the temperature reaches the peak, 98°F, the largest temperature difference is 53°F, and the strength reaches 1.4 ksi.

Knowing both the strength gain and the largest temperature difference in concrete, and the concrete formulation, one should be able to predict the possibility of thermal cracking. Also, knowing what the highest or lowest temperature is and when it occurs, one should be able to predict the possibility of permanent strength loss due to high temperature or freezing due to low temperature.

If the largest temperature difference greater than 36°F (20°C) and the strength gain less than 1.0 ksi would cause thermal cracking, and the peak temperature higher than 140°F (60°C) occurring before about 12 hours would cause permanent strength loss, we can produce simplified curing tables as shown in Tables 16–18, predicting the suitability of the concrete placement and formulation. TG stands for "risk of too large a Thermal Gradient" and HT for "risk of too High internal Temperature."

Table 16 is for a rectangular bridge pier or wall with thickness 48", 24" and 16", and nine (9) combinations of weather conditions and concrete temperatures. It shows that too large a difference between air and the concrete placement temperature, or too high air temperature will cause either too large temperature gradient in concrete, or too high internal temperature in concrete.

Table 17 is for pavement slab with insulation, and with thickness 16", 12", 10", 8" and 6". Table 18 is for pavement slab without insulation, and with thickness 16", 12", 10", 8" and 6". It clearly shows that insulation can avoid much possible thermal cracking and/or permanent strength loss.

Obviously, if one changes the criteria for thermal cracking and permanent strength loss, one will have different simplified curing tables from Tables 16–18. Usually, both the strength gain and the temperature difference in concrete should be taken into account in order to predict the possibility of thermal cracking, and both the highest temperature in concrete and when it occurs should be considered in order to predict the possibility of permanent strength loss. However, for initial estimation, one may also simply assume that if the temperature difference exceeds 36°F (20°C), the internal thermal stress will cause thermal cracking; and that if the temperature exceeds 140°F (60°C), the concrete will suffer permanent strength loss. If these assumptions that are solely based on the temperature or temperature difference in concrete are acceptable, simplified curing tables can be generated for pavement slabs, such as those provided here as Tables 19-36. These tables also include possible Early Freezing (represented by EF), which is assumed to occur if the concrete temperature falls below freezing point and the strength is below .725 ksi.

Tables 19–36 include variants as follows:

1) cement type: Type I, III and V;
2) cement content: 555, 575, 600, 620, 650 and 675 lb/yd^3;
3) concrete temperature: 50°, 60°, 70°, 80°, 90° and 100°F;
4) air temperature (daily average): 0°, 20°, 40°, 60°, 80° and 100°F;
5) slab thickness: 8, 12, 16 and 20";
6) base temperature: 32°F if the air temperature is below 40°F, and 8°F lower than the air temperature if the air temperature is above 40°F;
7) insulation: straw if the air temperature is below 32°F, and burlap if the air temperature is above 32°F.

The wind speed is assumed to be 14 mph. The six cement contents correspond to six concrete mixes. The formulations of these six mixes are shown in Table 37. The total number of simulations is $3 \times 6 \times 6 \times 6 \;\; 4 = 2592$.

From these tables, it can be seen that when the sulfate resistant cement is used, no curing problem will occur with concrete temperatures in the interval of 50°-80°F and the air temperatures between freezing point and 100°F. For concrete temperatures in the range 90°-100°F, the temperature difference in concrete may be too large, and the peak temperature may be too high. Placing this concrete mix when the air temperature is around 0°F will cause problem with early freezing and/or large temperature difference. For concrete mixtures with ordinary Portland cement, the problem free curing conditions are similar. However, the risks of temperature difference and high temperatures are slightly more frequent with increasing cement content and concrete temperatures in the range of 80° and 100°F.

As expected, the safe temperature intervals for the concrete mixture using rapid hardening cement are smaller. For mixtures with up to 620 lbs cement per cubic yard, concrete temperatures between 40° and 80°F and air temperatures in the interval 40°-100°F will cause no problems (except for a few cases for the 20 inch thick pavement). For cement content greater than 620 lbs/yd^3 and higher temperatures of concrete, higher temperatures and greater temperature differences will develop in the concrete.

It needs to be pointed out again that the prediction of potential thermal problems by these curing tables is based only on concrete temperatures, and no other factor is considered, such as strength gain. However, the initial prediction of this kind is usually pessimistic, which means safer in practice. If more accurate prediction is needed, other factors such as the strength gain must be taken into account.

Potential Applications of Curing Tables

If the prediction shows an undesirable curing regime under the given climatic conditions, precaution or preventions can be taken in order to achieve a satisfactory curing regime. For example, a large temperature difference in concrete can be reduced by:

1) reducing the temperature of the concrete before placement;
2) rapid insulation of the concrete slab immediately after placement and finishing;
3) reducing the cement content;
4) choosing a cement with a lower heat of hydration;
5) raising the temperature of the surrounding (heat vented tents).

Early freezing damages can be avoided by:

1) insulation of the concrete slab immediately after casting and finishing;
2) increasing the temperature of the concrete slab before placement;
3) raising the cement content;

4) choosing a cement with a higher heat of hydration;
5) raising the temperature of the surroundings (e.g., heat-vented tents).

Too high temperatures in the concrete slab can be reduced by:

1) cooling of the concrete before placement;
2) reducing the temperature of the surroundings (e.g., shading);
3) reducing the cement content;
4) choosing a cement with a lower heat of hydration.

Summary

This study has found that the maturity/curing model can serve as a tool for predicting possible damage to concrete due to adverse thermal conditions in concrete. This model can be employed in designing and fabricating high quality concrete. An important parameter included in the maturity/curing model is the activation energy for cement hydration. ASTM C1074-87 describes a method for determining the activation energy to be used to calculate maturity. Since this method requires long-term strength data to determine the activation energy. A new method, based on the kinetic models of cement hydration, has been proposed to determine the activation energy. This method needs only short-term measurement of the heat generated during hydration using isothermal calorimetry.

Two field studies have been conducted to evaluate a commercial software for maturity calculations. Although the results are still considered preliminary, they have shown that the predicted temperatures in the concrete exhibit basically the same trend observed in the field. It appears that by knowing both strength gain and the temperatures in concrete, one can predict the possibility of thermal cracking, the possibility of permanent strength loss, and early freezing in concrete. If the predictions can show accurately all possible damages, precautions can then be taken to achieve a satisfactory curing domain. More work can be done to include different geometries of concrete elements, to predict the heat and strength development more accurately, and to improve the sensitivity if the simulation to the effect of ambient temperature.

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9. P.W. Brown, J. Pommersheim and G. Frohnsdorff, "A Kinetic Model for the Hydration of Tricalcium Silicate," Cem. Concr. Res. 15, 35-41 (1985).

Appendix A—Figures

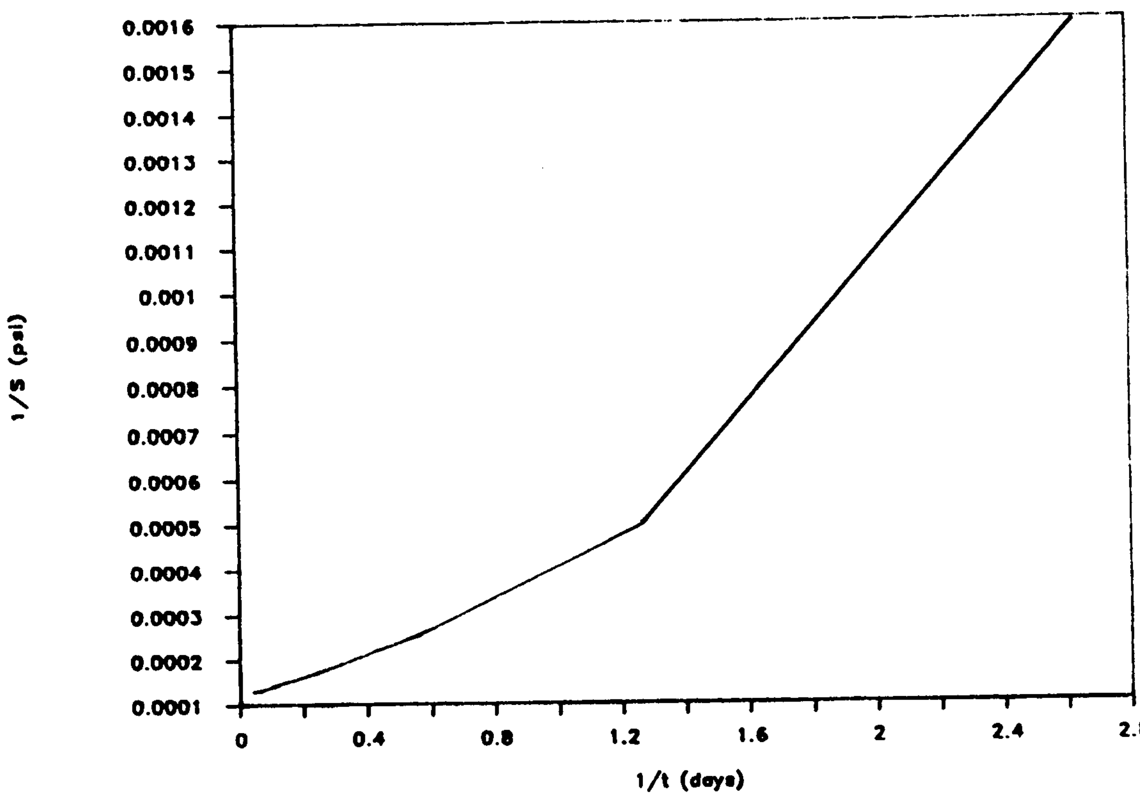

Figure 1. Plot of reciprocal of strength vs. reciprocal of time.

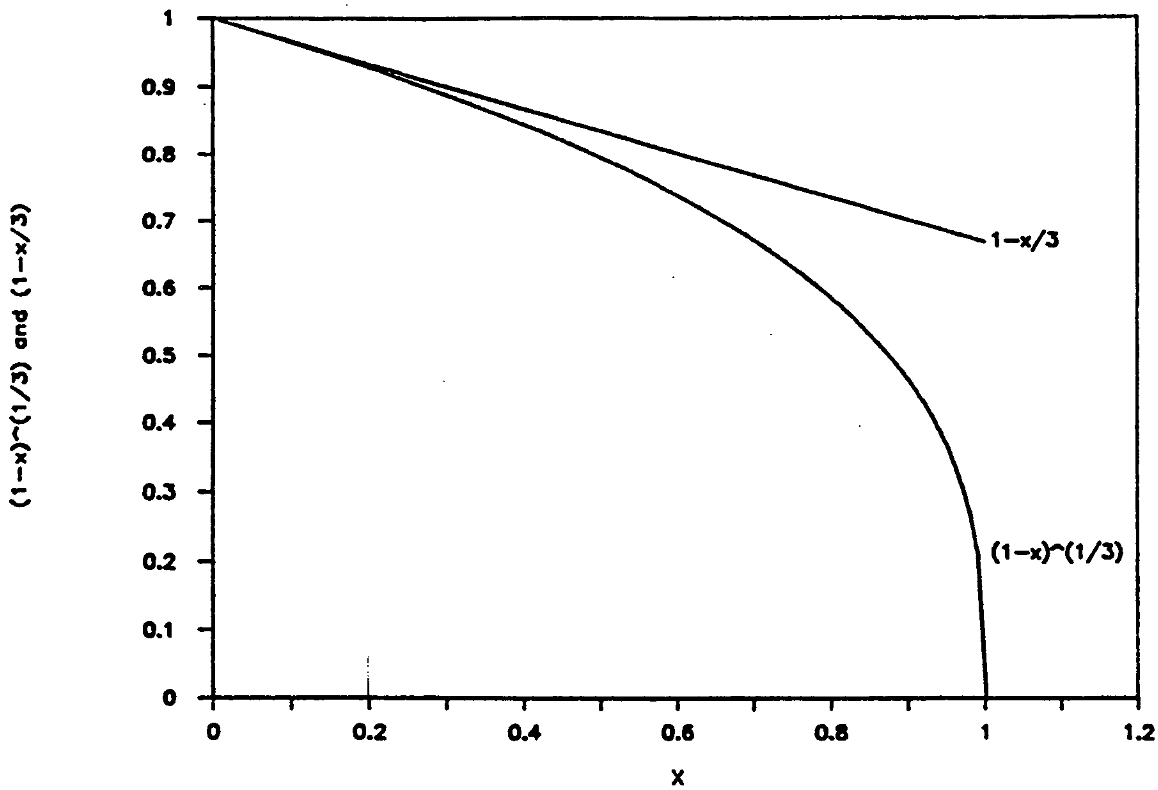

Figure 2. Comparison between $(1 - x)^{1/3}$ and $1 - x/3$.

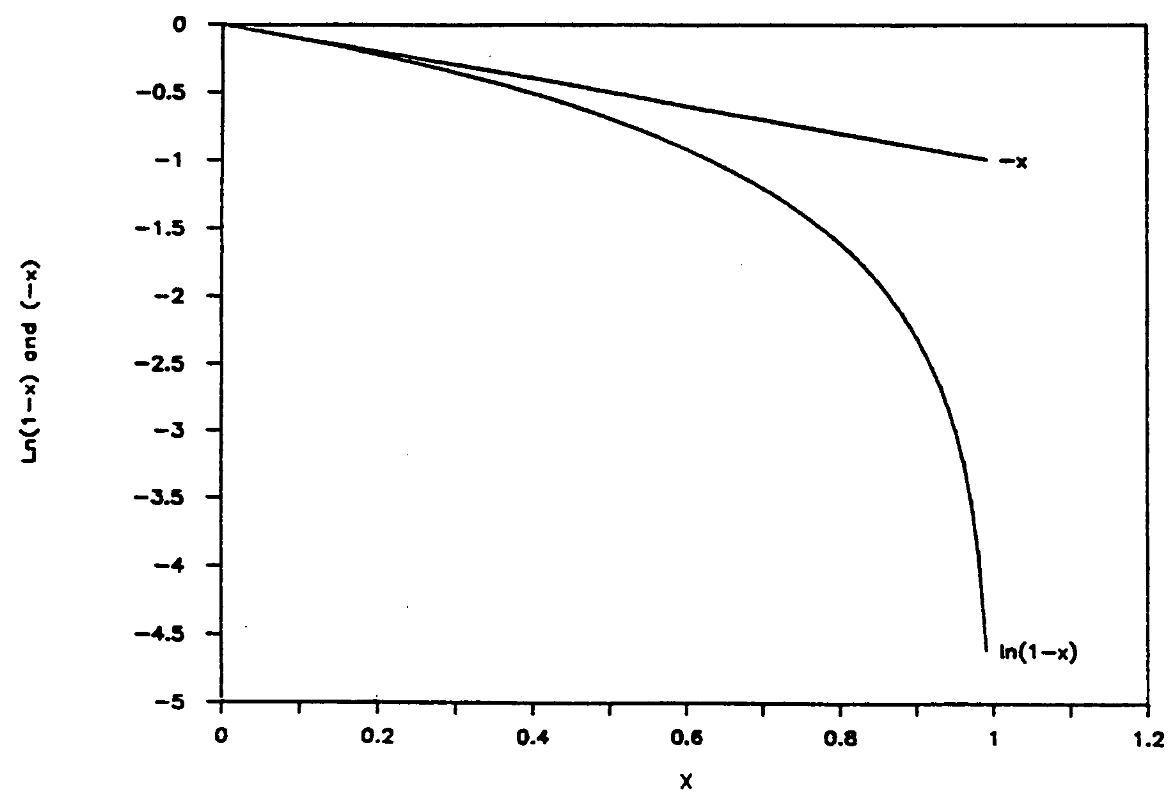

Figure 3. Comparison between $\ln(1 - x)$ and $-x$.

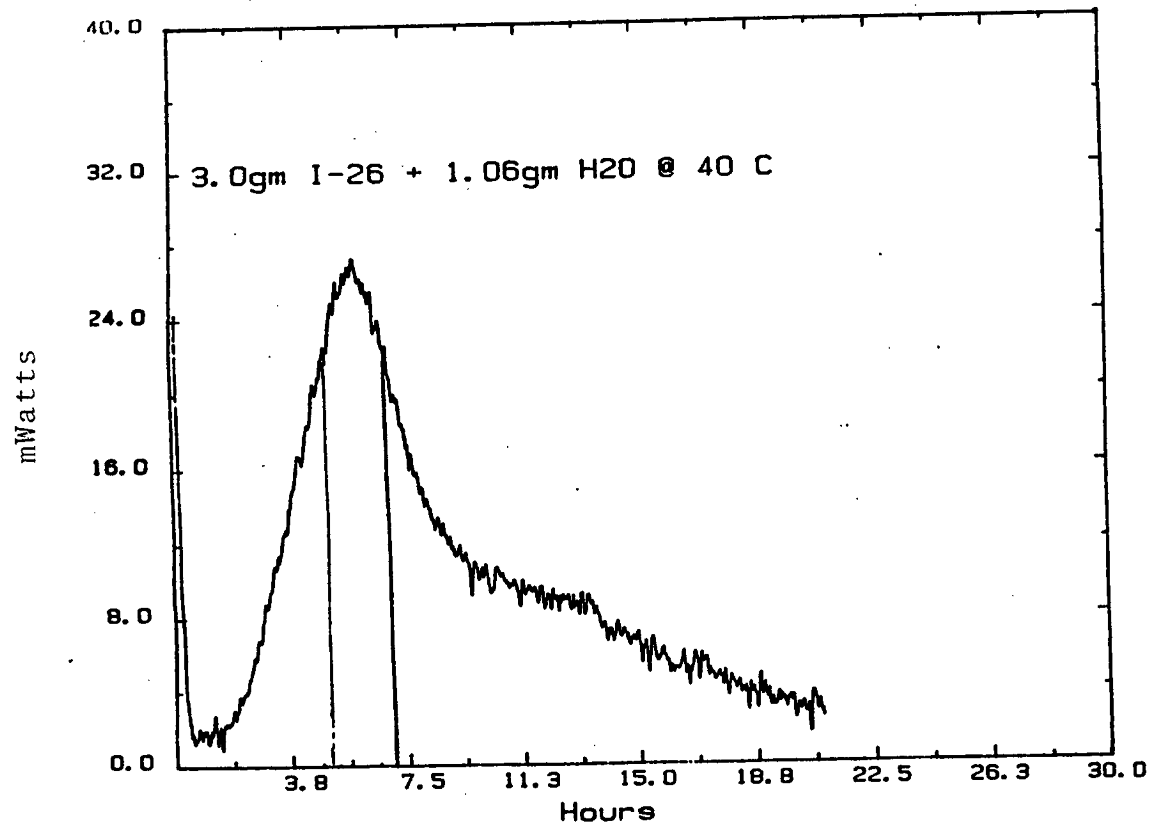

Figure 4. Typical isothermal calorimetry measurement, rate of heat generated vs. time.

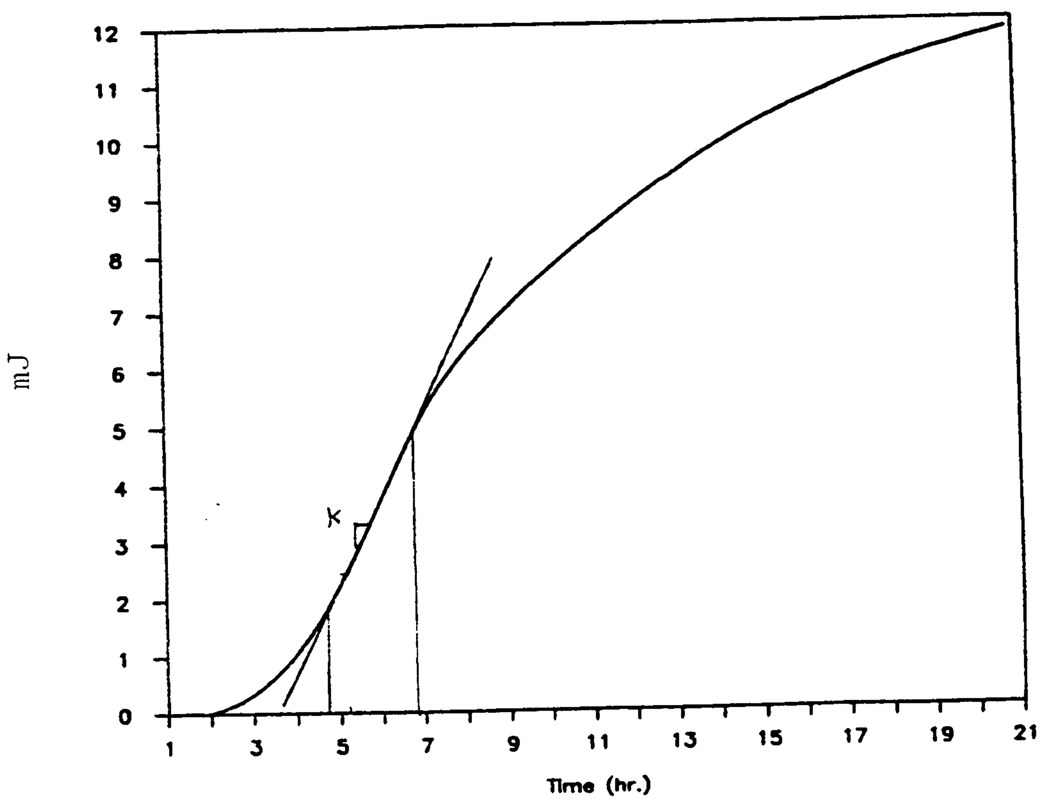

Figure 5. The integral curve from Figure 4, heat vs. time.

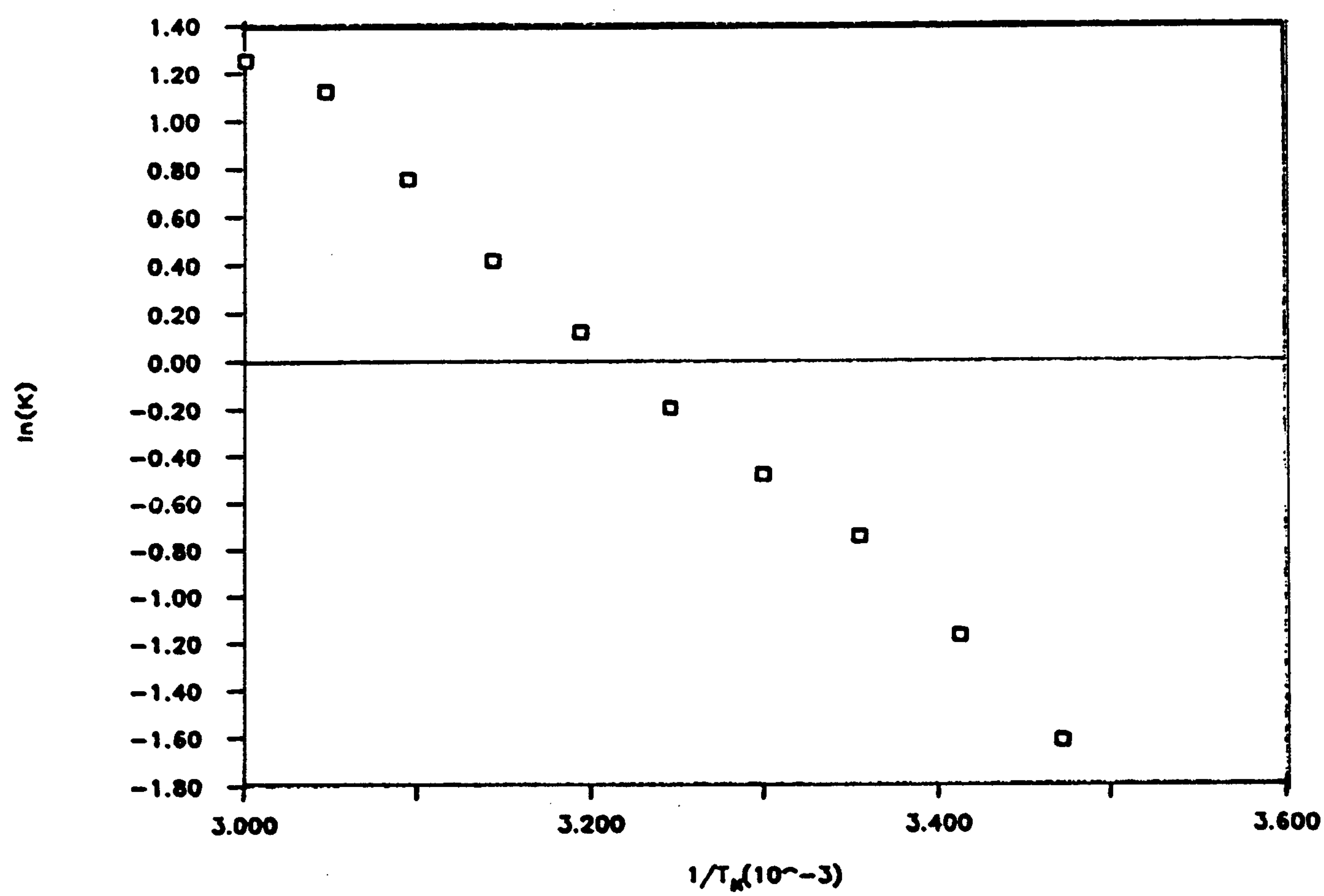

Figure 6. Plot of 1n(k) vs. $1/T_k$.

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HEAT DEVELOPMENT
Documentation sheet

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Name:

Number:
Date: 10-03-90

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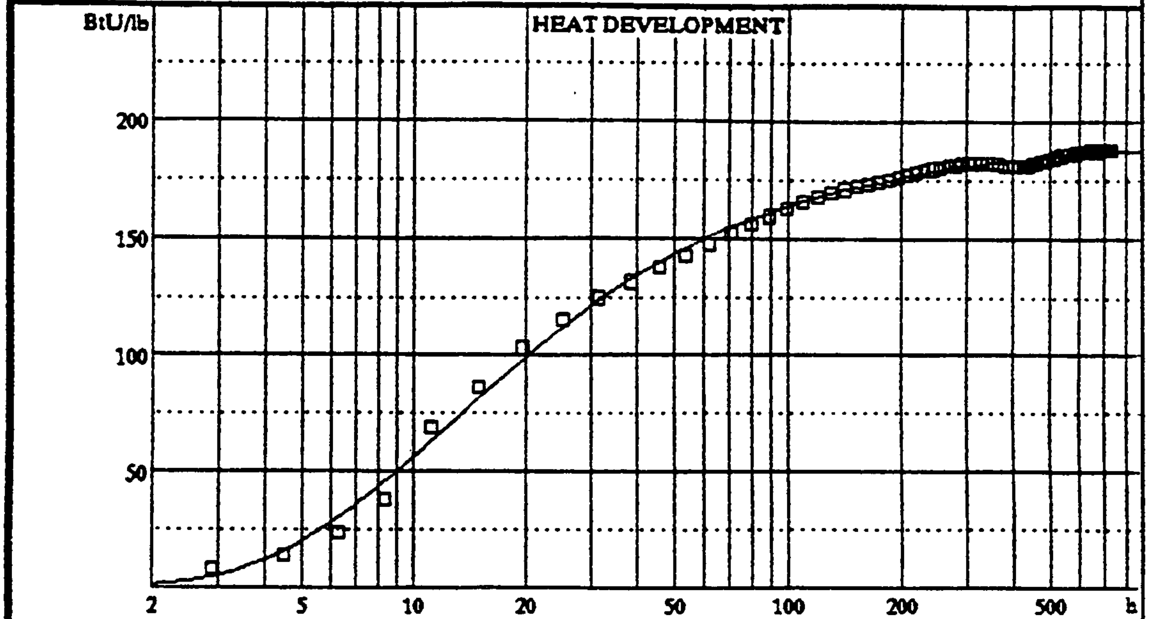
Job file: BRIDGE



DATAFILE: BRIDGE.HDV
CONCRETE: BRIDGE

Cement only

Specific heat: 0.255 BtU/lb/dF

LINEAR MODEL
Qo=62.72 BtU/lb To=4.07 h

EXPONENTIAL MODEL
Qinf=191.72 BtU/lb Te=12.53 h Alpha=0.89

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1197.0	0.273	
	LIMESTONE	168.6	1813.3	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	81.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
lb/ft3	lb/ft3	lb/lb	%
146.5	142.4	0.46	6.4

COMMENTS:

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Figure 7. Illustration of heat development curve, with the activation energy = 33.5 KJ/mol.

MATERIALS RESEARCH LABORATO	HEAT DEVELOPMENT
PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	Documentation sheet

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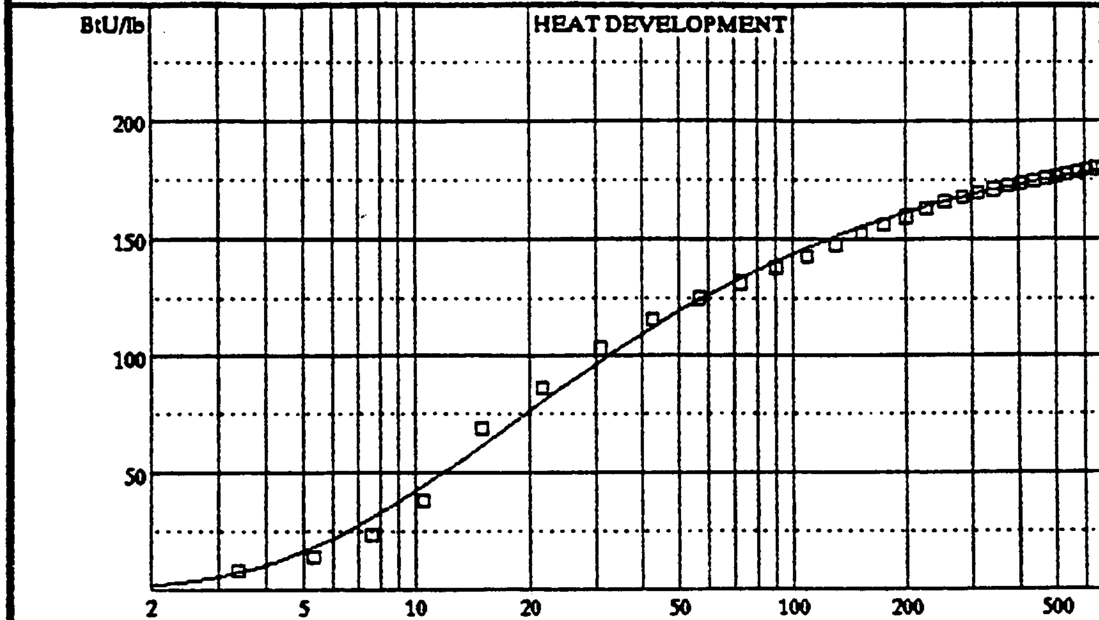

DATAFILE: BRIDGE.HDV

CONCRETE: BRIDGE   Cement only   Specific heat: 0.255 BtU/lb/dF

LINEAR MODEL
Qo=50.34 BtU/lb To=4.38 h

EXPONENTIAL MODEL
Qinf=193.25 BtU/lb Te=18.00 h Alpha=0.71

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1196.9	0.273	
	LIMESTONE	168.6	1813.2	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	79.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
lb/ft3	lb/ft3	lb/lb	%
146.5	142.4	0.46	6.4

COMMENTS:

User-defined maturity

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Figure 8. Illustration of heat development curve, with the activation energy = 48 KJ/mol.

MATERIALS RESEARCH LABORATO PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	STRENGTH DEVELOPMENT Documentation sheet

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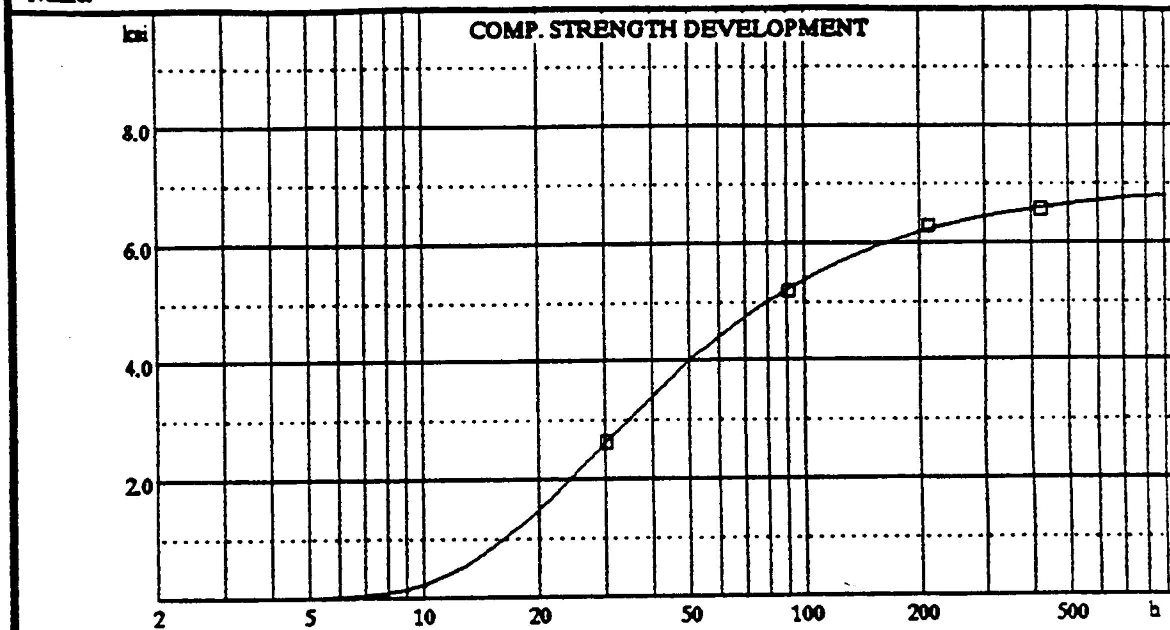
Name:
Number:
Date: 10-03-90
Initials: DS
Job file: BRIDGE



DATAFILE: BRIDGE.SDV
CONCRETE: BRIDGE

LINEAR MODEL
So=2.86 ksi To=12.1 h

EXPONENTIAL MODEL
Sinf=6.94 ksi Te=29.5 h Alpha=1.12

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1197.0	0.273	
	LIMESTONE	168.6	1813.3	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	81.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
lb/ft3	lb/ft3	lb/lb	%
146.5	142.4	0.46	6.4

COMMENTS:

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Figure 9. Illustration of strength development curve, with the activation energy = 33.5 KJ/mol.

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STRENGTH DEVELOPMENT
Documentation sheet

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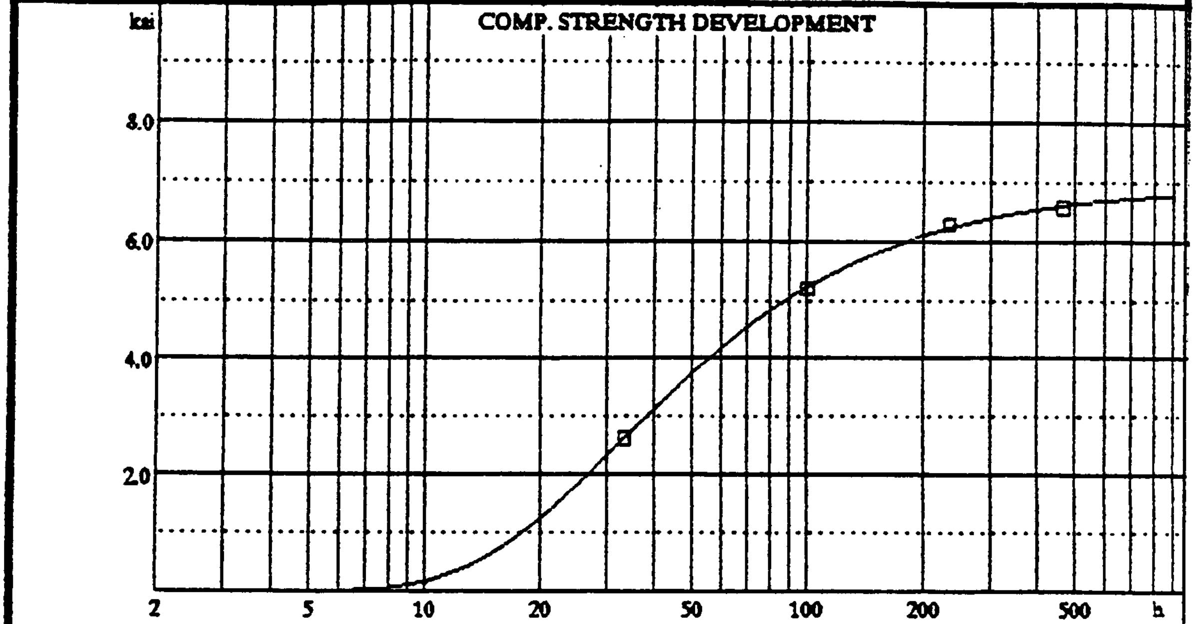
Name:	Date: 10-03-90	Job file: BRIDGE



DATAFILE: BRIDGE1.SDV
CONCRETE: BRIDGE

LINEAR MODEL	EXPONENTIAL MODEL
So=2.86 ksi To=13.3 h	Sinf=6.94 ksi Te=32.6 h Alpha=1.12

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1197.0	0.273	
	LIMESTONE	168.6	1813.3	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	81.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
lb/ft3	lb/ft3	lb/lb	%
146.5	142.4	0.46	6.4

COMMENTS:

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Figure 10. Illustration of strength development curve, with the activation energy = 48 KJ/mol.

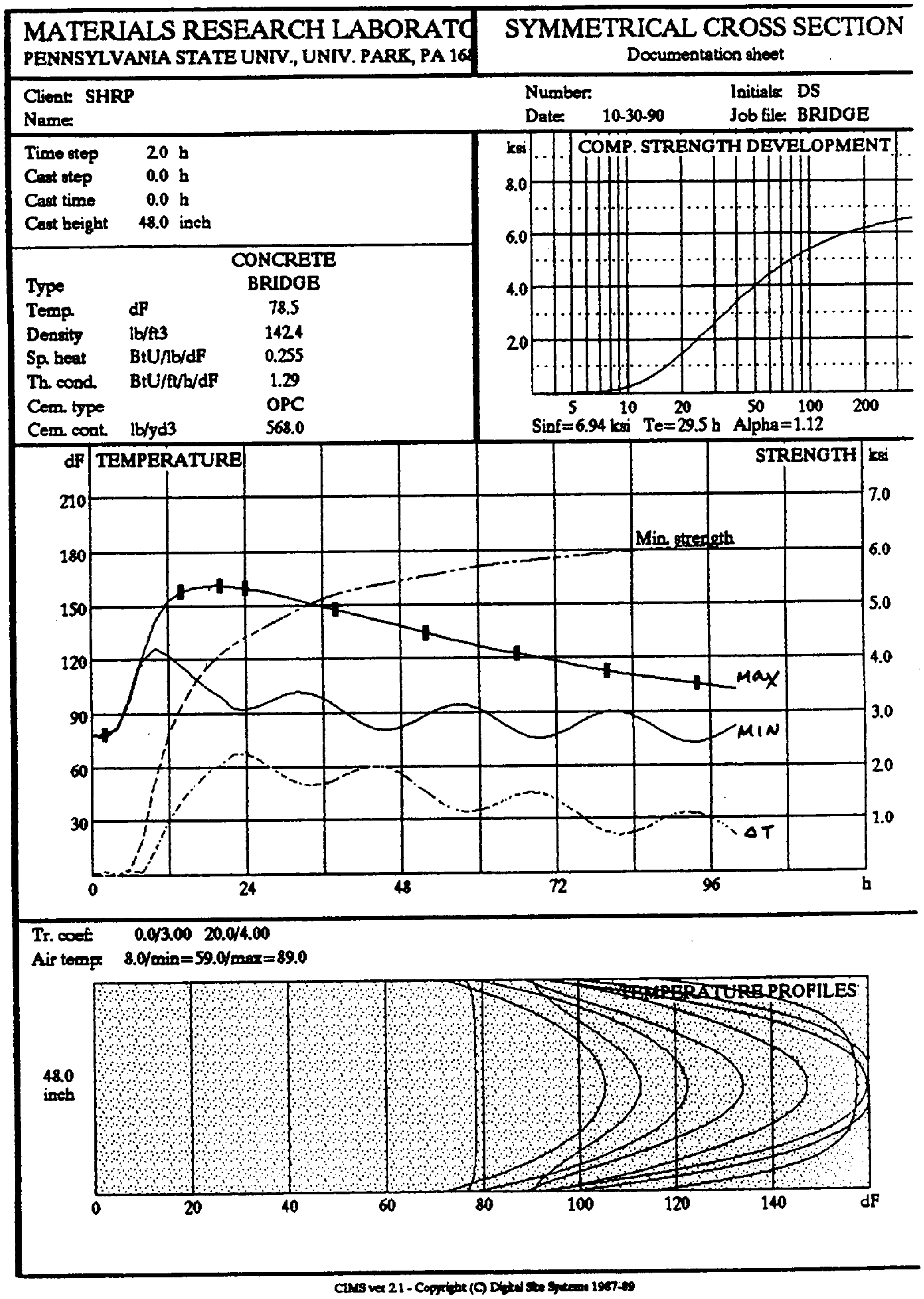


Figure 11. The changes in maximum temperature, minimum temperatures, strength and the difference between maximum and minimum temperature in bridge pier concrete with time up to 96 hours predicted by the curing technology computer program.

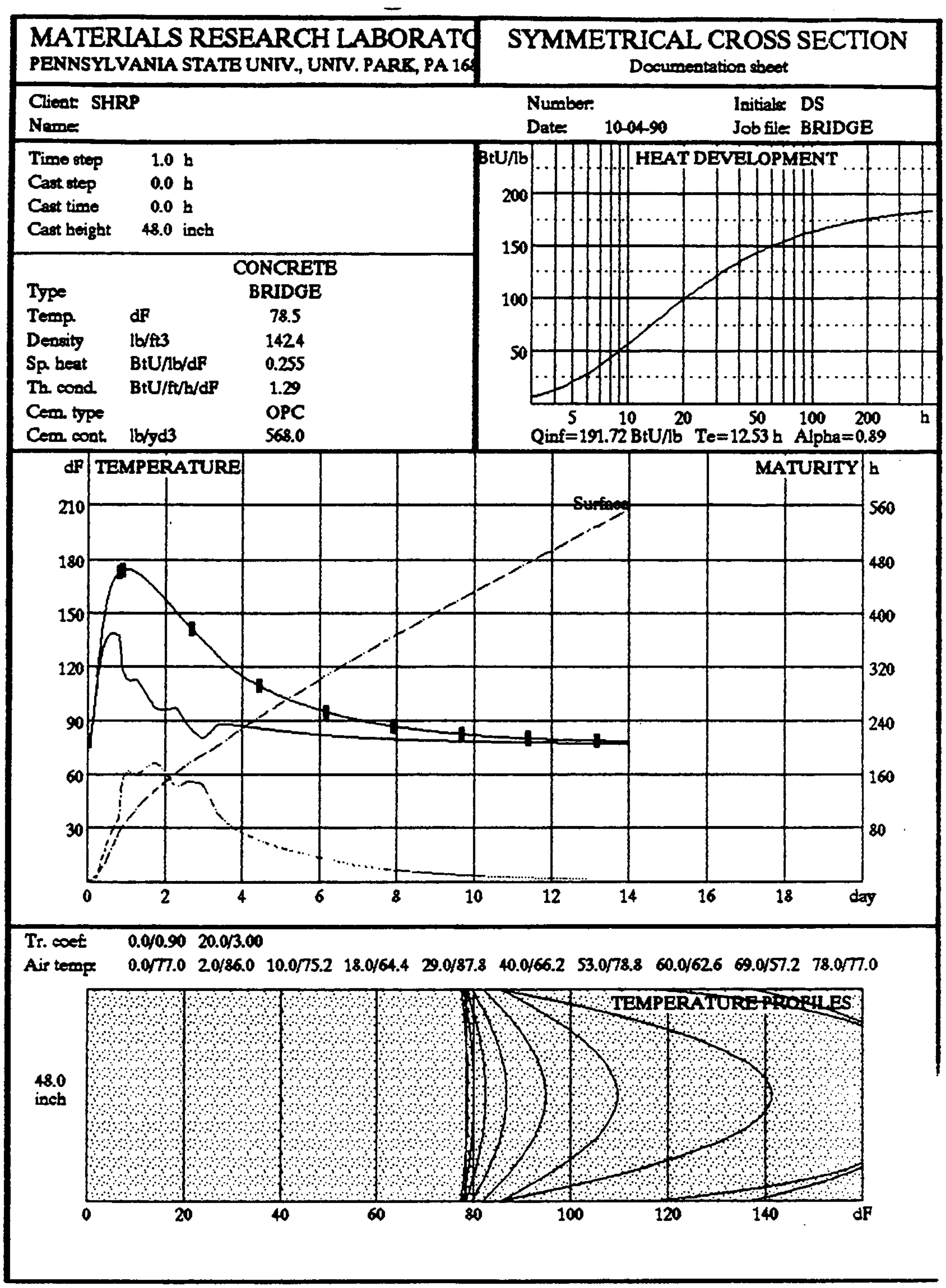
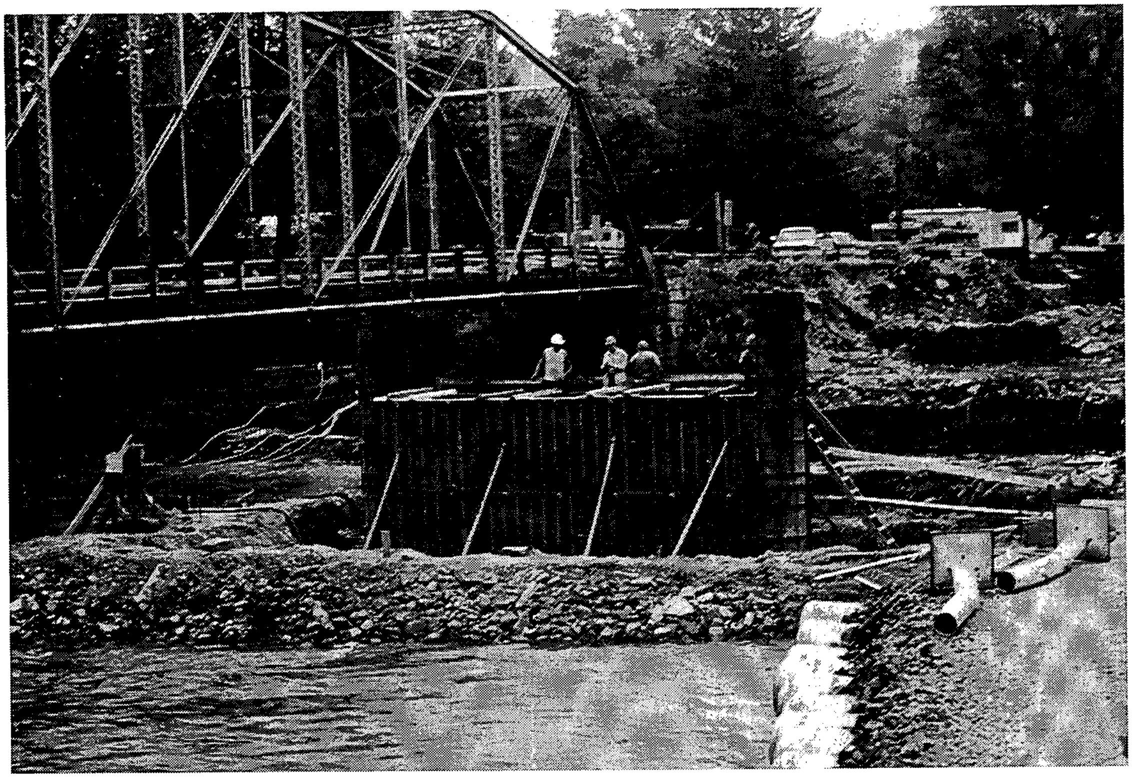


Figure 12. The changes in maximum temperature, minimum temperature, strength and the difference between maximum and minimum temperature in bridge pier concrete with time up to 14 days predicted by the computer program.

(a)



(b)

Figure 13. (a) and (b). Overview of the bridge location looking east to west and west to east, respectively.

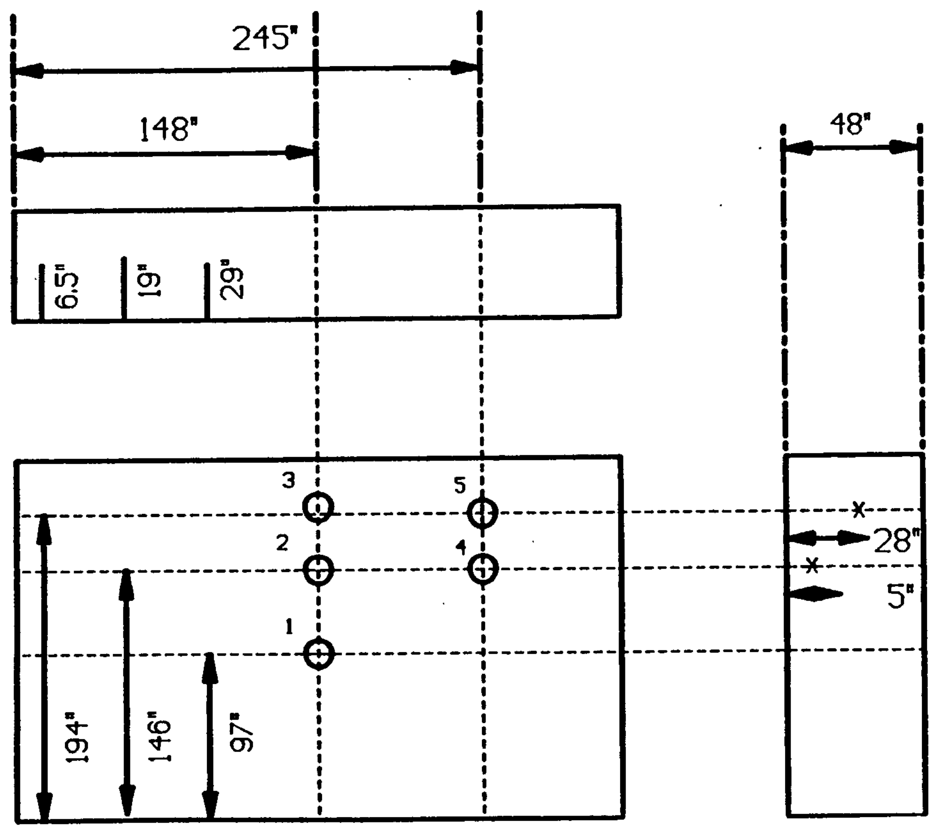


Figure 14. Locations of thermocouples in the bridge pier.

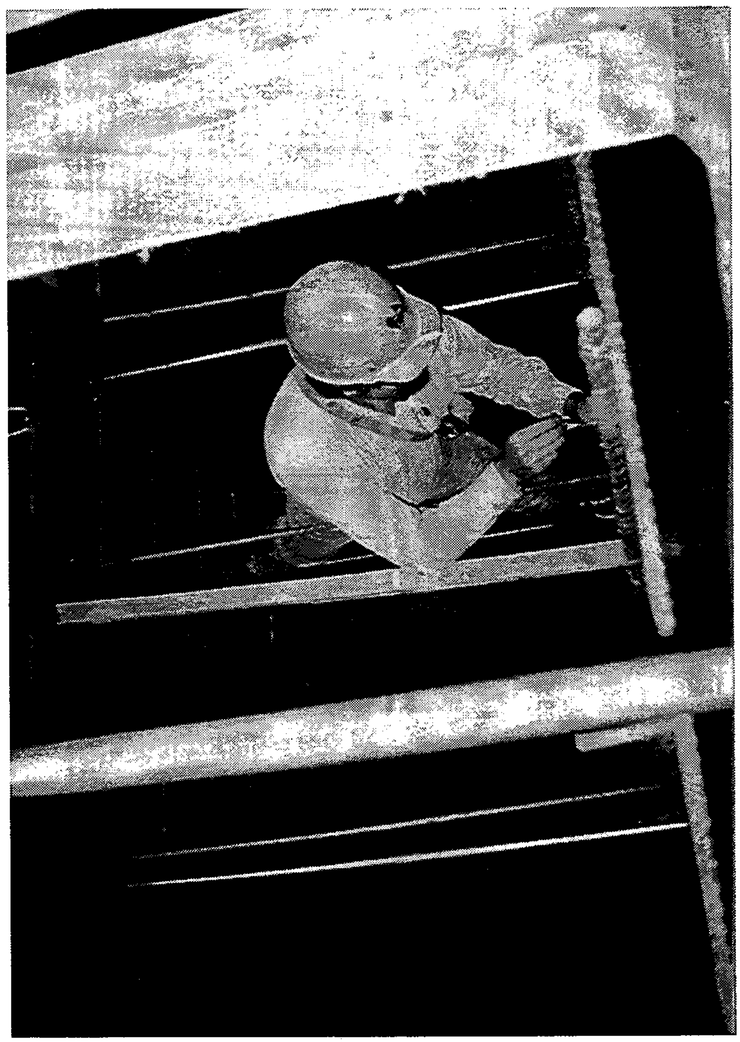


Figure 15. Installation of the thermocouples.

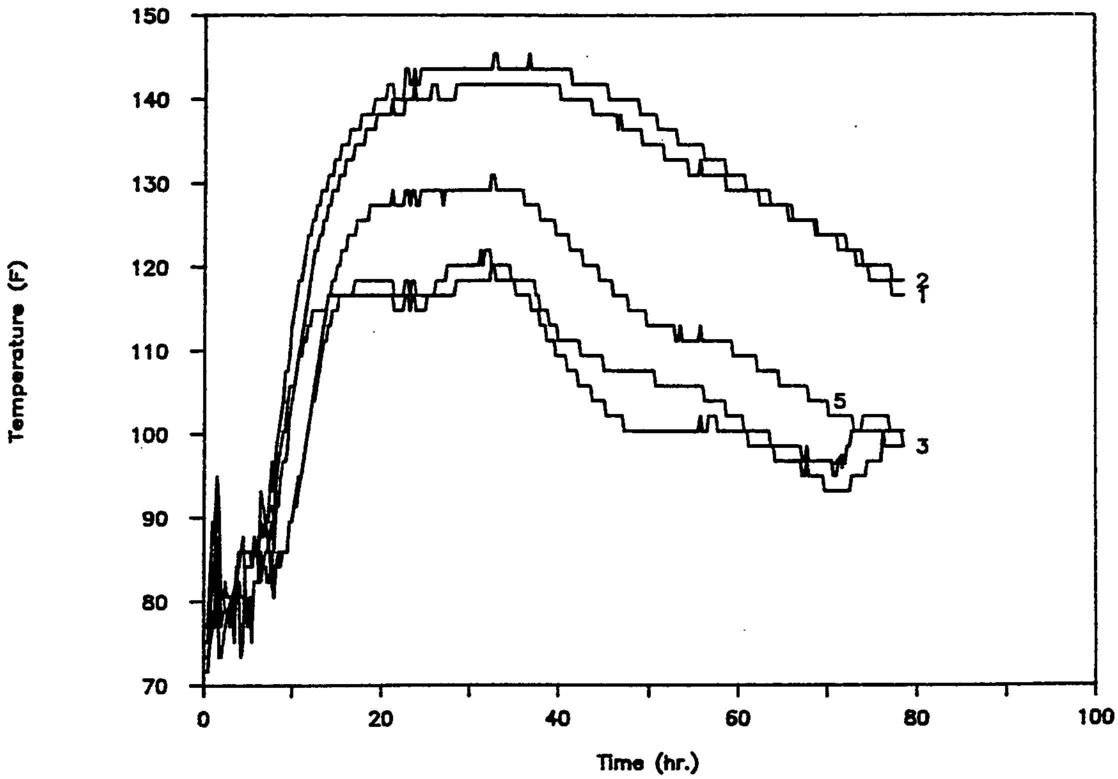


Figure 16. Temperatures from thermal couples 1-5 in bridge pier.

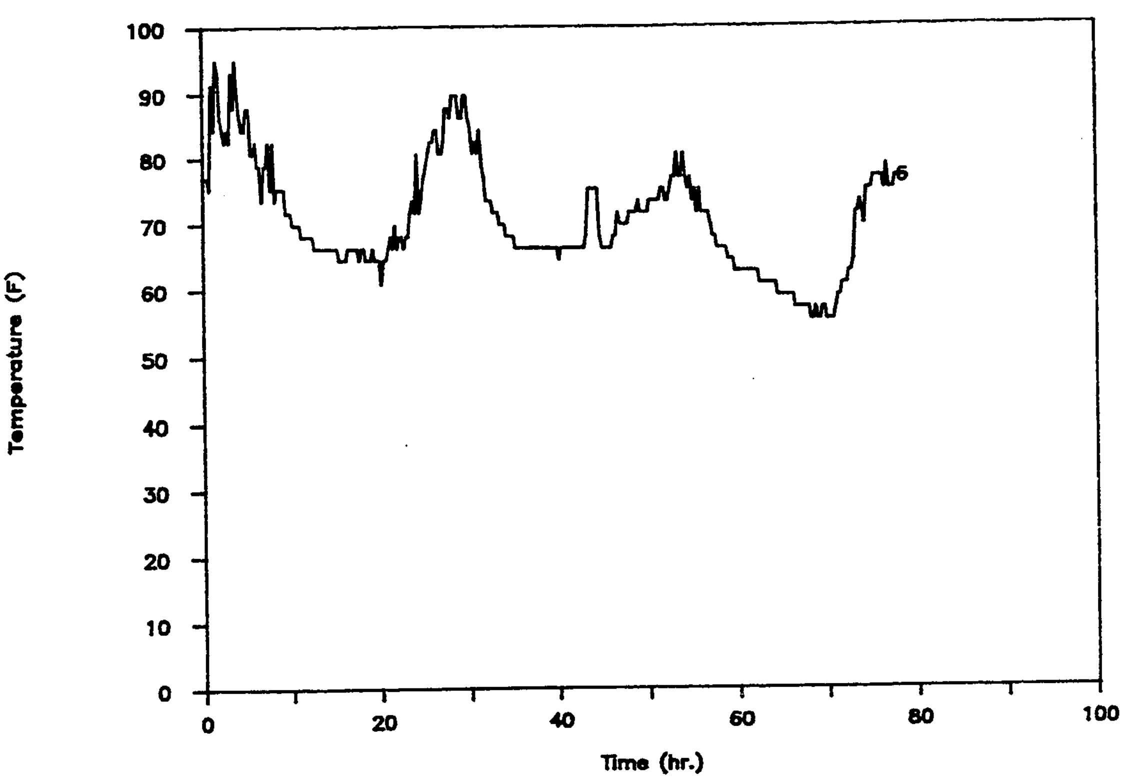


Figure 17. Ambient temperature (from thermal couple 6).

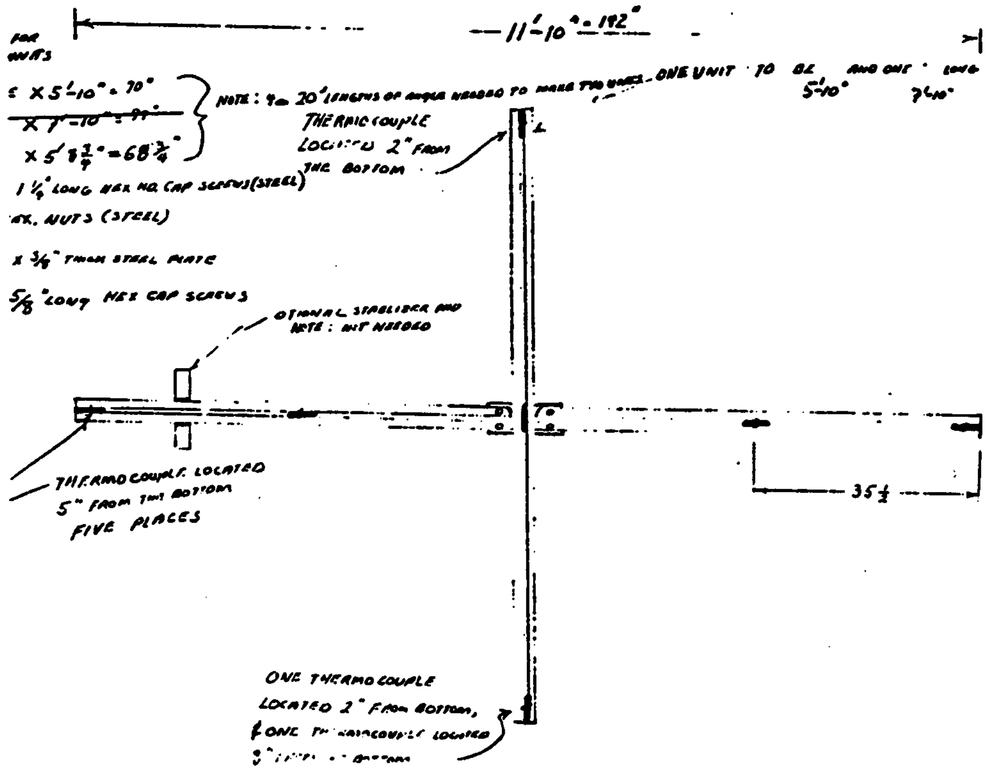


Figure 18. Shop drawing of thermocouple rack (for pavement slabs).

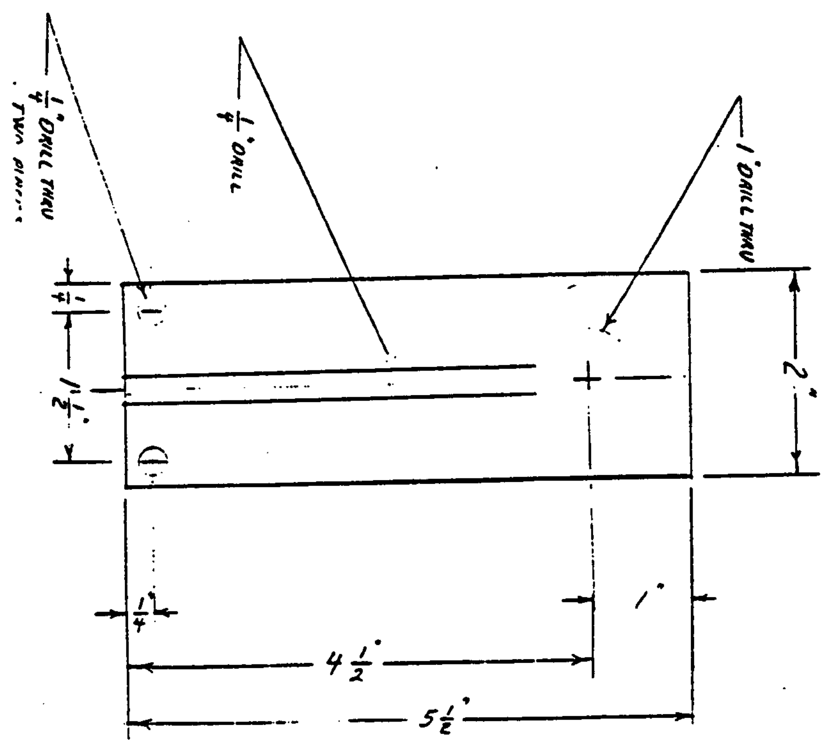


Figure 19. Shop drawing of high density polypropylene single thermocouple support.

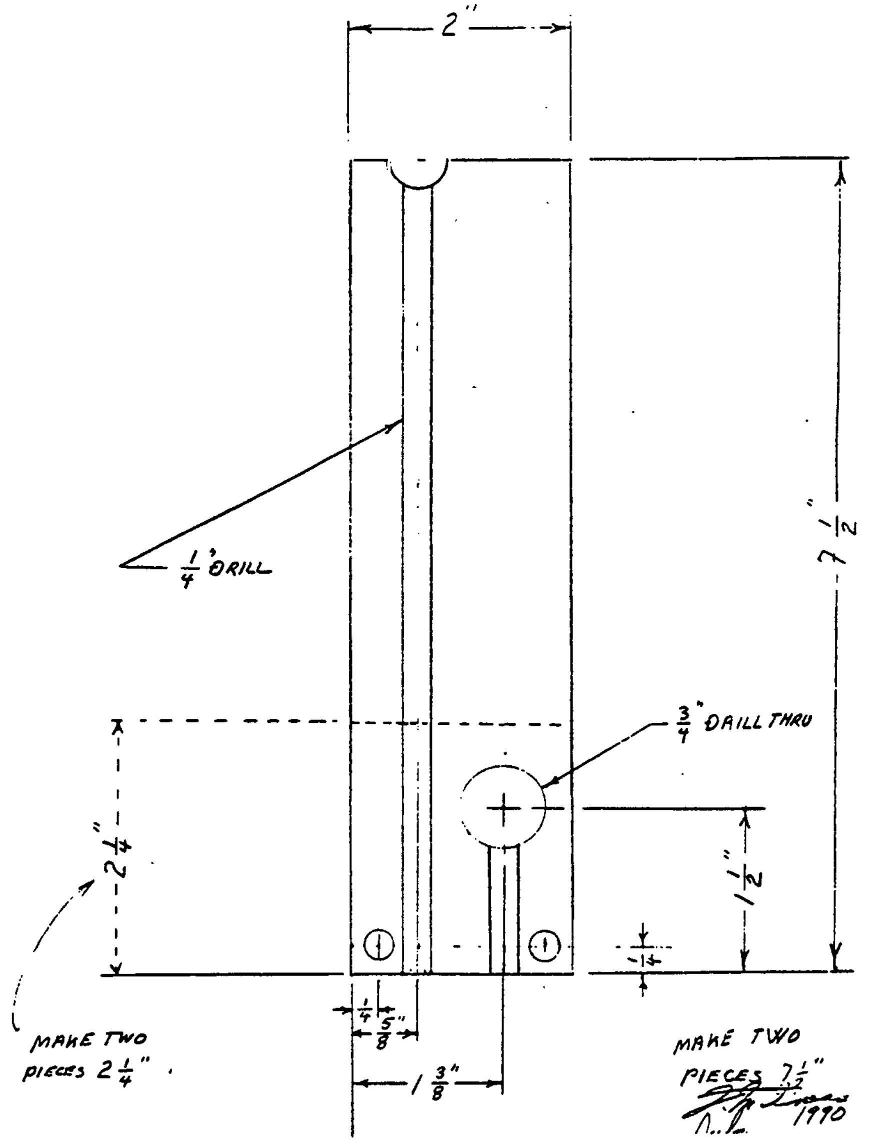


Figure 20. Shop drawing of high density polypropylene dual thermocouple support.

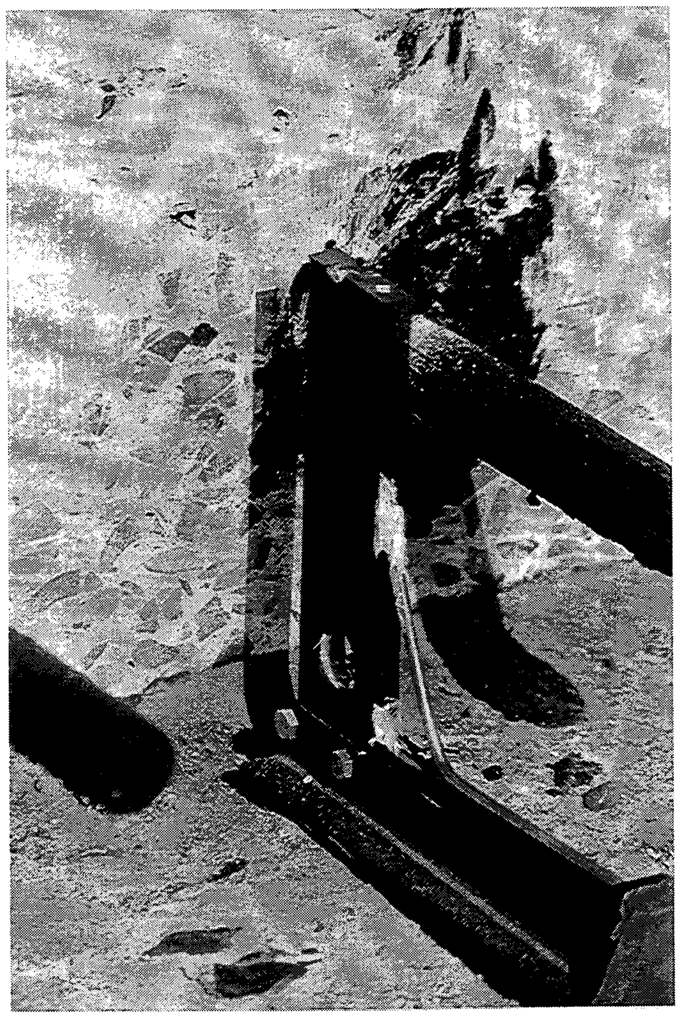


Figure 21. Close-up of sensor mounting as placed in patch slab.

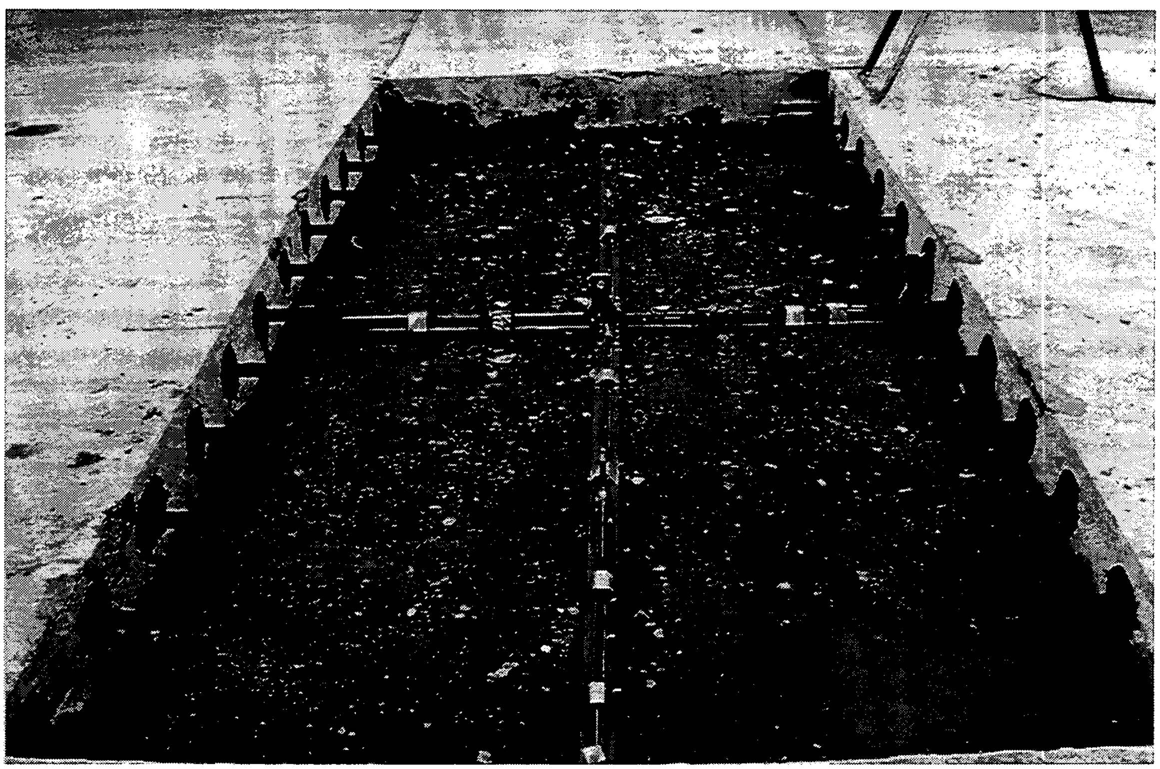


Figure 22. Thermocouple array as placed in patch slab.

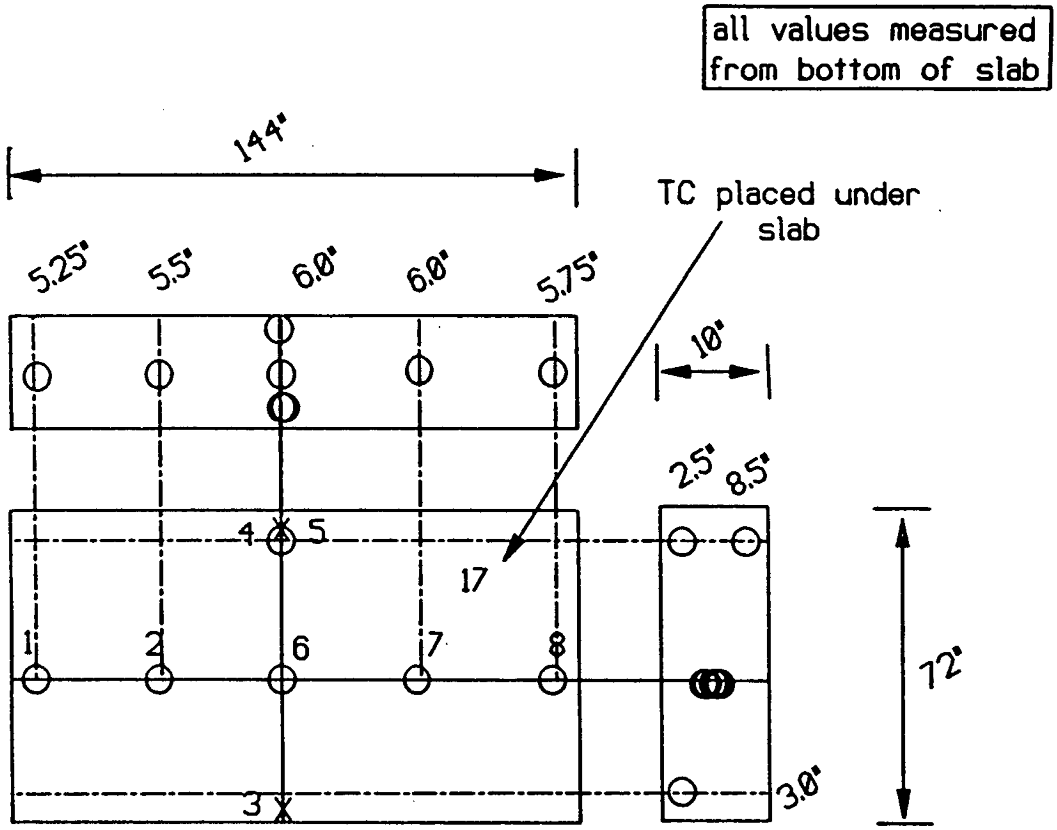


Figure 23. Exact location of thermocouples in "up hill" slab (all values in 10" section recorded from bottom of slab).

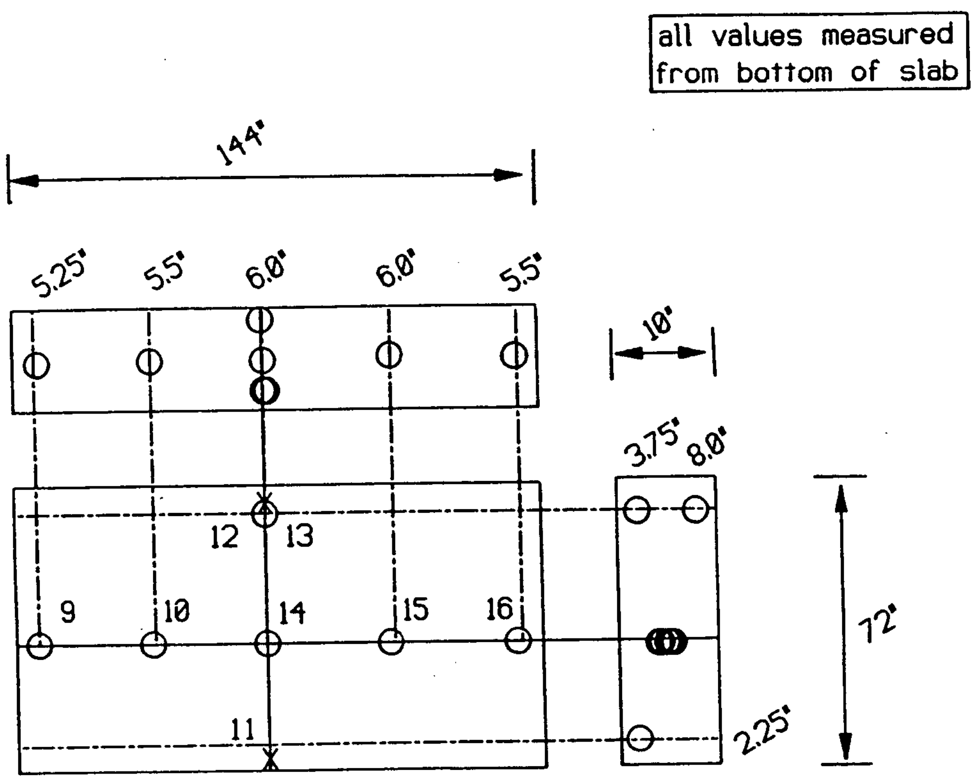
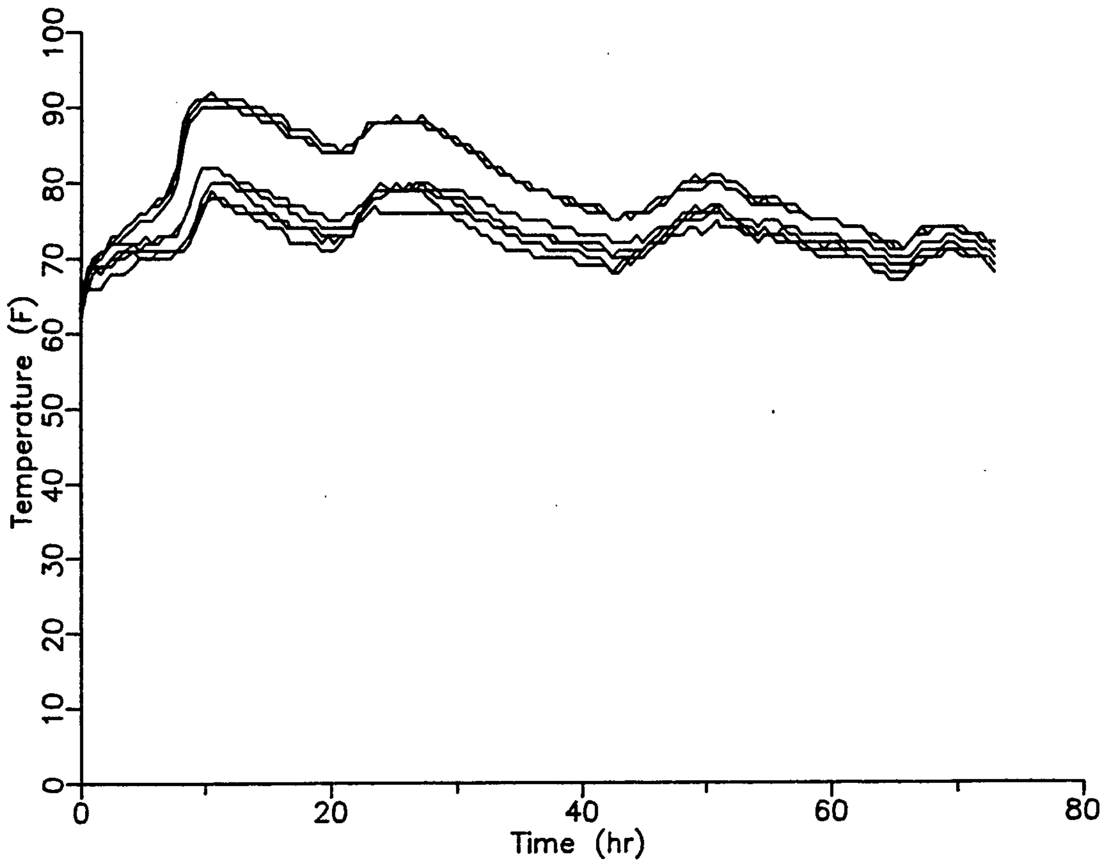


Figure 24. Exact location of thermocouples in "down hill" slab (all values in 10" section recorded from bottom of slab).

(a)



(b)

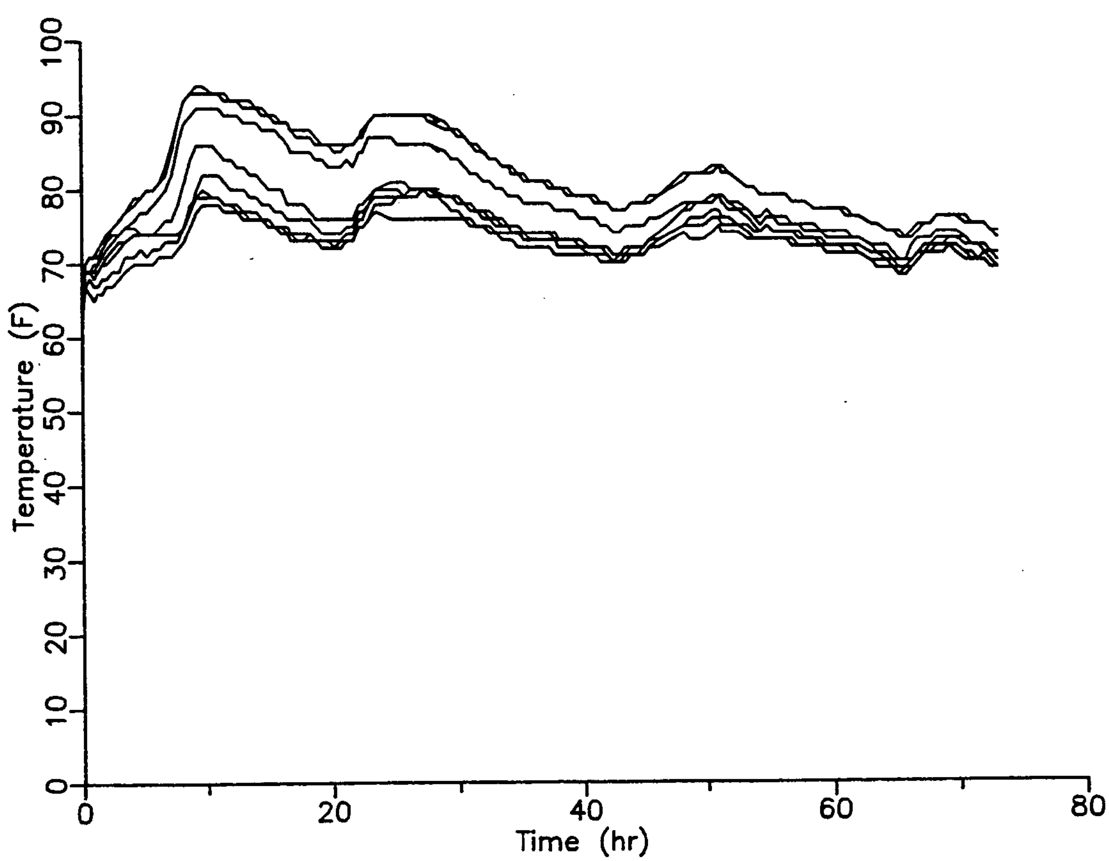


Figure 25. (a) Temperatures from thermocouples 1-8 "up hill" pavement slab; (b) temperatures from thermocouples 9-16 in "down hill" pavement slab.

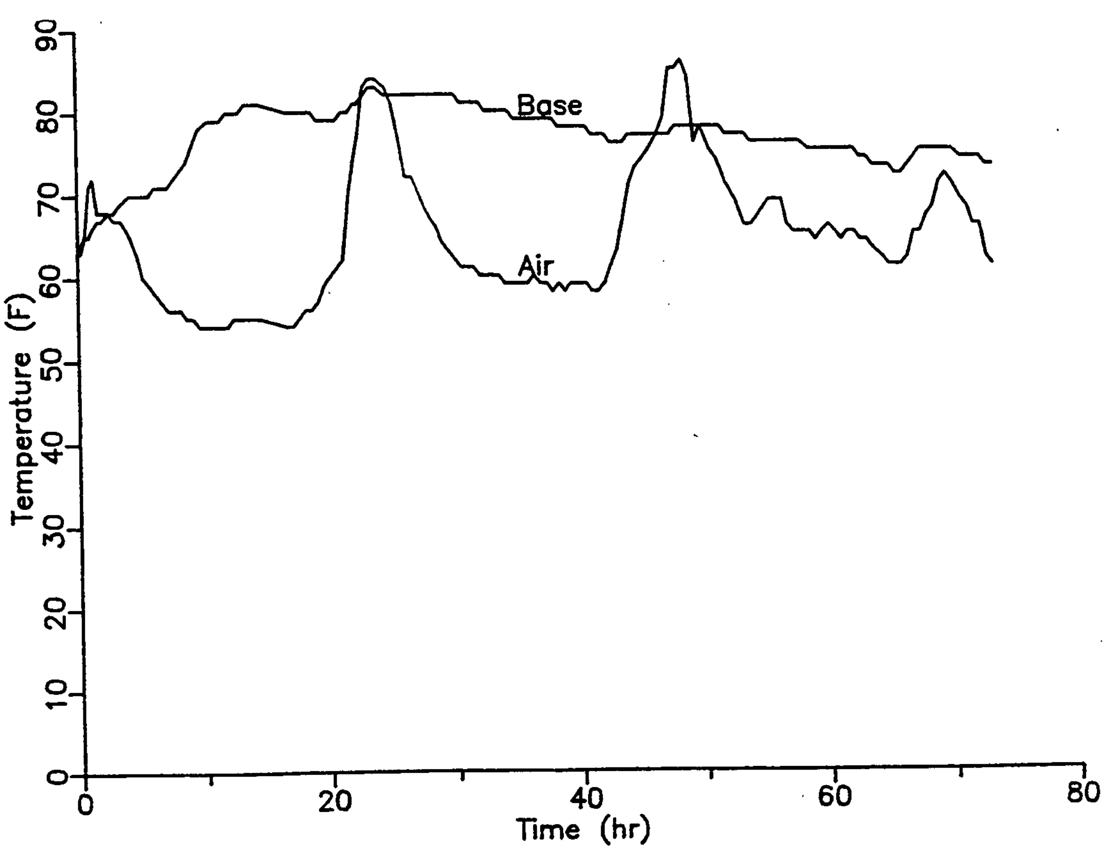
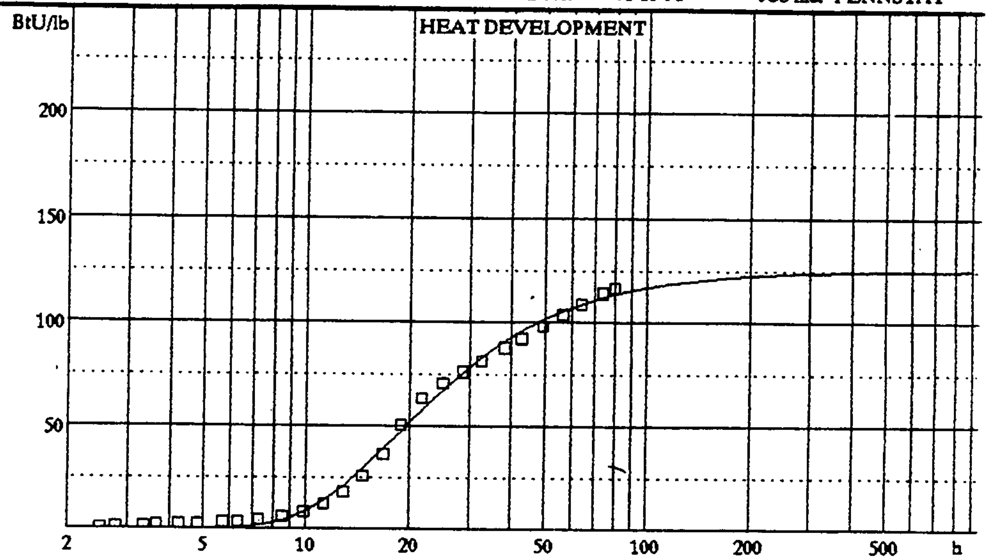


Figure 26. Base temperature and air temperature (slab).

MATERIALS RESEARCH LABORATO PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	HEAT DEVELOPMENT Documentation sheet

Client: PENN STATE UNIV. Number: SHRP TESTS Initials: DS
Name: MRL DEX SHI Date: 01-15-91 Job file: PENNSTAT



DATAFILE: PENN1218.LOG
CONCRETE: BRIDGE Cement only Specific heat: 0.255 BtU/lb/dF

LINEAR MODEL
Qo=72.70 BtU/lb To=9.86 h

EXPONENTIAL MODEL
Qinf=125.33 BtU/lb Te=18.59 h Alpha=1.58

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1196.9	0.273	
	LIMESTONE	168.6	1813.2	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	79.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured lb/ft3	density calculated lb/ft3	w/c-ratio lb/lb	air content %
142.5	142.4	0.46	6.4

COMMENTS:

User-defined maturity function

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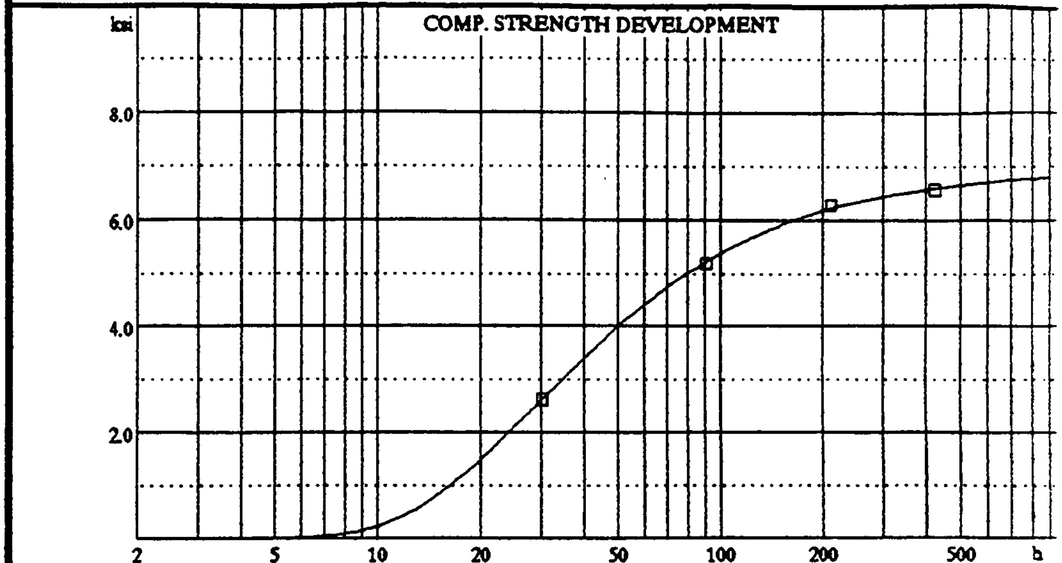
Figure 27. Heat development in bridge pier concrete, using activation energy = 48 KJ/mol.

MATERIALS RESEARCH LABORATO PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	STRENGTH DEVELOPMENT Documentation sheet

Client: SHRP | Number: | Initials: DS

Name: | Date: 10-03-90 | Job file: BRIDGE



DATAFILE: BRIDGE.SDV

CONCRETE: BRIDGE

LINEAR MODEL

So=2.86 ksi To=12.1 h

EXPONENTIAL MODEL

Sinf=6.94 ksi Te=29.5 h Alpha=1.12

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.3	0.156	
Cement	OPC	196.7	568.0	0.107	
Aggregate	FINE AGGREGATE	162.3	1197.0	0.273	
	LIMESTONE	168.6	1813.3	0.398	
Chemical Admixture	AIR ENTRAINING	64.3	0.8	0.000	
	WATER REDUCER	81.2	3.4	0.002	
Air				0.064	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
lb/ft3	lb/ft3	lb/lb	%
146.5	142.4	0.46	6.4

COMMENTS:

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Figure 28. Strength development in bridge pier concrete, using activation energy = 48 KJ/mol.

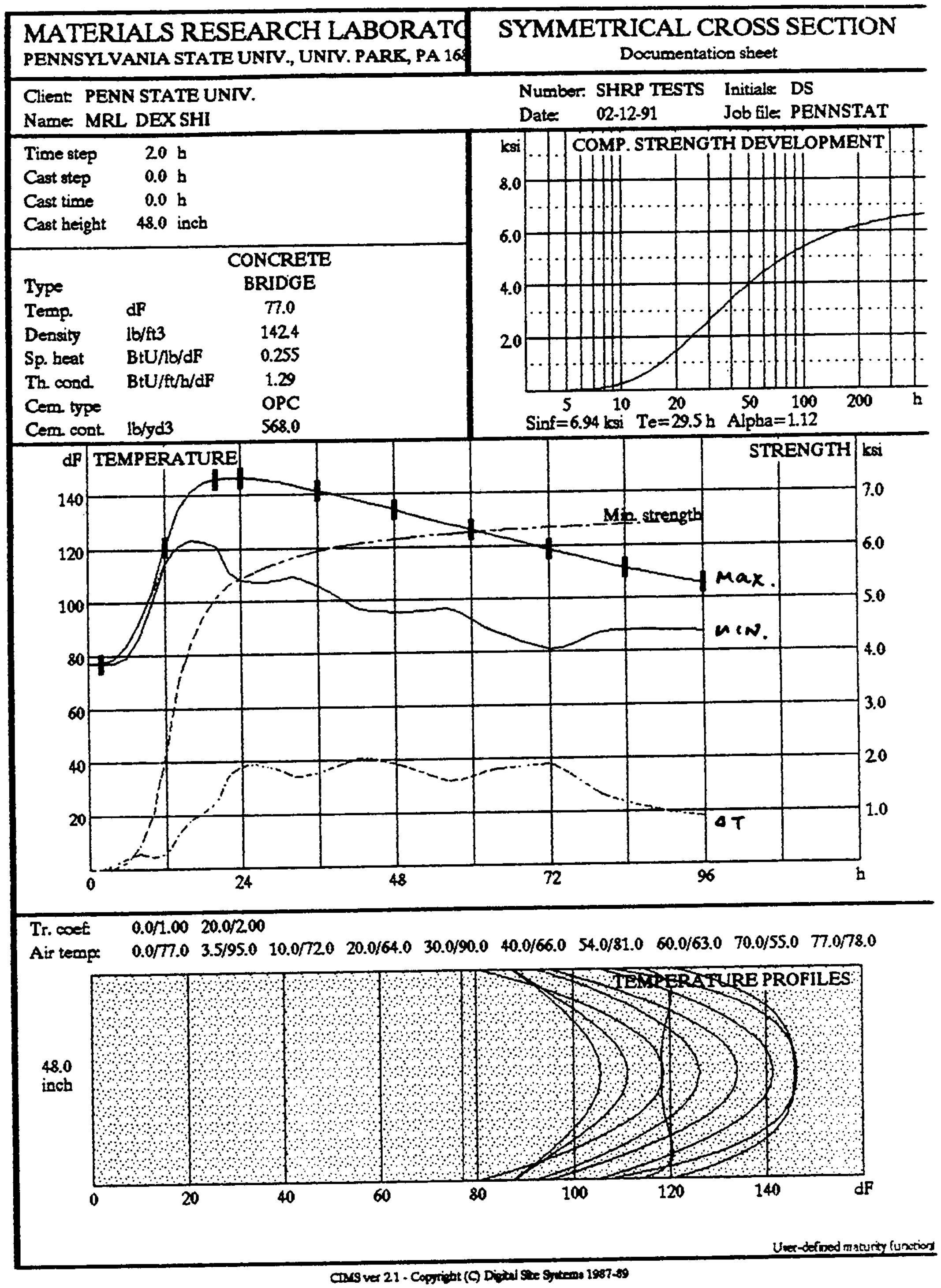
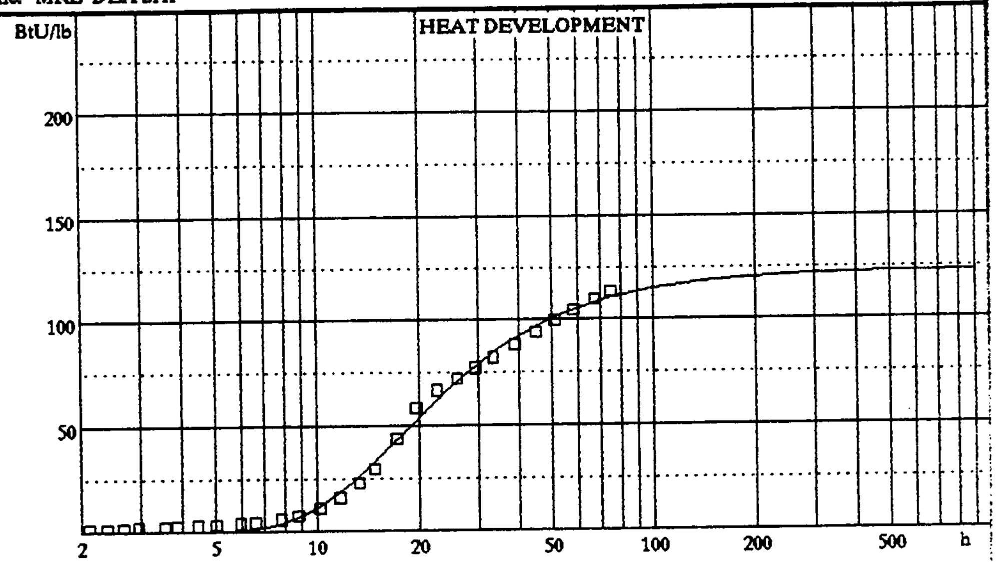


Figure 29. The changes in maximum temperature, minimum temperature, strength and the difference between maximum and minimum temperature in bridge pier with time up to 96 hours predicted by CIMS, using activation energy of 48 KJ/mol.

MATERIALS RESEARCH LABORATO	HEAT DEVELOPMENT
PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	Documentation sheet

Client: PENN STATE UNIV. Number: SHRP TESTS Initials: DS
Name: MRL DEX SHI Date: 01-16-91 Job file: PENNSTAT



DATAFILE: PENN1218.LOG
CONCRETE: ROAD Cement only Specific heat: 0.255 BtU/lb/dF

LINEAR MODEL
Qo=69.86 BtU/lb To=9.27 h

EXPONENTIAL MODEL
Qinf=122.96 BtU/lb Te=17.71 h Alpha=1.54

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.9	0.156	
Cement	OPC	196.7	588.5	0.111	
Aggregate	FINE AGGREGATE	162.3	1132.9	0.259	
	LIMESTONE	168.6	1879.6	0.413	
Chemical Admixture	AIR ENTRAINING	64.3	1.1	0.001	
	WATER REDUCER	79.2	2.7	0.001	
Air				0.060	

CONCRETE PROPERTIES

density measured lb/ft3	density calculated lb/ft3	w/c-ratio lb/lb	air content %
144.0	143.2	0.45	6.0

COMMENTS: User-defined maturity function

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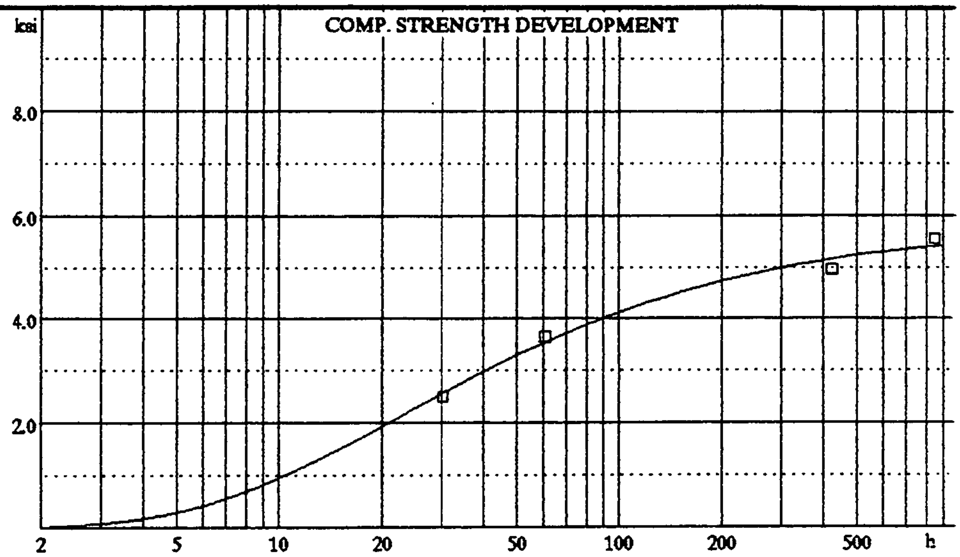
Figure 30. Heat development in pavement slab, using activation energy = 48 KJ/mol.

MATERIALS RESEARCH LABORATO PENNSYLVANIA STATE UNIV., UNIV. PARK, PA 16	STRENGTH DEVELOPMENT Documentation sheet

Client: PENN STATE UNIV. Number: SHRP TESTS Initials: DS
Name: MRL DEX SHI Date: 01-15-91 Job file: PENNSTAT



DATAFILE: ROAD.SDV
CONCRETE: ROAD

LINEAR MODEL
So=1.55 ksi To=5.8 h

EXPONENTIAL MODEL
Sinf=5.83 ksi Te=23.1 h Alpha=0.72

MIX MATERIALS	type	density lb/ft3	weight lb/yd3	volume yd3/yd3	comment
Water	TAP WATER	62.4	262.9	0.156	
Cement	OPC	196.7	588.5	0.111	
Aggregate	FINE AGGREGATE	162.3	1132.9	0.259	
	LIMESTONE	168.6	1879.6	0.413	
Chemical Admixture	AIR ENTRAINING	64.3	1.1	0.001	
	WATER REDUCER	79.2	2.7	0.001	
Air				0.060	

CONCRETE PROPERTIES

density measured lb/ft3	density calculated lb/ft3	w/c-ratio lb/lb	air content %
144.0	143.2	0.45	6.0

COMMENTS:

User-defined maturity function

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Figure 31. Strength development in pavement slab, using activation energy = 48 KJ/mol.

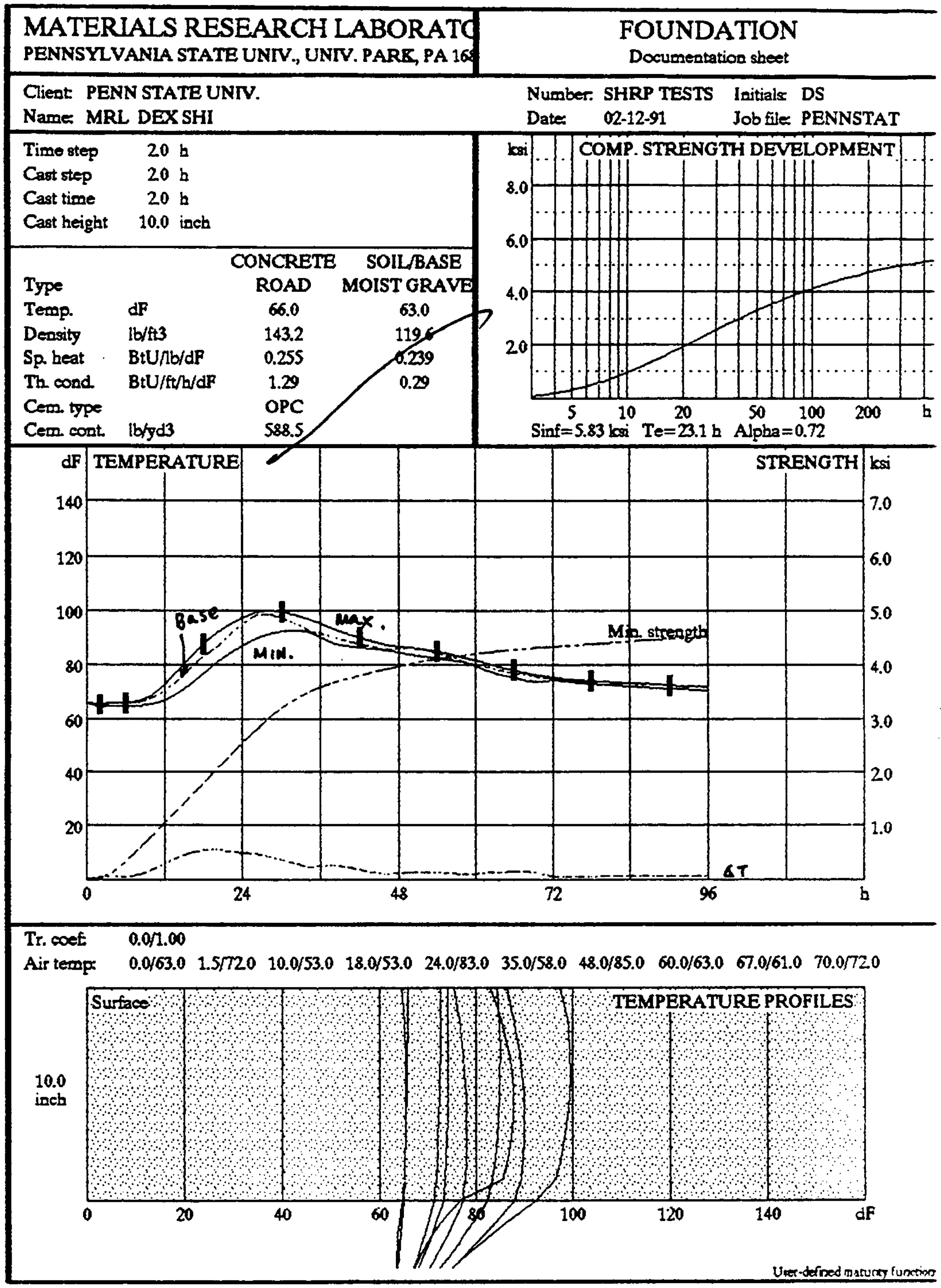

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Figure 32. The changes in maximum temperature, minimum temperature, strength and the difference between maximum and minimum temperature in slab with time up to 96 hours predicted by CIMS, using activation energy of 48 KJ/mol.

Appendix B—Tables

Table 1. Faunce Bridge concrete formulation.

Type I cement	588	lbs
Sand	1239	lbs
#57 limestone aggregate	1877	lbs
Water	271.5	lbs
Air entraining	13.75	oz
Water reducer	41.16	oz
Properties of Concrete		
Slump	2.25-3.00"	
Air entrainment	6.2-6.6%	
Temperature	77°-80°F	

Table 2. Route 15 highway repairs.

Type I cement	588	lbs
Sand	1132	lbs
#57 limestone aggregate	1878	lbs
Water	262	lbs
Air entraining	16.3	oz
Water reducer	31.3	oz
Properties of Concrete		
Slump	2.75"	
Air entrainment	6.0%	
Temperature	66°-68°F	

Table 3. Bridge Pier, 48" thick. Formulation as shown in Table 1.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50	38	0.9	36						8	0.01	40	
	45	1.3	57		45	4.8	34		12	0.05	55	
	48	1.4	53	98	45	4.8	34	123	32	4.2	30	135
77	10	0.1	50		22	5.5	37		16	4.8	40	
	18	0.5	83		45	6.2	44		22	5.2	53	
	18	0.5	83	135	22	5.5	37	146	22	5.2	53	147
100	4	0.1	55		18	6.2	37		10	5.1	45	
	22	2.2	50		24	6.3	53		22	5.8	68	
	10	0.7	90	165	12	5.7	23	170	12	5.3	53	170

Table 4. Wall, 24" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									10	0.01	40	
	44	1.2	28		46	5.2	20		22	4.3	43	
	44	1.2	28	66	36	4.1	11	117	22	4.3	43	138
77	14	0.2	33						14	4	33	
	22	0.7	42		22	5.3	21		22	5.3	40	
	18	0.4	41	95	17	4.7	17	142	15	4.5	37	150
100	4	0.1	45						12	5.2	38	
	8	0.3	70		22	6.3	34		16	5.7	40	
	8	0.3	70	140	10	5.5	15	165	9	4.7	20	165

Table 5. Wall, 16" thick. Formulation as shown in Table 3.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									18	4	38	
	45	1.2	16		46	5.2	12		18	4	38	
	39	0.8	14	57	33	4.2	7	112	18	4	38	141
77												
	21	0.5	18		21	5.3	20		14	4.5	30	
	0	0	0	77	16	4.2	13	138	14	4.5	30	146
100	6	0.2	36									
	8	0.5	41		22	6.2	23		22	5.7	18	
	8	0.5	41	106	9	5.5	8	160	18	4.6	15	156

Table 6. Pavement slab, 16" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50												
	70	3.2	15		40	2.8	18		18	0.8	23	
	54	2.5	10	77	40	2.8	18	103	36	2.8	18	110
77												
	46	3.2	16		22	2.7	24		12	1.1	32	
	30	2.3	11	92	24	2.8	20	113	21	2.7	23	118
100					10	2	37		8	1.3	40	
	48	3.8	17		10	2	37		8	1.3	40	
	16	2.3	15	115	14	2.8	35	125	13	2.5	38	138

Table 7. Pavement slab, 12" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50												
	44	2.2	12		36	2.7	16		18	1	21	
	44	2.2	12	73	36	2.7	16	99	33	2.7	17	107
77												
	46	3	10		18	1.9	20		12	1.2	28	
	33	2.3	7	82	21	2.7	18	105	20	2.6	20	113
100									8	1.3	40	
	16	2	15		12	2.3	32		8	1.3	40	
	16	2	15	103	14	2.6	27	127	12	2.4	33	130

Table 8. Pavement slab, 10" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50												
	46	2.2	10		33	2.8	15		30	2.7	13	
	42	2	7	72	33	2.8	15	97	30	2.7	13	103
77												
	46	2.8	10		21	0.7	14		12	1.2	27	
	33	2.4	15	75	21	0.7	14	100	18	2.2	20	110
10												
	16	1.8	11		14	2.5	24		24	2.3	37	
	16	1.8	11	89	14	2.5	24	119	12	2.3	37	125

Table 9. Pavement slab, 8" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50	46	2.3	8		33	2.7	12		18	1.5	20	
	38	1.8	5	70	33	2.7	12	96	30	3	14	100
77	18	1.2	10		20	2.2	13		12	1.3	22	
	33	2.1	5	72	20	2.2	13	95	18	2.2	19	107
100	15	1.7	10		12	2	23		12	2.3	25	
	0	0	0	90	12	2	23	110	12	2.3	25	118

Table 10. Pavement slab, 6" thick. Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50	18	0.7	8		30	2.6	10		18	1.6	16	
	36	1.8	5	67	30	2.6	10	86	20	2	14	95
77	18	1	9		18	2	14		15	1.9	18	
	33	2	4	67	18	2	14	90	15	1.9	18	100
100	15	1.5	7		12	1.8	20		10	1.8	22	
	0	0	0	90	12	1.8	20	100	12	2.1	20	110

Table 11. Pavement slab, 16" thick (no insulation). Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									8	0.1	45	
	42	1.6	28		12	0.4	20		10	0.2	47	
	42	1.6	28	68	36	2.8	13	100	10	0.2	47	104
77	20	0.8	38						8	0.7	47	
	20	0.8	38		10	0.7	26		8	0.7	47	
	22	0.9	36	77	21	2.3	24	110	18	2.1	24	117
100									8	1.3	43	
	12	0.8	16		12	2.3	31		8	1.3	43	
	14	1.09	16	104	14	2.4	28	128	12	2.4	3.5	134

Table 12. Pavement slab, 12" thick (no insulation). Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									8	0.1	40	
	42	1.7	23		14	1.6	20		10	0.3	45	
	42	1.7	23	63	33	2.8	10	95	10	0.3	45	105
77									8	0.5	35	
	20	0.9	28		12	1	24		10	1	40	
	18	0.8	26	66	20	2.5	18	103	16	2	30	115
100	16	1.2	38						8	1.3	35	
	16	1.2	38		9	1.7	30		8	1.3	35	
	0	0	0	90	14	2.5	22	120	12	2.3	28	125

Table 13. Pavement slab, 10" thick (no insulation). Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									8	0.2	33	
	45	1.7	20		14	1.7	20		10	0.5	40	
	38	1.5	14	60	33	2.8	16	94	10	0.5	40	105
77									8	0.7	35	
	18	0.7	24		12	1.2	22		8	0.7	35	
	0	0	0	66	18	2	16	98	15	1.5	32	112
100									8	1.4	40	
	18	1.2	34		12	2.1	23		8	1.4	40	
	0	0	0	90	12	2.1	23	113	9	1.8	32	122

Table 14. Pavement slab, 8" thick (no insulation). Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50									10	0.7	37	
	20	0.6	17		14	1.7	18		10	0.7	37	
	36	1.4	10	60	32	2.8	10	90	10	0.7	37	107
77												
	18	0.8	19		12	1.2	17		12	1.5	21	
	36	1.6	8	60	16	1.8	15	95	12	1.5	21	112
100												
	20	1.2	23		12	2	20		6	1	30	
	0	0	0	90	12	2	20	107	9	1.9	28	118

Table 15. Pavement slab, 6" thick (no insulation). Formulation as shown in Table 2.

	Weather condition											
	Temp 30°-50°F/wind speed 10 mph				Temp 59°-89°F/wind speed 2 mph				Temp 80°-100°F/wind speed 7 mph			
Concrete Temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)	Time (hrs)	Strength (ksi)	ΔT (°F)	max temp (°F)
50												
	18	0.6	13		14	0.9	12		9	0.8	33	
	36	1.4	7	39	33	2.8	10	85	9	0.8	33	108
77												
	18	0.7	17		12	1.2	18		9	1.3	30	
	0	0	0	66	12	1.2	18	91	9	1.3	30	110
100												
	18	1	18		10	1.7	20		8	1.7	30	
	0	0	0	90	10	1.7	20	100	8	1.7	30	115

Table 16. Bridge pier or wall.

Weather condition	16"	24"	48"	Concrete temperature (°F)
30	TG	TG/HT	TG/HT	100
	*	TG	TG	77
	*	*	TG	50
59	HT	HT	HT	100
	*	*	*	77
	*	*	*	50
80	*	HT	HT	100
	*	*	*	77
	*	TG	TG	50

TG stands for "risk of too large a Thermal Gradient", HT for "risk of too High internal Temperature", * = satisfactory curing conditions.

Table 17. Pavement slab.

Weather condition	6"	8"	10"	12"	16"	Concrete temperature (°F)
30	*	*	*	*	*	90
	*	*	*	*	*	66
	*	*	*	*	*	40
59	*	*	*	*	*	90
	*	*	*	*	*	66
	*	*	*	*	*	40
80	*	*	*	*	HT	90
	*	*	*	*	*	66
	*	*	*	*	*	40

TG stands for "risk of too large a Thermal Gradient", HT for "risk of too High internal Temperature", * = satisfactory curing conditions.

Table 18. Pavement slab (no insulation).

Weather condition	6"	8"	10"	12"	16"	Concrete temperature (°F)
30	*	*	*	*	*	90
	*	*	*	*	*	66
	*	*	*	*	*	40
59	*	*	*	*	*	90
	*	*	*	*	*	66
	*	*	*	*	*	40
80	*	*	*	*	HT	90
	*	*	TG	TG	TG	66
	*	TG	TG	TG	TG	40

TG stands for "risk of too large a Thermal Gradient", HT for "risk of too High internal Temperature", * = satisfactory curing conditions.

Table 19. Cement content: 555 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	TG	TG	TG	20
		*	*	*	*	TG	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	TG	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	HT	TG/HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	HT	HT	TG/HT	20
		*	*	*	*	HT	HT	16
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 20. Cement content: 575 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	TG	TG	TG	TG	20
		*	*	*	*	TG	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	TG/HT	TG/HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	HT	TG/HT	TG/HT	20
		*	*	*	HT	HT	HT	16
		*	*	*	*	*	HT	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 21. Cement content: 600 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	TG	TG	TG	TG	20
		*	*	*	*	TG	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	TG	TG/HT	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	TG/HT	TG/HT	20
		*	*	*	*	*	TG/HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	HT	HT	TG/HT	TG/HT	20
		*	*	*	HT	HT	TG/HT	16
		*	*	*	*	HT	HT	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 22. Cement content: 620 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	TG	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	TG	TG	TG	TG/HT	20
		*	*	*	*	TG	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	TG	TG/HT	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	TG	TG/HT	TG/HT	20
		*	*	*	*	*	TG/HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	HT	HT	TG/HT	TG/HT	20
		*	*	HT	HT	HT	TG/HT	16
		*	*	*	*	HT	HT	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 23. Cement content: 650 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	TG	TG	TG/HT	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	TG	12
		EF	*	*	*	*	*	8
40		*	*	TG	TG	TG/HT	TG/HT	20
		*	*	*	TG	TG	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	TG	TG	TG/HT	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	TG/HT	TG/HT	TG/HT	20
		*	*	*	*	TG/HT	TG/HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	HT	TG/HT	TG/HT	TG/HT	TG/HT	20
		*	*	HT	HT	TG/HT	TG/HT	16
		*	*	*	HT	HT	HT	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 24. Cement content: 675 lbs/cu.yd. Cement type: rapid.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	TG	TG	TG	TG/HT	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	TG	12
		EF	*	*	*	*	*	8
40		*	TG	TG	TG	TG/HT	TGHT	20
		*	*	*	TG	TG	TG/HT	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	TG	TG/HT	TG/HT	20
		*	*	*	*	TG	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	TG	TG/HT	TG/HT	TG/HT	20
		*	*	*	*	TH/HT	TG/HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		HT	TG/HT	TG/HT	TG/HT	TG/HT	TG/HT	20
		*	HT	HT	TG/HT	TG/HT	TG/HT	16
		*	*	HT	HT	HT	HT	12
		*	*	*	*	*	HT	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 25. Cement content: 555 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.						slab thickness (inches)
	50	60	70	80	90	100	
0	EF	EF	EF/TG	EF/TG	TG	TG	20
	EF	EF	EF	EF/TG	TG	TG	16
	EF	EF	EF	EF	TG	TG	12
	EF	EF	EF	EF	EF	*	8
20	EF	*	*	*	TG	TG	20
	EF	*	*	*	*	TG	16
	EF	*	*	*	*	*	12
	EF	*	*	*	*	*	8
40	*	*	*	*	TG	TG	20
	*	*	*	*	*	TG	16
	*	*	*	*	*	TG	12
	*	*	*	*	*	*	8
60	*	*	*	*	*	*	20
	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8
80	*	*	*	*	*	*	20
	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8
100	*	*	*	*	*	*	20
	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 26. Cement content: 575 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	EF	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	*	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	*	HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 27. Cement content: 600 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	*	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	*	HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 28. Cement content: 620 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	*	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	*	HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 29. Cement content: 650 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	*	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	HT	HT	20
		*	*	*	*	*	HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 30. Cement content: 675 lbs/cu.yd. Cement type: sulfate resistant.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	HT	HT	20
		*	*	*	*	*	HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 31. Cement content: 555 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	TG	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	*	HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 32. Cement content: 575 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	*	HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 33. Cement content: 600 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp. 50	60	70	80	90	100	slab thickness (inches)
0	EF	EF	EF/TG	EF/TG	TG	TG	20
	EF	EF	EF	EF/TG	TG	TG	16
	EF	EF	EF	EF	TG	TG	12
	EF	EF	EF	EF	*	*	8
20	EF	*	*	*	TG	TG	20
	EF	*	*	*	TG	TG	16
	EF	*	*	*	*	*	12
	EF	*	*	*	*	*	8
40	*	*	*	*	TG	TG	20
	*	*	*	*	*	TG	16
	*	*	*	*	*	TG	12
	*	*	*	*	*	*	8
60	*	*	*	*	*	TG	20
	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8
80	*	*	*	*	*	*	20
	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8
100	*	*	*	*	HT	HT	20
	*	*	*	*	*	HT	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 34. Cement content: 620 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	*	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	*	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	*	HT	HT	20
		*	*	*	*	*	HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 35. Cement content: 650 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	TG	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	*	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	TG/HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	HT	HT	HT	20
		*	*	*	*	HT	HT	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 36. Cement content: 675 lbs/cu.yd. Cement type: ordinary.

Air temp. (°F)	Conc. temp.	50	60	70	80	90	100	slab thickness (inches)
0		EF	EF	EF/TG	EF/TG	TG	TG	20
		EF	EF	EF	EF/TG	TG	TG	16
		EF	EF	EF	EF	TG	TG	12
		EF	EF	EF	EF	*	*	8
20		EF	*	*	*	TG	TG	20
		EF	*	*	*	TG	TG	16
		EF	*	*	*	*	*	12
		EF	*	*	*	*	*	8
40		*	*	*	TG	TG	TG	20
		*	*	*	*	*	TG	16
		*	*	*	*	*	TG	12
		*	*	*	*	*	*	8
60		*	*	*	*	TG	TG	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
80		*	*	*	*	*	TG/HT	20
		*	*	*	*	*	*	16
		*	*	*	*	*	*	12
		*	*	*	*	*	*	8
100		*	*	*	HT	HT	TG/HT	20
		*	*	*	*	HT	HT	16
		*	*	*	*	*	HT	12
		*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab; EF = risk of early freezing; HT = risk of too high temperature within the concrete slab.

Table 37. Six concrete mixtures.

Concrete mix no.	1	2	3
Cement content (lbs/cu.yd.)	675	650	620
Water content (lbs/cu.yd.)	305	295	280
Aggregate content (lbs/cu.yd.)	2778	2866	2957
Air content (% of concentration)	7.0	6.0	5.5
Water/cement ratio	0.45	0.45	0.45
Density (lbs/cu.yd.)	3758	3816	3857
Strength (psi)	5000	4750	4760

Concrete mix no.	4	5	6
Cement content (lbs/cu.yd.)	600	575	555
Water content (lbs/cu.yd.)	270	260	250
Aggregate content (lbs/cu./yd.)	3023	3070	3114
Air content (% of concentration)	5.0	5.0	5.0
Water/cement ratio	0.45	0.45	0.45
Density (lbs/cu.yd.)	3893	3905	3919
Strength (psi)	4890	4800	4760

Table 38. Cement content: 670 lb/cu.yd. Cement type: NBS-18.

Air temp. (°F)	50	60	70	80	90	100	slab thickness (inches)
40	*	*	*	TG	TG	TG	16
	*	*	*	TG	TG	TG	12
	*	*	*	*	TG	TG	8
60	*	*	*	*	*	TG	16
	*	*	*	*	*	TG	12
	*	*	*	*	*	*	8
80	*	*	*	*	*	*	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8
100	*	*	*	*	*	HT	16
	*	*	*	*	*	*	12
	*	*	*	*	*	*	8

*satisfactory curing conditions; TG = risk of too large thermal gradients within the concrete slab (>36°F); HT = risk of too high temperature within the concrete slab (>140°F).