THERMAL STRESS DEVELOPMENT IN CONCRETE PAVEMENTS AT EARLY AGES

Will Hansen, Associate Professor
Ashraf R. Mohamed, Research Fellow
Phil Mohr, Graduate Student
Department of Civil & Environmental Engineering
The University of Michigan

ABSTRACT

Internal stresses are present in Portland cement concrete pavement at early ages due to restrained curling and axial contraction. The risk of cracking in the pavement is largely associated with the temperature and tensile strength development of the concrete mixture as it cures. The temperature development is heavily influenced by heat released during cement hydration, the temperature of the concrete ingredients, and daily and seasonal fluctuations in ambient temperature. It has been observed that thermal stress development is most severe when the peak in the heat developed from hydration coincides with maximum daily ambient temperature. Thus, consideration should be given to placing concrete in the late afternoon or evening, especially during summer time placing conditions.

INTRODUCTION

It is well known that concrete undergoes dimensional changes as it cures due to temperature variations. As the hydration process commences, the developed heat causes the concrete to expand, while upon cooling the concrete contracts. In concrete pavements, as the slab is restrained externally by both its self-weight and subgrade friction, stresses will develop within the slab. A common practice is to install contraction joints to control the location of cracking. The amount of axial contraction that occurs is related to the heat developed in the concrete, the thermal expansion properties of the concrete constituents, the restraint from movement provided by foundation friction and adjoining slabs, and drying shrinkage. As the hydration takes place, heat is dissipated from the slab both to the foundation and to the air above. Because the ambient temperature fluctuates, and because heat is dissipated much more readily to the air than to the foundation, the temperature distribution through the slab thickness is not even. A temperature gradient develops which causes the slab to curl. For many years, the temperature gradient has been assumed to be linear (1,2,3). However, measurements of the temperature variation through the slab thickness reveal a highly non-linear distribution(4). Recently, a closed form solution has been developed by Mohamed and Hansen (5) for handling the non-linearity of the temperature profile. The contribution from both contraction and curling can induce significant stresses through the slab thickness, especially at early ages when concrete has not acquired its full tensile strength.

There exist many internal and external factors contributing to the early age (first few days after placement) temperature development. Internal factors include the heat generated from hydration of the cement and pozzolanic reactions, the thermal conduction properties of the concrete ingredients, and the slab dimensions (particularly its thickness). The external factors include changes in environmental factors such as the ambient air temperature and the underlying base temperature, solar radiation, wind velocity, and relative humidity (6,7). The heat exchange between the concrete and the environment occurs through conduction, convection and solar radiation.

The temperature of the concrete and the surroundings at the time at which the concrete is placed have a significant impact on the overall temperature development in the slab, and in turn on the resulting internal stresses. Furthermore, the time of day of placement will determine whether the peak in hydration coincides with, or counteracts the maximum daily temperature (8,9).

RESEARCH SIGNIFICANCE AND OBJECTIVE

Temperature variation within a concrete pavement slab at early ages has a significant influence on the slab's cracking tendency. Due to the restraint offered by the subgrade and the slab weight, internal stresses develop as a result of these variations. In some cases, especially at early ages, these stresses are comparable to the tensile strength of concrete. Controlling the temperature and time of concrete placing may result in a reduction in the cracking tendency of concrete pavement. Currently, pavement design does not explicitly account for thermal stresses. However, early cracking has been observed in concrete pavement slabs placed at high temperatures (>29.4 ^{o}C (85 ^{o}F)). For instance, a section of pavement on US-23 south of Dundee, Michigan was found to exhibit cracking within one month of opening to traffic. This roadway was placed on a windy 90^{o}F day. Cored samples from these slabs showed that these cracks were located within the top 5-7.5 cm (2-3 in) of the slab.

The objective of this investigation is to evaluate the internal thermal stresses that occur in a concrete pavement within the first few days after placing. The concrete mix design from US-23 is used, and various placing conditions are simulated.

RESEARCH APPROACH

The heat exchange between the concrete and its surroundings is a complex process. In this study a heat transfer analysis program ("Quadrel 1.5" (10)) is used for predicting the concrete temperature profile and maturity versus time for a variety of placement and environmental conditions. Solar radiation effects are not considered. The simulation process is based on a heat signature of the concrete mix, which has been identified through laboratory measurements using adiabatic calorimetry. The concrete strength (compressive and split tensile) development at early ages is measured in the laboratory. After predicting the temperature variation through the slab thickness at different time steps, the temperature gradient through the thickness is determined. As the temperature distribution has been found to be non-linear, the newly developed methodology (5) has been used to evaluate the stresses induced by such gradients. Strength development from the laboratory, adjusted for simulated conditions using the maturity function, are compared to these stresses to examine the risk of cracking.

PREDICTION OF TEMPERATURE PROFILES

In order to predict temperature profiles for a concrete pavement, a concrete batch with the same mix design is cast in the laboratory, from which adiabatic heat development is measured. Once this heat signature for the concrete has been obtained, field conditions such as slab thickness, temperature cycles, and wind speed are entered as input to a simulation program, which in turn develops the predicted temperature profile in the slab over time.

As this study utilizes commercially available software to simulate the temperature profiles, it is important to first verify whether the software is suitable for simulation of the conditions that are imposed in the study. This verification was done through a two stage procedure. First, the program was compared to known boundary cases. For example, to determine whether the program accurately measures the effects of temperature cycles, the slab thickness was reduced to near zero, which should cause the slab temperature to vary similarly to the air temperature. Indeed it was found that the program provides accurate results with respect to the cases investigated in this step.

Second, in order to determine the accuracy of the simulation program compared to measured data, a test slab section was cast in the laboratory. The slab was well insulated, and cast on an aggregate base to simulate similar conditions to those in the field. Thermocouples were placed through the thickness of the slab. Figure 1 shows the design and dimensions of the laboratory test slab. The slab was placed under controlled temperature and humidity conditions, and temperature measurements were recorded every 15 minutes for 3 days. The temperature was cycled over a 24 hour period from 15.6-26.7 ^{o}C (60 to 80 F) to simulate field conditions. Relative humidity was held constant at 50%. Concurrently, the adiabatic heat development for the same mix was measured as input to the computer simulation. Computer simulations were run on the same mix for the same conditions, and the results were compared. As can be seen from Figure 2, very close results have been found between the measured and simulated temperature variations. The small differences between the measured and predicted might be attributed not only to the fact that simulation does not account for all factors affecting heat transfer, but also to the imperfect boundary conditions in the experimental slab. Based on this finding, the computer simulation technique has been used for the remainder of the study.

Prediction of Thermal Stresses and Concrete Strength

The combination of the hydration and ambient temperatures lead to the early temperature rise in the concrete. It is somewhere near the peak temperature rise that final set occurs, and stresses can begin to develop in the slab. The formation of internal stresses in the slab follows through the mechanisms of uniform contraction and temperature curling. Figure 3 depicts the internal temperature loading in the concrete, which results in the development of stresses in the slab.

The uniform contraction of the slab is partially restrained by base course friction, as described by Okamoto (11). In this study, the restraint from movement is calculated from a modified form of the joint opening equation presented by Huang (12), and in essence accounts for the deformation the slab would undergo in space minus the amount the joint actually opens. When simplified, Equation 1 gives restrained portion of the movement due to uniform contraction.

$$\Delta L/L=(1-C)\alpha_t\Delta T/2 \qquad \text{[Eq. 1]}$$

in which ΔL is the restrained movement of the slab due to temperature change; L is the slab length; C is the adjustment factor due to slab-subbase friction; α_t is the coefficient of thermal expansion of the concrete taken as $1x10^{-5}$ /°C ($5.5x10^{-6}$/°F); and ΔT is the change in temperature. This determines the strain in the slab. Elastic modulus is calculated from strength using the ACI equation

$$E = 4.73\sqrt{f_c'}, \qquad \text{[Eq. 2]}$$

where E in GPa and f_c' in MPa ($E = 57,000\sqrt{f_c'}$ in psi units). The slab is assumed to behave in a linear elastic fashion, and stresses due to uniform contraction are calculated on that basis.

The second mechanism for stress development is the restrained curling in the slab. The slab tries to curl upward as the top cools more rapidly than the bottom. At the same time, the slab's weight restricts this movement. It has been documented (e.g. Thompson (4)) and will be shown that the temperature gradients are highly non-linear through the thickness of the slab. While traditional analysis of temperature gradient induced stress is based on linear gradient analysis, it has been shown (5) that this type of analysis may significantly underestimate the stress development through the thickness of the slab. For this reason, the recently developed closed form solution by Mohamed and Hansen (5) is being used in this context which takes into account the non-linear effects of temperature gradients through the slab thickness.

The concrete strength development begins at final set, and continues as the hydration reaction progresses. This process is highly influenced by curing conditions. The use of the maturity function concept allows the strength development under various field conditions to be related back to a standard laboratory condition. In this study, a laboratory batch was cast and tested to develop the standard maturity condition for the field mix design. The maturity function is then used to relate the laboratory strength development to the various batch temperatures and placing times in question.

REFERENCE CASE: US-23 MICHIGAN

In order to investigate the effect of time and temperature of placement on the cracking tendency of concrete pavement, a reference case is needed. The reference case in this study is a section of pavement on US-23 south of Dundee, Michigan. It has been found to exhibit cracking within one month of opening to traffic. This roadway was placed on a windy 32 °C (90 °F) day. Thus, all parameters in this study are limited to the conditions that existed in this case. For instance, the temperature has been varied between 21-35 °C (70-95 °F), which represents a typical temperature variation in that location. Furthermore, the friction coefficient C in Eq. (1) has been set to 0.8, resembling that recorded for the type of base course in the reference study. The slab dimensions are 3.66x8.25 m(12x27 ft).

Simulation of Placing Conditions for the Reference Case

Once it has been established that the simulation software provides acceptable results, the conditions in the field at US-23 can be simulated to determine the cracking susceptibility of the pavement during the first few days after placement. This field condition will be referred to as case 1, and is shown in Table 1. For this and all placing conditions studied, a 26.7 cm (10.5 in.) slab thickness and 12.5 km/h (7.5 mph) wind speed were used.

As shown in Figure 4, the temperature at the top of the slab is typically cooler than at the bottom at early ages, and the gradients are highly nonlinear. This causes the pavement to curl upward. The upward curling of the slab is restrained by its own weight. Therefore, the concrete develops tensile stresses at the top. Stresses due to nonlinear temperature gradients are calculated based on the methodology in (5). The stresses due to curling account for the majority of stresses developed within the first 24 hours. The distribution of stresses through the slab thickness over time is shown in Figure 5.

As shown in Figure 6, the average temperature of the concrete rises to roughly 43.3 ^{o}C (110^{o}F) and then drops to less than 29.4 ^{o}C (85^{o}F) over the next 2 days. This 13.9 ^{o}C (25^{o}F) drop over such a short period of time causes the slab to contract very rapidly. The frictional restraint from the base does not allow the concrete to contract fully, causing it to develop tensile stresses at the mid span.

Due to thermal effects alone, the tensile stresses that develop in the concrete amount to approximately 1.378 MPa (200 psi) 24 hours after placement. This is approaching the tensile strength which is only about 2.067 MPa (300 psi) at 24 hours after placement. For this study, moisture shrinkage is not taken into account. If the stresses developed due to moisture loss are added, the tensile stresses in the concrete would most likely exceed the tensile strength and cause the concrete to crack at the top near the mid span of the slab.

Effects of Varying Batch Temperature and Placing Time on Risk of Early Cracking

In addition to the US-23 field condition, the effects of varying time of placement and concrete temperature at placement are also investigated. Seen in Table 1 are the conditions of all test cases that are studied.

It can be seen from Figures 7-9 that the development of stress in the slab is significantly influenced by both time of placement and concrete temperature at time of placement. This is particularly evident for the afternoon and evening cases, where stress development is delayed because of the offset between hydration and ambient temperatures. The influence of reduced placing temperature has the greatest effect on uniform contraction of the slab. Internal stress development due to nonlinear gradients is not significantly influenced by changes in batch temperature at placement. A combination of low batch temperature and late in the day placement can avoid significant stress development until later ages, when the concrete has gained considerably more strength. By controlling the temperature rise, the risk of cracking due to thermal stresses can be reduced significantly.

CONCLUSIONS

- The thermal stresses that develop in concrete pavements placed during high temperatures (>29.4 ^{o}C (85 ^{o}F)) are significant within the first several days after placement.
- Delaying concrete placement until the afternoon or evening can delay the buildup of thermal stresses in the slab until the concrete has gained considerably more strength.
- Reducing batch temperature has a limited effect in reducing internal stresses, but is accompanied by a corresponding reduction in tensile strength gain at early ages.
- The retardation of stress development in afternoon placements is caused by the peak temperature from hydration being reached during the coolest period of the day, reducing the overall temperature rise in the concrete.
- More work is needed to explore the other factors affecting the cracking tendency of concrete at early ages. This includes, but is not limited to, the range of temperature variation, the slab thickness, and the concrete thermal properties, as well as inclusion of radiation effects.

Table 1. Placing conditions of the various test cases.

Figure 1. Schematic of the concrete test slab used to verify accuracy of program temperature predictions

Figure 2. Measured and Simulated temperature profiles for verification of temperature simulation.
a) Profile measured in the laboratory.
b) Simulated profile.

Figure 3. Early temperature loading through the thickness of the concrete pavement slab.

Figure 4. Nonlinear temperature distribution through the slab thickness at various times after placement for the reference case.

Figure 5. Thermal curling stress distribution through the slab thickness at various times for the reference case.

Figure 6. Temperature profile for the field condition for the first 120 hours after placement.

Figure 7. Tensile strength and thermal stress development for a pavement placed at 8:00 AM at three different placing temperatures.

Figure 8. Tensile strength and thermal stress development for a pavement placed at 4:00 PM at two different placing temperatures.

Table 1. Placing conditions of the various test cases.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Air Temp.	21-35	21-35	21-35	21-35	21-35	21-35	21-35
Batch Temp. at Placement	32.2	23.9	15.6	32.2	15.6	26.7	15.6
Soil Temp.	26.7	26.7	26.7	26.7	26.7	21.1	21.1
Time of Placement	8 AM	8 AM	8 AM	4 PM	4 PM	8 PM	8 PM

1°F=(f-32)/1.8 °C

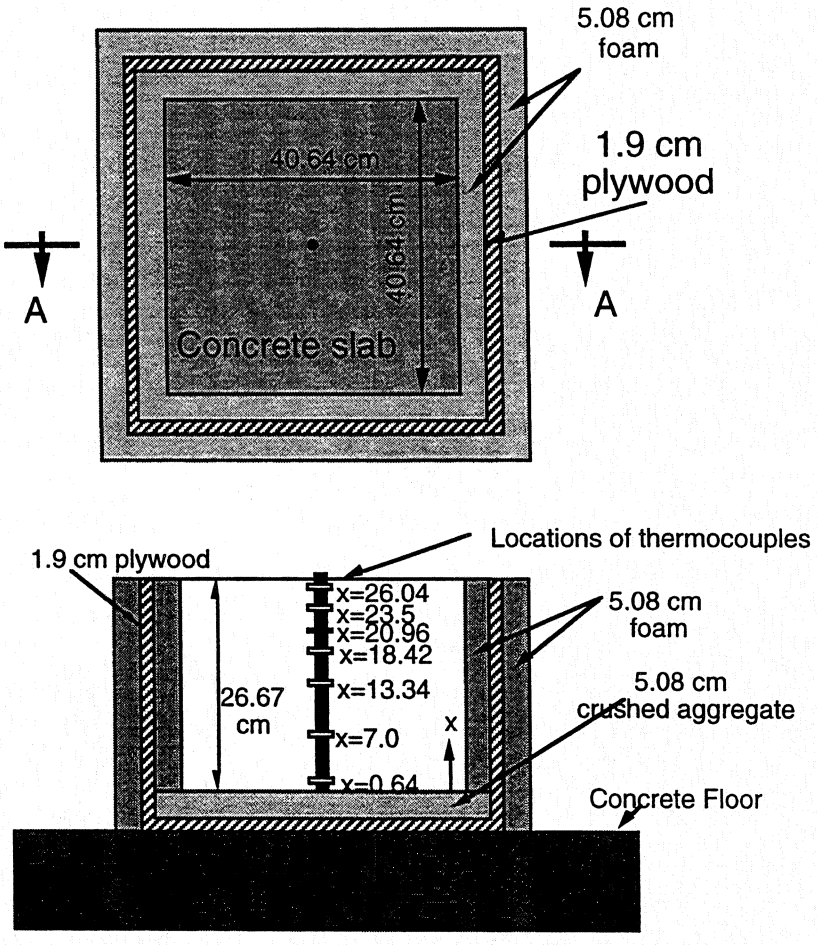
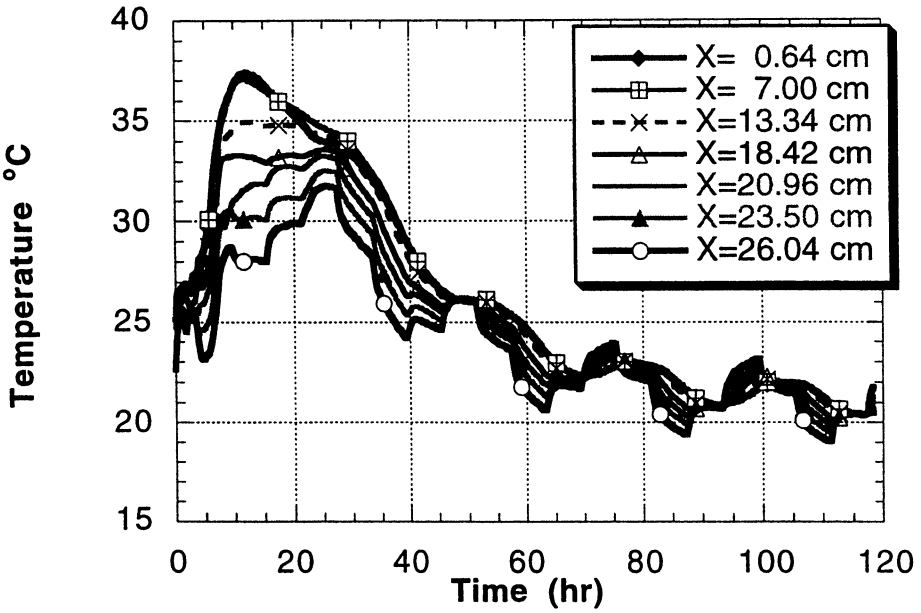


Figure 1.


Temperature °C
40
35
30
25
20
15
0
20
40
60
80
100
120
Time (hr)
X= 0.64 cm
X= 7.00 cm
X=13.34 cm
X=18.42 cm
X=20.96 cm
X=23.50 cm
X=26.04 cm

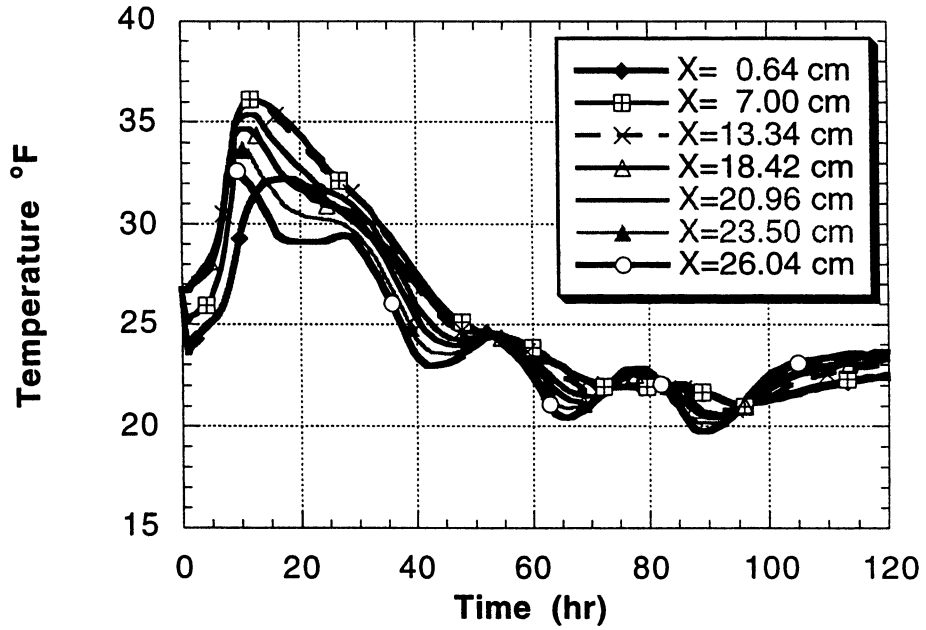

Temperature °F
40
35
30
25
20
15
0
20
40
60
80
100
120
Time (hr)
X= 0.64 cm
X= 7.00 cm
X=13.34 cm
X=18.42 cm
X=20.96 cm
X=23.50 cm
X=26.04 cm

Figure 2.

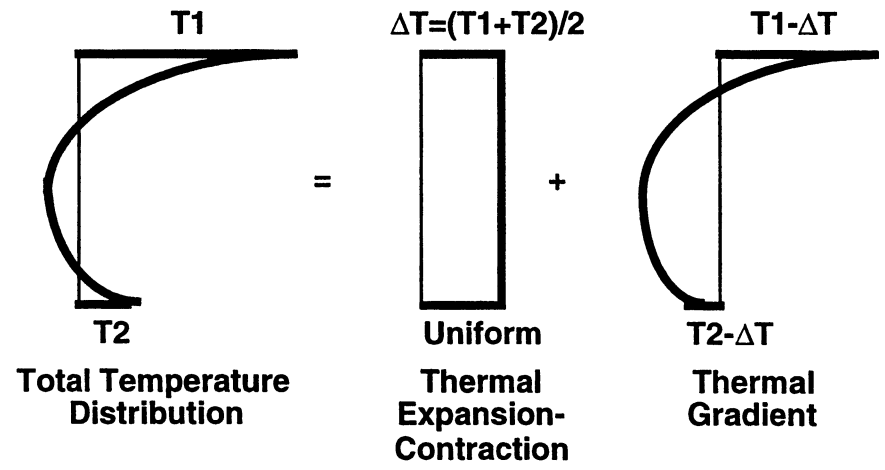


Figure 3.

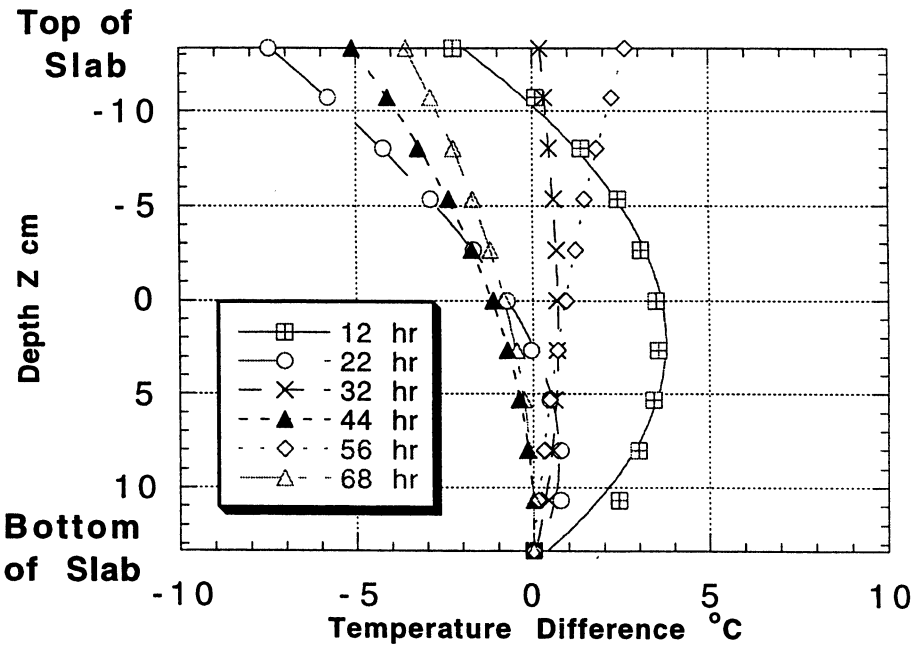


Figure 4.

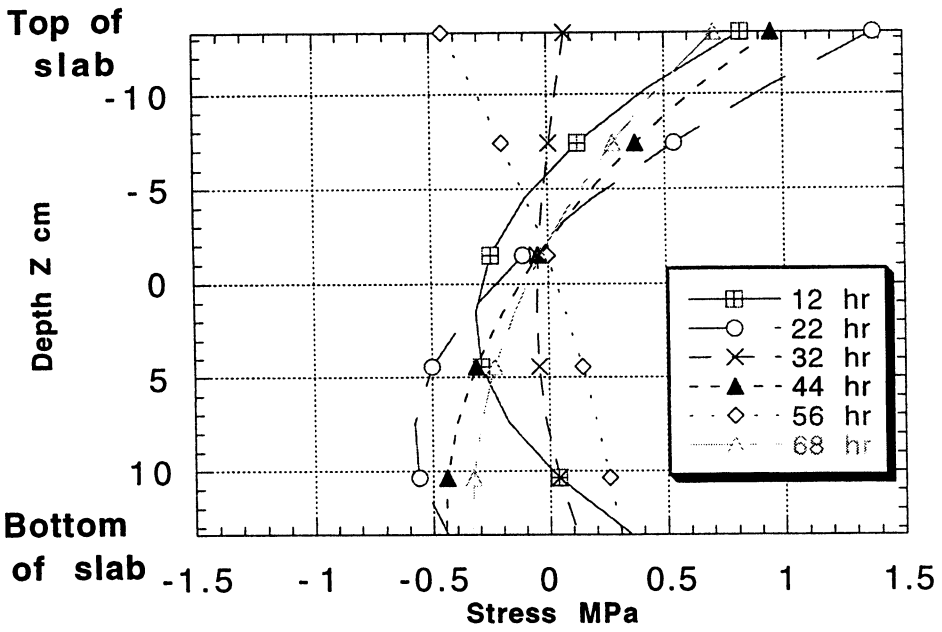


Figure 5.

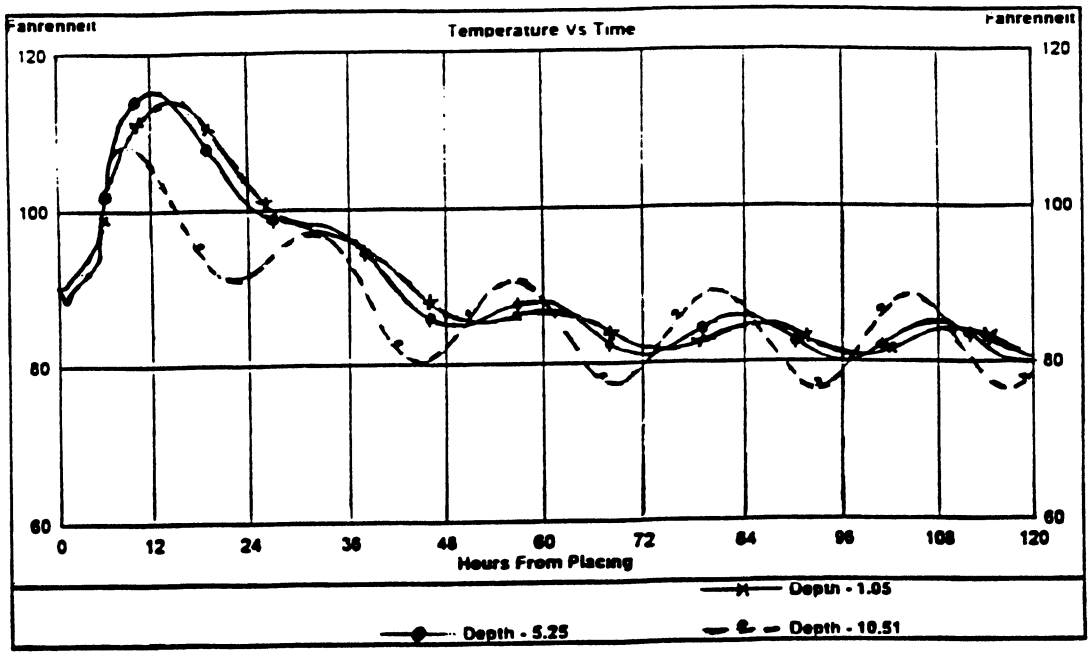


Figure 6.

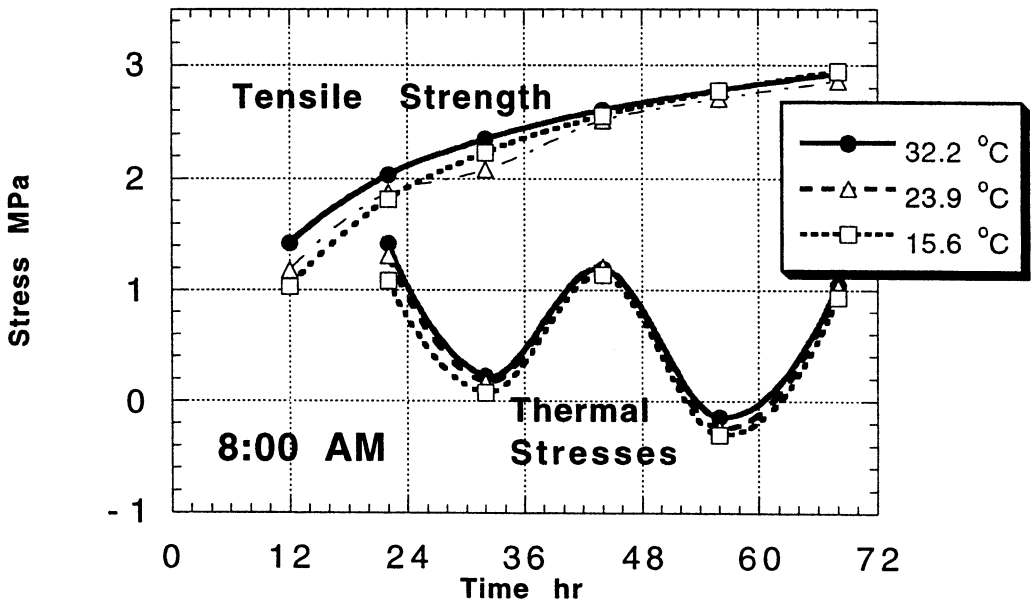


Figure 7.

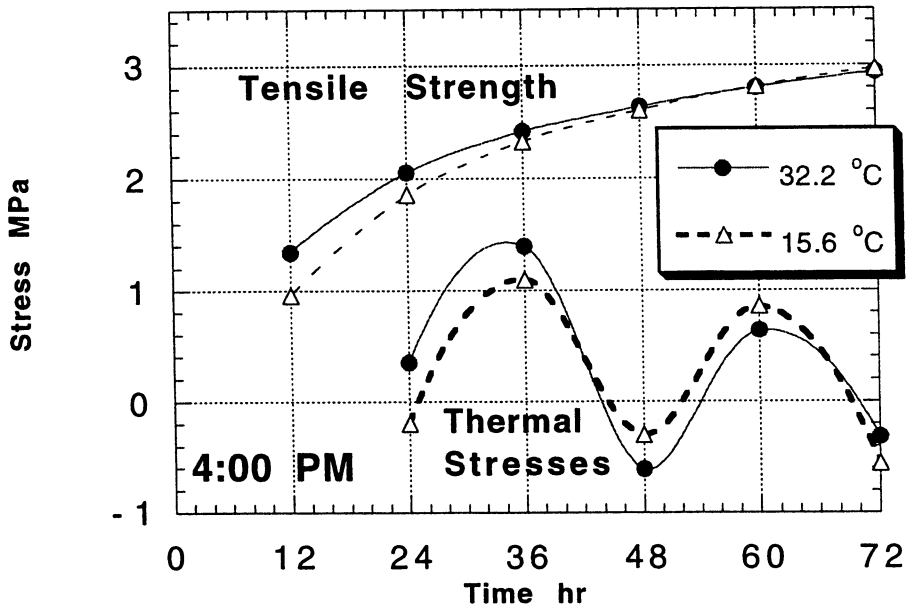


Figure 8.

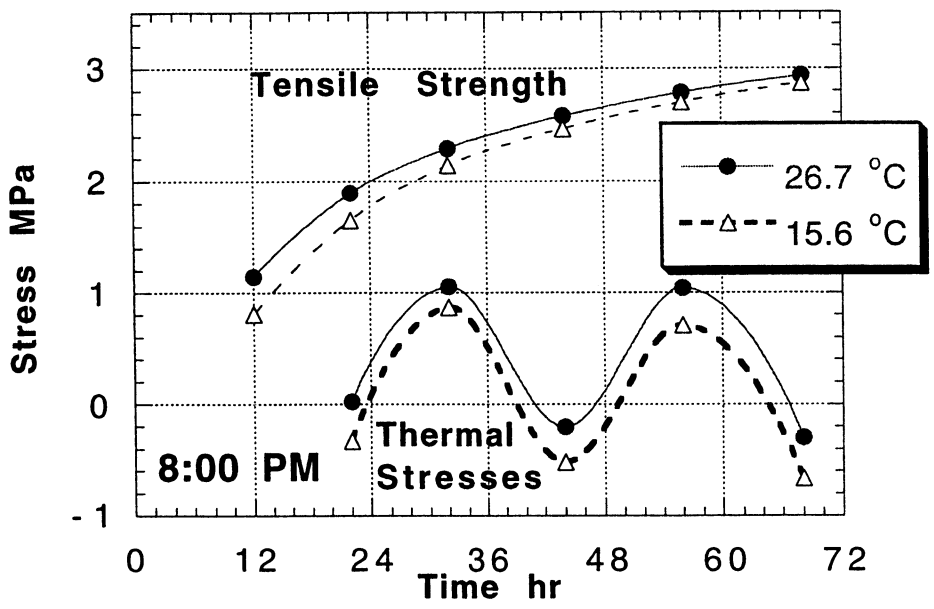

Tensile Strength
26.7 °C
15.6 °C
Thermal Stresses
8:00 PM
Stress MPa
Time hr
3
2
1
0
- 1
0
12
24
36
48
60
72

Figure 9.

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