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INVESTIGATION OF THE USE OF MATCH CURE TECHNOLOGY IN THE PRECAST CONCRETE INDUSTRY

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16. Abstract

This project was proposed to evaluate the feasibility and methodology of implementing match cure technology and maturity measurement systems into TxDOT acceptance criteria for concrete construction projects. This report will deal strictly with the investigation into the use of match cure technology.

There are four main objectives of this research project. First, the potential for using match cure technology in the precast concrete industry will be evaluated. Second, a set of guidelines will be developed for using this technology in the field. Third, the limitations of the technology will be evaluated and addressed. And, fourth, a revision of the current specifications will be developed to include the use of match cure technology as acceptance criteria for precast concrete.

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by

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and

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CHAPTER 1. INTRODUCTION

As practiced in the precast concrete industry, an owner buys quality-control specimens but pays for structural members. This can be a problem, given that the acceptance criteria may be less concerned with the quality of concrete in the member and more with the quality of concrete in the control specimen. Accordingly, it has become increasingly important to take advantage of new technology that can close the differences between these separate entities. The use of match cure technology is one way to ensure that quality control specimens better represent the actual concrete in a precast concrete member. Moreover, match cure technology can assist the precaster in producing the best quality concrete possible under all circumstances, including those associated with harsh weather, variable mix proportions, and tight production schedules.

1.1 PROBLEM STATEMENT

In today's construction industry, time is money. To save time, construction practice demands faster concrete strength development. In the precast concrete industry, a precaster wants to strip forms as quickly as possible, believing that the benefits of accelerated concrete strength gain overshadow any increase in material costs. Thus, 28-day design compressive strengths are often achieved in 1 day by increasing the cement content of the concrete. Yet the increase in cement content can generate higher internal member temperatures. And the effect of the higher temperature yields concrete that differs substantially from the quality control specimens intended to represent that concrete in the member.

1.2 SIGNIFICANCE OF RESEARCH

Because standard quality-control specimens may not accurately represent the concrete in the member, a procedure needs to be implemented that allows the actual in-place characteristics of the concrete to be more accurately accounted for in production. The use of match cure technology is one technique that creates quality-control specimens that better represent the actual concrete in the member. Match cured specimens do this by accounting completely for the effect of internal member temperatures on the concrete. Current quality control specimens account only partially for these temperatures. Because of this, using match cure technology will produce control specimens that better represent the quality of the concrete in the member. Furthermore, this technology will allow the precaster to concentrate on improving the quality of the in-place concrete instead of the quality of the concrete in the control specimens.

1.3 OBJECTIVE OF THE RESEARCH

There are four main objectives of this research project. First, the potential for using match cure technology in the precast concrete industry will be evaluated. Second, a set of guidelines will be developed for using this technology in the field. Third, the limitations of the technology will be evaluated and addressed. And, fourth, a revision of the current specifications will be developed to include the use of match cure technology as acceptance criteria for precast concrete.

1.4 PROJECT DESCRIPTION

This research, part of Project 0-1714, has been funded by the Texas Department of Transportation (TxDOT). The project was proposed to evaluate the feasibility and methodology of implementing match cure technology and maturity measurement systems into TxDOT acceptance criteria for concrete construction projects. This report will deal strictly with the investigation into the use of match cure technology.

1.5 RESEARCH PLAN

Research was conducted on high performance concrete (HPC) and normal strength concrete (NSC). The research started in the field at Texas Concrete, a precast concrete plant in Victoria, Texas. The field data were then verified through lab testing at the Construction Materials Research Group at The University of Texas at Austin. The effect of curing temperature on the 24-hour release characteristics and the long-term design characteristics of concrete was evaluated. The characteristics evaluated included compressive strength, modulus of elasticity, and permeability.

CHAPTER 2. LITERATURE REVIEW

2.1 CURRENT QUALITY CONTROL PROCEDURES

In order to understand the benefits of match cure technology, it is important to first understand the current procedures for curing quality-control specimens in the Texas precast industry. TxDOT's *Manual of Testing Procedures* (Ref 1) requires the following for curing compression test specimens for prestressed concrete:

1. *Release of Tension Cylinders, Partial Tensioning Cylinders, and Tensioning Cylinders* shall be cured identical to, and along with, the members they represent, and shall be placed where the most unfavorable conditions are offered. If elevated temperature curing is used, the cylinders shall be cured at the coolest point. If post-tensioned members are partially tensioned and removed from the casting bed to a curing area, the tensioning cylinders shall also be moved to this area and again resume curing identical to the members. If curing requirements of the members are completed prior to final tensioning, curing of the tensioning cylinders shall also cease at this point. However, prior to testing cylinders that have completed this curing period, the cylinders shall be moisture conditioned by submerging in water for a minimum period of 40 hours. This is to assure a uniform moisture condition in the cylinder.

2. *Design Strength Cylinders* shall be cured identical to, and along with, the members they represent until release of stress or partial tensioning strength is obtained. At this time they shall be inspected carefully to determine any inaccuracies of molding and if the cylinder has any inaccuracies of molding and if the cylinder has any visible evidence of damage, marked with a serial number and date of casting and placed in a curing tank or moist cabinet or room.

Basically, this procedure produces specimens that are subjected to only a percentage of the heat of hydration generated by the member up to the time of transfer of prestress. The specimens made for determining release strength are tested and assumed to represent the concrete in the member. The specimens made for determining design strength are then moist cured at room temperature until it is time to test them.

2.2 EXPLANATION OF MATCH CURE TECHNOLOGY

The concept of match cure technology is very simple, given that it is basically a direct application of the concrete maturity theory. This theory is based on the fact that temperature is a critical factor in the strength development of concrete, especially in the first 24 hours. The maturity of concrete is determined by multiplying an interval of time by the temperature of the concrete in question. This product is summed over time, and the maturity of the concrete is equal to the sum of these time-temperature products. In other words, maturity is simply the area under the time-versus-temperature plot. Maturity has been shown to be an excellent indication of the development of concrete from fresh concrete to hardened concrete. The following figure illustrates the calculation of maturity.

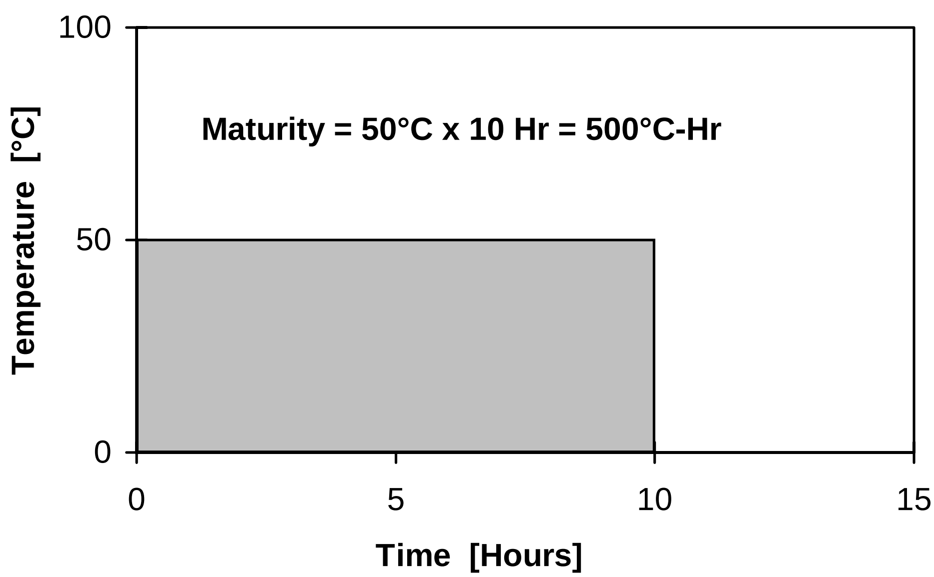

Figure 2.1 Calculation of maturity

Match cure technology implements the maturity concept to the curing of quality control specimens. By monitoring the internal temperature of a concrete member, the maturity of that concrete can be determined. Furthermore, the quality-control specimens can be cured at the same temperature profile over the same time period as was the actual concrete member. This procedure produces quality-control specimens that have a maturity equal to that of the concrete in the member. Moreover, the resulting quality-control specimens represent the actual concrete in the member better than traditional quality control specimens.

2.3 HISTORY OF MATCH CURE TECHNOLOGY

Usage of match cure technology, also referred to as temperature-matched curing, can be traced as far back as the late 1920s. At that time, laboratory research in England and the United States began investigating the effect of cement types, cement contents, and concrete placing temperatures on the temperature rise and strength development of the concrete. This was done by monitoring the temperature conditions within mass concrete and match curing specimens at the same temperature profile. The specimens were then compared with standard specimens cured at normal room temperatures (Ref 2).

In the 1970s, the John Laing Research and Development Company in England developed a temperature-matched curing system that was available for hire and use in the field. Several companies made use of the equipment for field applications that included the determination of the curing time required before removal of formwork. In the 1980s, the uses for match cure technology expanded to include determining stress transfer times and uses on slipform operation projects (Ref 2). In 1989, Hirst described the use of thermal matched cubes to accelerate fast-track construction on a major building in Blackwall Yard, London (Ref 3).

Over the last 30 years, several researchers have continued to use match cure technology to study the effect of curing temperature over time on the characteristics of concrete. While research continues in the laboratory, field use of the technology has become more prevalent as well. The primary use in the field has been to determine formwork striking times and prestress transfer times. Perhaps Cannon summarized the technology best when he wrote (Ref 2)

> temperature-matched curing, although not reproducing all in-situ conditions, does eliminate one of the major differences between ‘labcrete’ and ‘realcrete’, in that it can apply the temperature rise, as it occurs, to specimens of concrete identical to that being monitored.

2.4 CONCRETE CURING TEMPERATURES

According to Harrison, there are five factors that affect the curing temperature of fully hydrated concrete. Those factors are (1) types and quantities of cementitious materials, (2) size and shape of the section, (3) the insulating effectiveness of the formwork, (4) the concrete placing temperature, and (5) the ambient conditions (Ref 4). The combined effect of these factors often result in large temperature gradients within a member. Furthermore, the effect of the concrete temperature appears to be most critical in the first 24 to 48 hours of curing (Ref 5).

2.4.1 Cementitious Materials

The type and quantity of cementitious materials usually has the largest effect on the concrete temperature. It is generally accepted that the concrete temperature increases about 5.6 to 6.7° Celsius per 60 kilograms of cementitious material per cubic meter (10 to 12° Fahrenheit per 100 pounds of cementitious material per cubic yard). Carlton's research verified this relationship for both Type I and Type III cement (Ref 6). Although this estimate considers only the first factor on Harrison's list, it generally produces an accurate estimation.

The cementitious materials most commonly consist of cement and fly ash, with both materials influencing the amount of heat generated during hydration. However, it has been shown that the partial replacement of cement with fly ash has two effects: It reduces the total temperature rise of the concrete, and it delays the time at which the maximum temperature occurs (Ref 7).

2.4.2 Section Size and Shape

The section's size and shape also have a significant effect on the concrete temperature profile. It has been well documented that larger concrete sections produce larger internal temperature rises (Ref 2). The internal heat of hydration does not dissipate as quickly in massive sections as it does in thin or small sections. This is simply a result of the small surface-area-to-volume ratio that exists in large mass concrete members. Plum found that the internal temperature profile of a thick section follows a temperature profile similar to the adiabatic temperature profile of the concrete (Ref 5).

2.4.3 Formwork, Placing Temperature, and Ambient Conditions

The final three factors, according to Harrison, are the insulating effectiveness of the formwork, the concrete placing temperature, and the ambient conditions (Ref 4). Each of these factors can significantly affect the concrete curing temperature. The insulating effectiveness of the formwork can cause heat to be retained or dissipated in the concrete. The placing temperature of the concrete sets the level at which heat generation begins. And, finally, the ambient conditions affect how much heat is contributed from the environment to the concrete. All of these factors are important and should be considered when predicting the internal temperature rise of concrete.

2.5 EFFECT OF TEMPERATURE

Curing temperature is one of the critical factors that can affect the quality of the concrete. In the precast concrete industry, the most important short-term characteristic is concrete strength, given that concrete must develop strength quickly so that the transfer of prestress can occur. Once this transfer occurs, the long-term characteristics of the concrete become a concern. The concrete must develop adequate design strength with an acceptable modulus of elasticity. Creep and shrinkage of the concrete will affect the severity of prestress losses. Furthermore, permeability should be considered in order to address any durability concerns. All of these concrete characteristics are affected by the curing temperature of the concrete.

2.5.1 Compressive Strength

Temperature is the most important factor affecting the strength gain of concrete at early ages (Ref 8). During the first 24 hours, elevated temperatures tend to produce elevated strengths. Plum found that adiabatic curing conditions lead to early strength gain (Ref 5). However, there is a downside to this early strength gain: Concrete that is subjected to high early temperatures tends to develop lower later-age strengths (Ref 6). Since both early strength and long-term strength are important in the precast industry, the effect of curing temperature on compressive strength should be thoroughly researched.

2.5.2 Modulus of Elasticity

The effect of temperature on modulus of elasticity has been found to be similar to the effect on compressive strength. Cetin's research indicates that the elastic modulus development of high performance concrete tended to be higher at early ages for concrete that experienced accelerated heat curing. Furthermore, it was observed that the long-term development of modulus of concrete was lower for higher early-age curing temperatures (Ref 9). Other researchers have observed a similar result when investigating the modulus gain of concrete subjected to temperature matched curing. Tests by Khan et al. indicate that the rate of modulus gain increases as curing temperatures increased (Ref 10).

2.5.3 Permeability

Because permeability is an important factor affecting durability, the permeability of concrete should always be a concern. Cannon, in reviewing the research on this topic, found that the initial surface absorption of ordinary portland cement concrete increased with curing temperature, but that the opposite occurred for concretes containing fly ash. Further research on cement pastes and mortars confirmed this information. Most of the research was done using constant curing temperatures up to 60° C (140° F) (Ref 2). However, it is unclear how long of a pre-set period was used, how long the heat curing lasted, and at what age the concrete permeability was tested.

Research by Sherman et al. found that heat curing can substantially decrease the chloride ion permeability of concrete when compared to identical concrete moist-cured. In this study, heat curing began after approximately a 4-hour pre-set period, and the concrete was subjected to 63° C (145° F) air temperatures for 7.5 hours. The concrete was then air cured for 28 days before saltwater ponding began. The heat-cured concrete was compared with similar concrete that was moist cured at room temperatures for 7 days and then air cured until ponding began at 28 days. The concrete tested was a conventional portland cement mix with no fly ash. After 1 year of continuous saltwater ponding, the heat-cured concrete showed lower chloride ion penetration than the moist-cured concrete (Ref 11).

Sherman's study also included ASTM C 1202-94 "coulomb" testing to determine concrete permeability (Ref 12). Once again, heat cured specimens were compared with moist-cured specimens having the same concrete mix. The "coulomb" test was run after 42 days to make a rapid determination of the concrete permeability. The results of the study showed that the coulomb values of heat-cured specimens increased with water-cement ratio. The study also showed that coulomb values for heat-cured specimens were higher than the coulomb values for identical moist-cured specimens (Ref 11). This finding seems to disagree with the results of the saltwater ponding tests, but the age of testing differed by almost 1 year.

2.6 MATCH CURE VS. STANDARD CURE

The difference between quality-control specimens that are match cured and standard cured can be quite significant. Carlton found that current quality-control specimens are subjected to temperatures well below the actual temperatures in the member (Ref 6). This results in match cure specimens that have a higher compressive strength than the companion standard cured specimens at early ages; however, the ratio of match cure strength to standard cure strength decreases over time (Ref 13). In research by Mani et al., it was found that match cure specimens can develop 2 to 5 times the strength of standard specimens after 1 day. Over time, this ratio decreases to 1 or even less in some cases (Ref 7). All of these areas will be addressed in this research project.

Match cured specimens will also have an elastic modulus that differs from the standard cured specimens. Cetin found that the manner in which elastic modulus of concrete is affected by temperature is similar to how compressive strength is affected (Ref 9). Very little research has been undertaken to determine the effect of curing temperature on the permeability of concrete.

CHAPTER 3. EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

This chapter describes the experimental program established for investigating the use of match cure technology in the precast concrete industry. The program was broken down into three components, within which both high performance concrete and normal strength concrete were evaluated. The first component consisted of collecting temperature data from precast concrete members in the field. This was done at Texas Concrete in Victoria, Texas. The second component involved investigating the effect of curing temperatures on the 24-hour release characteristics of precast concrete. The release characteristics analyzed were compressive strength and modulus of elasticity. The final component looked at the effect of curing temperatures on the design characteristics of precast concrete. In the third phase, we examined the design characteristics of the concrete, including compressive strength, modulus of elasticity, and permeability.

3.2 TYPES OF CONCRETE

Given the differences in concrete characteristics, research was conducted on two types of concrete: high performance concrete (HPC) and normal strength concrete (NSC). The high performance concrete mix analyzed was developed for another research project at The University of Texas at Austin. This made it possible to collect HPC data in the field and in the lab. In order to maintain consistency, the design slump for the HPC mix was 200 millimeters (8 in.). The mix design is given in Table 3.1.

Table 3.1 Mix Design for high performance concrete

Material	Quantity	Unit	Description
Rock	1138	kg/m^3	12.7mm (½”) Crushed Limestone
Sand	610	kg/m^3	Natural Concrete River Sand
Water	147	kg/m^3	Potable
Cement	398	kg/m^3	Type III
Fly Ash	187	kg/m^3	Class C
Retarder	1.0	kg/m^3	ASTM C 494-92 Type D (Ref 14)
HRWR	8.4	kg/m^3	ASTM C 494-92 Type F (Ref 14)

Two normal strength concrete mixes were evaluated in this research project. Both mixes were used in the laboratory to evaluate the effect of curing temperature on the characteristics of normal strength concrete. The first mix was a six-sack mix with no fly ash. Consistency was controlled from mix to mix by keeping the slump at about 65 millimeters (2.5 in.). Table 3.2 details the mix proportions for the normal strength concrete containing no fly ash.

Table 3.2 Mix design for NSC without fly ash

Material	Quantity	Unit	Description
Rock	1112	kg/m^3	19mm (¾”) Crushed Limestone
Sand	768	kg/m^3	Natural Concrete River Sand
Water	148	kg/m^3	Potable
Cement	335	kg/m^3	Type III
Retarder	0.6	kg/m^3	ASTM C 494-92 Type D (Ref 14)
Reducer	1.8	kg/m^3	ASTM C 494-92 Type A (Ref 14)

The second normal strength concrete mix was a modification of the first NSC mix containing 25 percent cement replacement with fly ash. This modification made it possible to reduce the amount of water in the mix while keeping the slump at about 65 millimeters (2.5 in.). Table 3.3. contains the mixture proportions for the second NSC mix design.

Table 3.3 Mix design for NSC with fly ash

Material	Quantity	Unit	Description
Rock	1112	kg/m^3	19mm (¾") Crushed Limestone
Sand	768	kg/m^3	Natural Concrete River Gravel
Water	131	kg/m^3	Potable
Cement	251	kg/m^3	Type III
Fly Ash	84	kg/m^3	Class C
Retarder	0.6	kg/m^3	ASTM C 494-92 Type D (Ref 14)
Reducer	0.8	kg/m^3	ASTM C 494-92 Type A (Ref 14)

3.3 MEMBER TEMPERATURES

The internal temperatures generated in a member are affected by several different factors. The most important factor, as outlined in section 2.4, is the type and quantity of the cementitious materials in the concrete. For this reason, temperature data for both high performance concrete and normal strength concrete were collected in the field. The field data were used to develop a temperature profile model that was used in the laboratory for curing concrete under field temperature conditions.

3.3.1 High Performance Concrete

Temperature data for high performance concrete members were collected for two types of precast concrete beams. The first set of data was collected from U-54 girders produced in 1994 at Texas Concrete for another research project. The second set of data came from AASHTO Type IV girders produced in 1997 at Texas Concrete.

Temperatures were monitored using a SURE CURE system made by Products Engineering. The system uses an IBM-compatible PC in conjunction with an input/output unit to monitor and record the concrete temperature inside a member. Temperatures were measured using thermocouples placed inside the member before placement of the concrete. Shielded thermocouple wires were used to protect against electrical noise.

Thermocouples were placed at various points within each concrete member to monitor the variation in temperatures from location to location. For the U-54 girders, thermocouples were placed in the end block, the flange, and the web. Because the U-54 girder has a large end block, the effect of massive concrete sections on curing temperature was investigated. The flange and web thermocouples were placed to generate temperature data from the less massive areas of the member. This produced temperature data that reflected the hottest and coolest temperatures within the member.

The AASHTO Type IV girders were monitored in a similar manner. Initially, temperatures were monitored at several places along the vertical centerline of the member. After the first few casting dates, the thermocouple arrangement was modified as the critical temperature regions of the section were identified. For every casting date, thermocouples were place at three critical locations in the AASHTO Type IV girders: the end block, the upper flange, and the web. Once again, this generated data that reflected the two extreme temperature readings for the concrete in the member.

Finally, temperatures were measured within the standard quality-control cylinders that were cured directly next to the member. This was done to determine the curing temperature differences between the standard quality-control specimens and the actual concrete in the member.

3.3.2 Normal Strength Concrete

We collected temperature data for normal strength concrete as we did for high performance concrete. Once again, the data were collected at Texas Concrete; the NSC mix was the standard eight-sack mix used at that precast plant. Conveniently, Texas Concrete had a large database of recorded temperature profiles for their standard mix. This database allowed for a limited amount of further temperature data collection.

Normal strength concrete temperatures were monitored in two types of members — the AASHTO Type IV girder and the U-54 beam. Temperatures were obtained by placing thermocouples in the member and using the SURE CURE system to record the data. Furthermore, the temperature profiles of the standard quality control cylinders were recorded for each casting date.

3.3.3 Temperature Profile Model

After collecting temperature profiles for both high performance concrete and normal strength concrete in the field, we developed a temperature profile model from the data collected. The intent of the model was to provide consistent temperature profiles that could be used for curing specimens in the laboratory. By curing specimens using the same temperature profiles every time, comparisons could be made of the concrete characteristics from different mix dates. This model was not developed with the intent of predicting member temperatures in the field; it was developed only to represent a typical temperature profile from the field.

The temperature model was initially developed from the high performance concrete temperatures collected in the field. These temperatures varied over a wide range of maximum temperatures, with the model consisting of several curves that reflect that variation. As expected, the model did not fit every curve exactly, but it did fit most of the curves in general. The model was then compared with the normal strength concrete curves collected from the field. Once again, the model was found to fit the field curves reasonably well. This made it possible to use the same model when curing high performance concrete and normal strength concrete specimens in the laboratory. Figure 3.1 displays the curves developed for the temperature profile model.

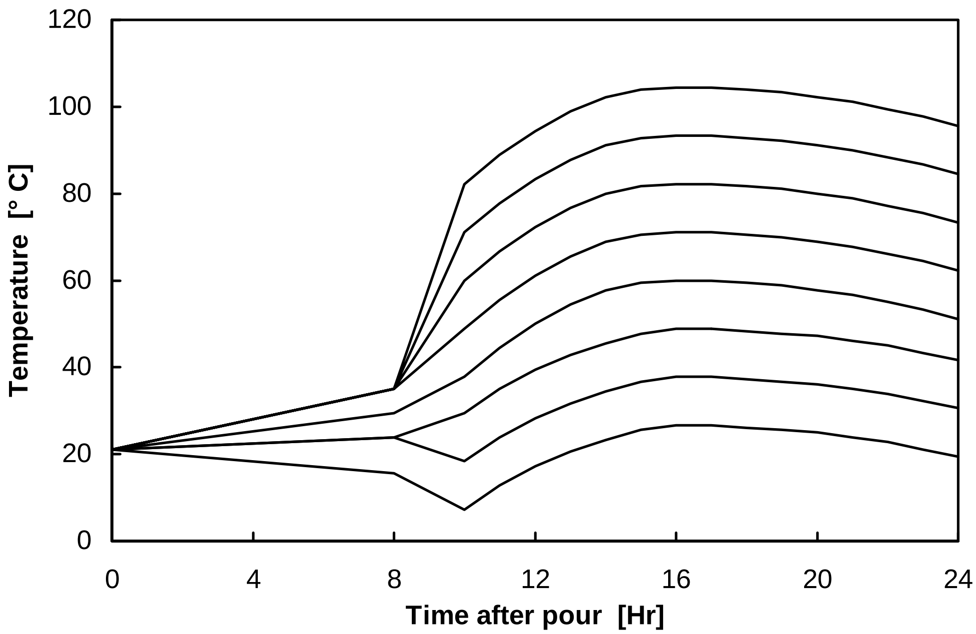

Figure 3.1 Temperature profile model

The temperature profile model has a few key characteristics that can be seen in the previous figure. First, the model starts at a temperature equal to the initial temperature of the fresh concrete. This temperature varies but is generally close to the 21° C (70° F) used in the model. Second, there is very little change in temperature during the first 8 hours. This period is referred to as the pre-set time, and it represents the period before significant cement hydration begins. The ambient temperature has the greatest effect on concrete temperature during this period. The third key characteristic is the maximum temperature achieved by each curve. This temperature occurs at the time of maximum heat generation, which usually occurs about 8 hours after the pre-set period ends. The maximum temperature is very important from a curing standpoint, and it is also useful when referring to each individual curve from the model. The final important characteristic is the cool-down period of the curve. This occurs after the heat generation peaks and the heat dissipation exceeds the internal heat generation owing to hydration. The insulating effect of the formwork and the ambient temperature have the greatest effect on the cool-down period. All of these characteristics can be seen in the temperature profile model.

A second model was developed by modifying the original model slightly. The modifications involved reducing the pre-set time to 4 hours and extending the cool-down period by 4 hours. This model represents a situation in which heat of hydration is accelerated owing to early steam curing by the precaster. The other characteristics of the model remained the same, as can be seen in the following figure.

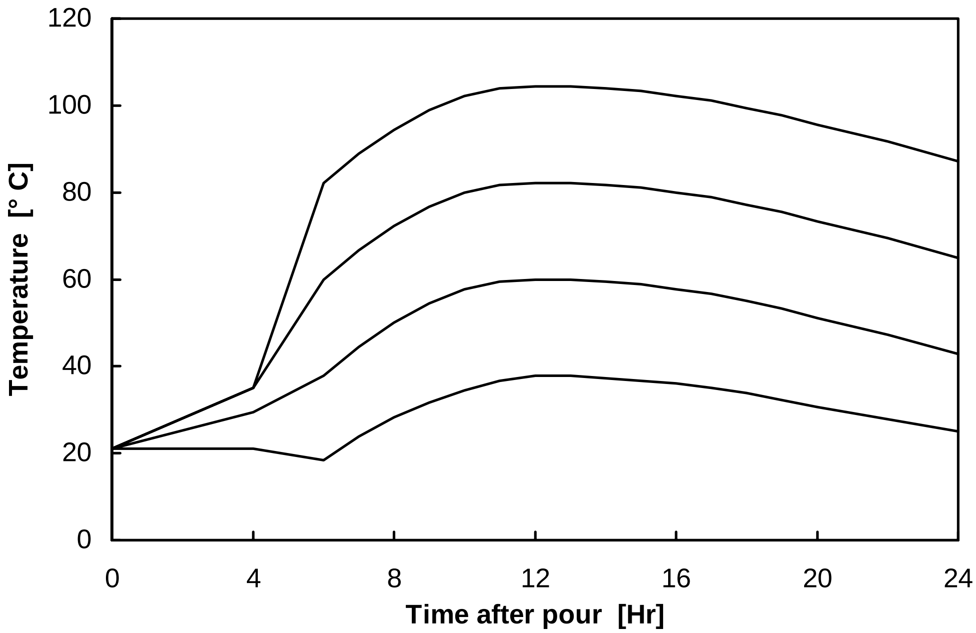

Figure 3.2 Four-hour pre-set temperature profile model

The second model contains half as many curves for two reasons. Based on experience with the first model, we found that fewer curves were needed to provide a significant data sample. Furthermore, the limitations of the SURE CURE system made curing four curves an ideal number. Despite the reduction in the number of curves, the second model still covers the entire range of temperatures that would be expected in the field.

3.4 RELEASE CHARACTERISTICS

There are three concrete characteristics that are important at the time of prestress release: compressive strength, flexural strength, and modulus of elasticity. Research was conducted on high performance concrete and normal strength concrete to determine the effect of the curing temperature profile on the 24-hour release characteristics of precast concrete. Because compressive strength and flexural strength are closely related, only compressive strength and modulus of elasticity were evaluated on this research project.

Release data were collected in the field at Texas Concrete from both AASHTO Type IV girders and U-54 girders. These data were then verified through laboratory testing using the temperature model profiles described in the previous section. Finally, a comparison was made between standard quality-control specimens and match cured specimens.

Three types of cylinders were made to evaluate the effect of curing temperature on the 24-hour release characteristics of concrete: member cured cylinders, match cured cylinders, and ASTM cylinders. All of the cylinders were 100 millimeters (4 in.) in diameter by 200 millimeters (8 in.) long and were made according to ASTM C 31/C 31M-95 procedure (Ref 15).

Member Cured Cylinders

This type of cylinder represents the standard quality-control cylinder used for testing release strength according to current TxDOT specifications. Member cured cylinders are placed directly next to the member until the time of release. The cylinder is generally covered by tarps placed over the entire member. This creates a situation where the cylinder is exposed to some of the heat generated by the member during hydration.

Match Cured Cylinders

Match cured cylinders were made using the SURE CURE system. In addition to the temperature recording capabilities described earlier, the SURE CURE system allows the user to cure cylinders following a specified temperature profile. This is done through the use of special cylinder molds that have the ability to heat the concrete in the mold. The molds have an internal temperature probe and a power connection. An IBM-compatible PC is used to monitor the temperature of the match cure cylinders and guide the input/output unit in regulating the power needed to heat the concrete in the molds. The computer directs the cylinder temperatures to follow a reference temperature profile being monitored simultaneously or a temperature profile programmed by the user. In the field, member temperatures were monitored at various locations in the member; thus, match cure cylinders were cured using several different reference temperatures. In the laboratory, cylinders were cured over a wide range of temperatures using the model temperature profile. This curing method produces cylinders that have a maturity at the time of testing equal to the actual concrete they were made to represent.

ASTM Cylinders

For every mixing date, cylinders were cured according to ASTM C 31/C 31M-95 procedure (Ref 15). This involves curing the cylinders in a 23° C (73° F) room for 24 hours and then removing the plastic cylinder molds. These cylinders were used as control cylinders to account for the differences in concrete from mix date to mix date.

Two characteristics of concrete were evaluated after 24 hours of curing at various temperature profiles: compressive strength and modulus of elasticity.

Compressive Strength

Cylinder compressive strengths were measured using a hydraulic, 2,669 kiloNewton (600 kip) capacity Forney testing machine. The cylinders were capped with unbonded neoprene pads using steel retaining rings, and the proper neoprene pad hardness was used for the different concrete strengths tested. All compressive strength testing was performed according to ASTM C 39-94 procedure (Ref 16).

Modulus of Elasticity

The elastic modulus of the concrete was determined using a compressometer. The specimens were loaded to 40 percent of their expected ultimate strength and the elastic deformation was recorded. Based on this information, a modulus of elasticity was calculated according to ASTM C 469-94 (Ref 17).

After collecting 24-hour release data from specimens made and cured in the field, laboratory testing was performed to verify the field data. The field specimens were cured using actual member temperature profiles that were being monitored simultaneously with the curing of the specimen. The laboratory specimens were cured using the model temperature profile that was developed from actual field temperatures. The data were then compared to determine the effect of curing temperatures on the 24-hour release characteristics of precast concrete quality control specimens.

3.5 DESIGN CHARACTERISTICS

From a concrete quality standpoint, three design characteristics are important within the precast concrete industry: compressive strength, modulus of elasticity, and permeability. Research was conducted on high performance concrete and normal strength concrete to determine the effect of curing temperatures on the long-term characteristics of precast concrete. Field data were collected at Texas Concrete from both AASHTO Type IV girders and U-54 beams. These data were then verified through laboratory testing using the model temperature profiles developed from field temperature data. Finally, a comparison was made between standard quality-control specimens and match cured specimens.

Several types of cylinders were made to evaluate the effect of curing temperature on the long-term design characteristics of concrete. All of the cylinders were 100 millimeters (4 in.) in diameter by 200 millimeters (8 in.) long and were made according to ASTM C 31/C 31M-95 procedure (Ref 15). The different cylinder types are described below.

TxDOT Cylinders

This type of cylinder is the standard quality control specimen for determining design strength according to TxDOT specifications. The cylinders are placed next to the member until the time of release in the same manner as member cured cylinders for release strength. Then the cylinder is removed from the mold and moist cured at approximately 23° C (73° F) until it is time to test for design strength. For normal strength concrete, design strength is tested at 28 days. The design strength of high performance concrete is tested at 56 days.

Member Cured Cylinders

Member cured cylinders are also placed next to the member until the time of prestress release, as described in the previous section. Then the cylinder is removed from the mold and air cured outside under cover at ambient temperatures. This subjects the specimen to a long-term temperature profile that is similar to that which the member experiences while curing in the casting yard.

Match Cured/Moist Cylinders

This type of cylinder is very similar to the TxDOT cylinder. However, instead of placing the cylinder next to the member, the cylinder is match cured until prestress release using the SURE CURE system. Cylinders were cured at temperature profiles from different locations in the member — at the end block, web, and flange. The cylinder was then moist cured until it was time to test. These cylinders were then compared with the TxDOT cylinders to determine the effect of curing temperatures on the concrete characteristics.

Match Cured/Dry Cylinders

This type of cylinder is very similar to the member cured cylinder described previously. The only difference is that the cylinder was match cured until release. The cylinder was then air cured outside under cover at ambient temperatures until testing. The characteristics of these cylinders were compared with the member cured cylinders.

ASTM Cylinders

ASTM cylinders were made on every mix date according to ASTM C 31/ C 31M-95 procedure (Ref 15). The cylinders were cured in a 23° C (73° F) room for 24 hours, the molds were removed, and then the cylinders were moist cured at 23° C (73° F) until testing. These cylinders were used as control cylinders.

The effect of curing temperature was evaluated for three long-term concrete characteristics: compressive strength, modulus of elasticity, and permeability.

Compressive Strength

Compressive strength was tested in a manner similar to that described in section 3.4. All testing was done according to ASTM C 39-94 guidelines (Ref 16).

Modulus of Elasticity

The elastic modulus was determined using the procedure described in section 3.4. Testing was performed following ASTM C 469-94 procedures (Ref 17).

Permeability

The permeability of concrete specimens was measured according to ASTM C 1202-94, "Electrical Indication of Concrete's Ability To Resist Chloride Ion Penetration" (Ref 12). The test involves measuring the electrical current that passes through a 4 inch diameter by 2 inch thick slice of concrete. The total charge passed has been found to be related to the resistance of the specimen to chloride ion penetration. The following table details the ASTM guidelines for evaluating the results of the test.

Table 3.4 Chloride ion penetrability (Ref 12)

Charge Passed (coulombs)	**Chloride Ion Penetrability**
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
<100	Negligible

After collecting design data from specimens made and cured in the field, laboratory testing was performed to verify the field data. The field specimens were cured using actual member temperature profiles that were being monitored simultaneously with the curing of the specimen. The laboratory specimens were cured using the model temperature profile that was developed from actual field temperatures. The data were then compared to determine the effect of curing temperatures on the design characteristics of precast concrete.

CHAPTER 4. TEST RESULTS

4.1 INTRODUCTION

This chapter presents the data collected from the experimental program described in Chapter 3. Member temperature data were collected from field precast, prestressed beam members at Texas Concrete in Victoria, Texas. The effect of curing temperature on three concrete characteristics was evaluated. These characteristics included compressive strength, modulus of elasticity, and permeability. In most cases, the concrete characteristics were determined as the average of two companion test specimens.

4.2 MEMBER TEMPERATURES

Several member temperature profiles were recorded using the SURE CURE system. Two types of beams, Texas U-54 girders and AASHTO Type IV girders, were analyzed; both contained high performance concrete and normal strength concrete. A few selected temperature profiles are shown in Figures 4.1 through 4.3.

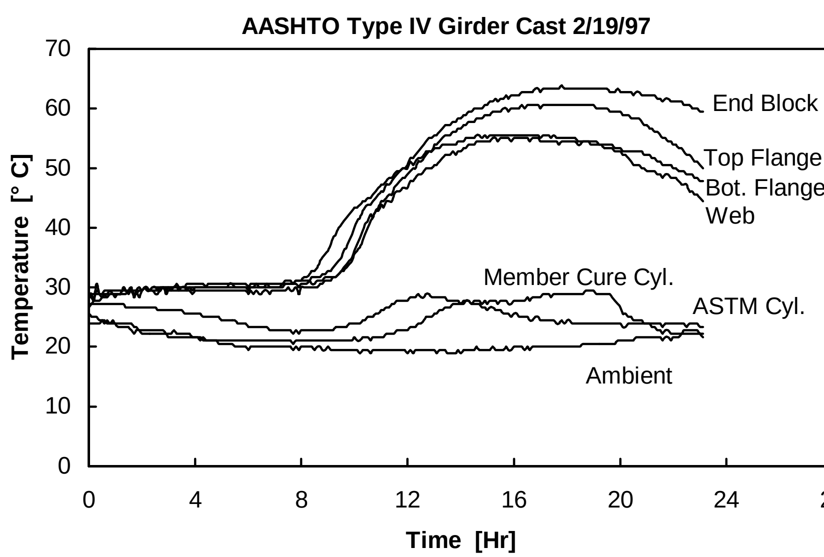

Figure 4.1 HPC temperature profile

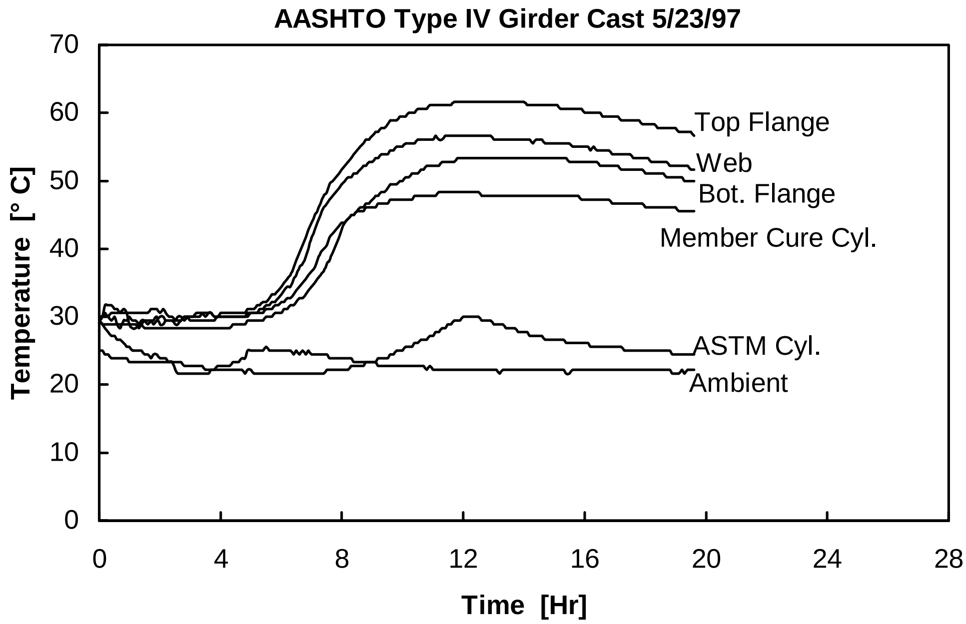

Figure 4.2 NSC temperature profile

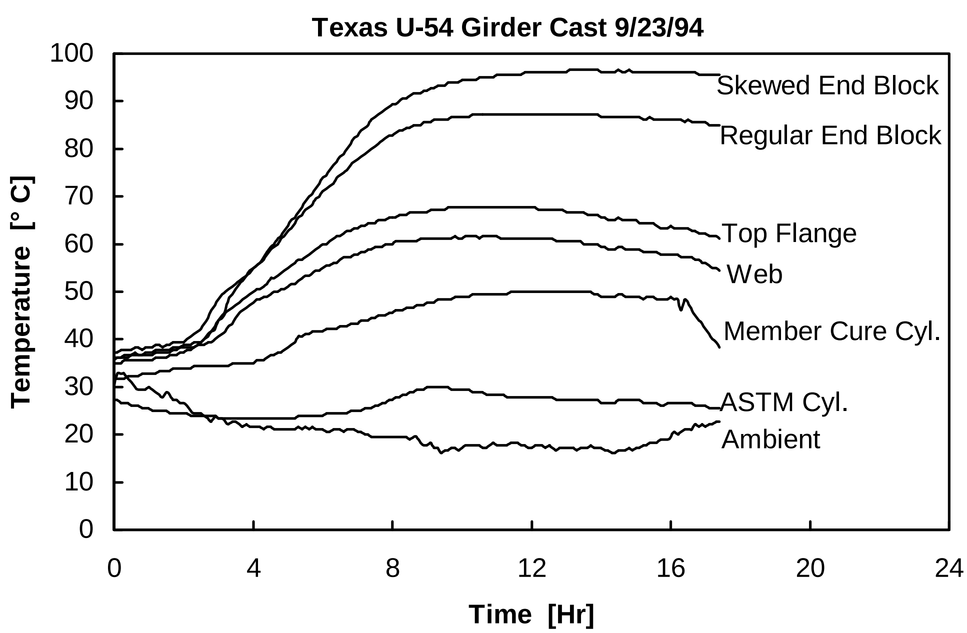

Figure 4.3 HPC temperature profile with 4-hour pre-set

Figures 4.1 and 4.2 represent a typical field temperature profile with an 8-hour pre-set period. As seen in these figures, the temperature profiles for both normal strength concrete and high performance concrete are similar. Figure 4.3 displays a temperature profile with a 4-hour pre-set period. The profile is comparable to those shown in Figures 4.1 and 4.2; however, the curve is shifted to the left by about 4 hours and the maximum temperature is different. (More field temperature profiles can be found in Appendix A.) Tables 4.1 through 4.3 summarize the maximum internal concrete temperatures recorded in the field.

Table 4.1 Texas U-54 girder maximum temperatures for HPC

Date	**Skewed End Block (° C)**	**Regular End Block (° C)**	**Web (° C)**	**Flange (° C)**	**Member Cure Cyl. (° C)**
9/23/94	97	87	62	68	50
9/30/94	95	85	32	34	52
10/7/94	95	90	65	69	57
10/29/94	85	79	60	61	56
11/10/94	83	78	54	58	50

Table 4.2 AASHTO Type IV girder maximum temperatures for HPC

Date	**End Block (° C)**	**Top Flange (° C)**	**Web (° C)**	**Member Cure Cyl. (° C)**
2/19/97	64	61	55	29
2/25/97	54	52	41	41
3/3/97	64	62	-	53
3/8/97	61	59	54	47
3/15/97	59	53	50	41
3/22/97	69	67	61	53
3/29/97	74	64	56	33
4/7/97	75	60	68	47
4/12/97	46	44	38	31
4/18/97	66	62	57	47
4/28/97	73	67	63	51

Table 4.3 NSC maximum temperatures

Date	Beam Type	Top Flange (° C)	Web (° C)	Bottom Flange (° C)	Member Cure Cyl. (° C)
5/23/97	Type IV	62	57	53	48
1/2/97	Type IV	-	67	-	61
1/3/97	Type IV	-	66	-	56
1/3/97	Type IV	-	66	-	61
1/10/97	Type IV	-	60	-	56
1/24/97	Type IV	-	59	-	57
1/29/97	Type IV	-	53	-	51
1/7/97	U-54	-	49	-	44
1/17/97	U-54	-	53	-	48
1/31/97	U-54	-	44	-	51

The same high performance concrete mix was used in the Texas U-54 girders and AASHTO Type IV girders, from which the temperature data were collected. The mix design for the HPC mix can be found in Table 3.1, and the temperature data for that mix can be found in Tables 4.1 and 4.2. The temperature data for normal strength concrete were collected at Texas Concrete. The NSC mix was the standard eight-sack mix used at that precast plant. Table 4.3 summarizes the temperature data collected for that mix.

4.3 RELEASE CHARACTERISTICS

The effect of curing temperature on the 24-hour compressive strength and modulus of elasticity of concrete was examined. The following three types of concrete were evaluated: high performance concrete, normal strength concrete without fly ash, and normal strength concrete with fly ash. Furthermore, specimens were cured in the laboratory using both the 8-hour and 4-hour pre-set temperature profile models. Data from the laboratory will be compared with field data cured under the same conditions.

In some cases, concrete was mixed on different days and cured under the same conditions. Because of this, it was necessary to normalize the results from different mixing dates so that the data could be compared. Normalization was done using the ASTM control cylinders that were made for every mix. Compressive strength and modulus of elasticity values from each test specimen were divided by the corresponding ASTM values from the same concrete. This value was then multiplied by a standard strength or modulus value that varied for each mix type. When normalization was necessary, the results are reported as adjusted strength or adjusted modulus. This can be seen in the following figures, which display the 24-hour release characteristics of each concrete type tested.

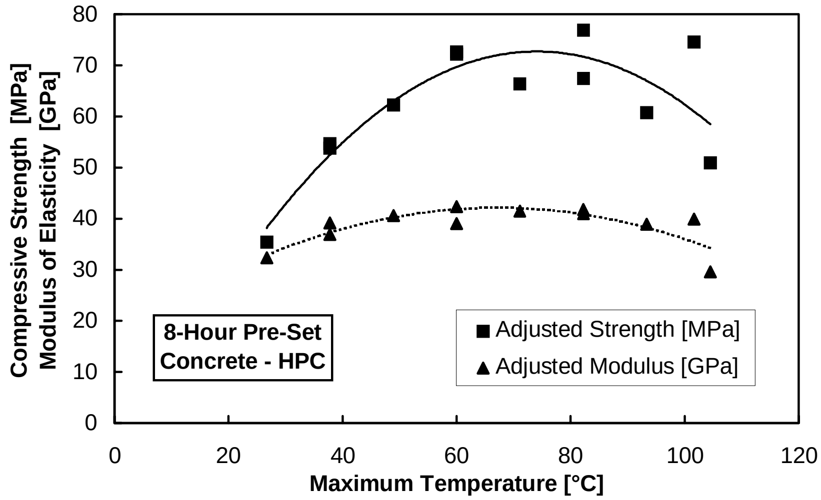

Figure 4.4 Release data for HPC cured with an 8-hour pre-set period

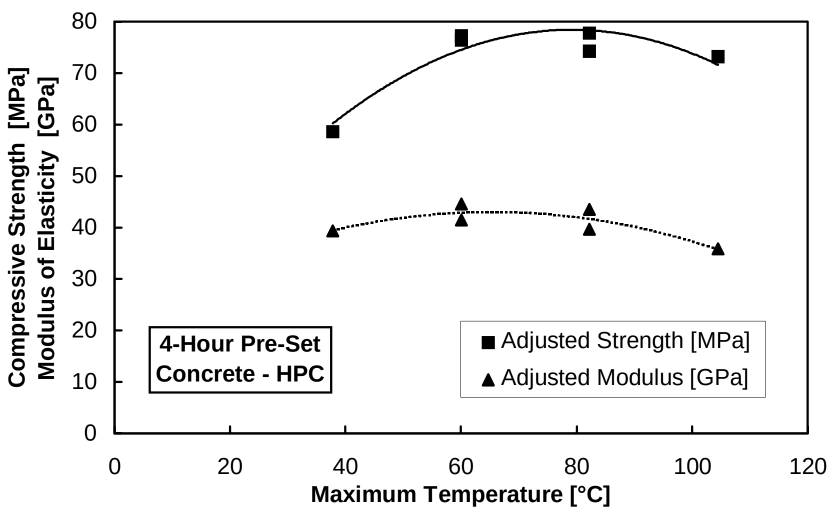

Figure 4.5 Release data for HPC cured with a 4-hour pre-set period

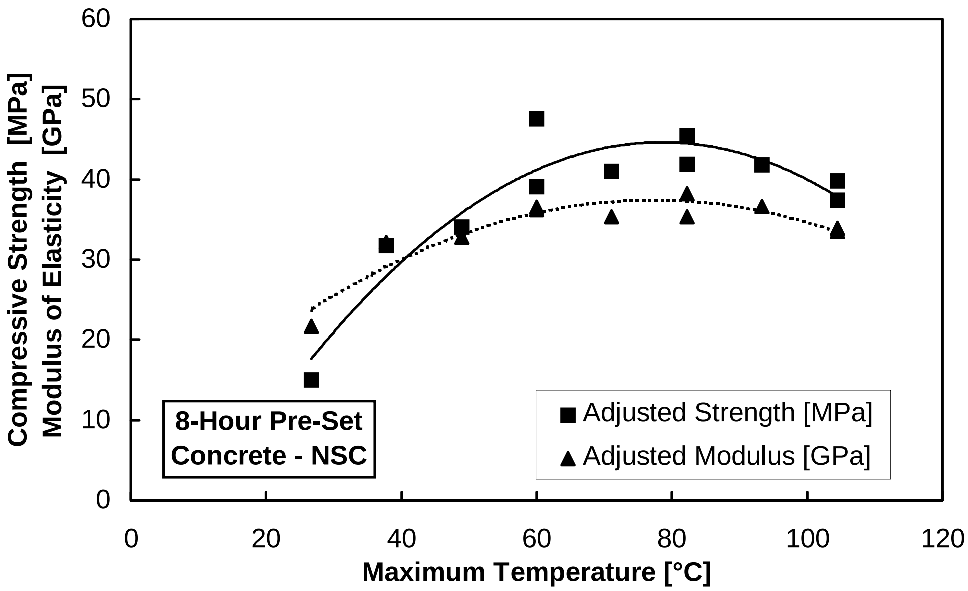

Figure 4.6 Release data for NSC cured with an 8-hour pre-set period

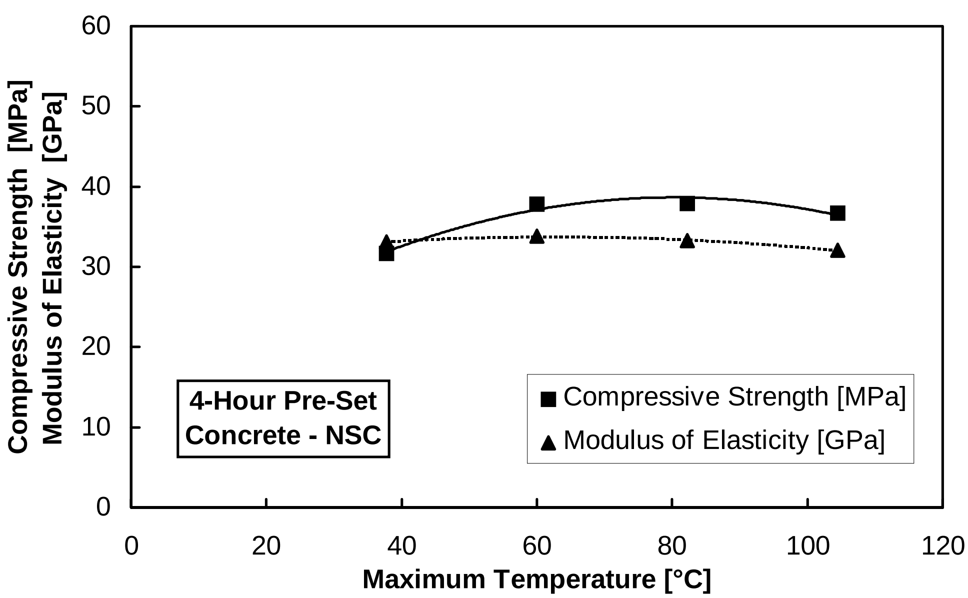

Figure 4.7 Release data for NSC cured with a 4-hour pre-set period

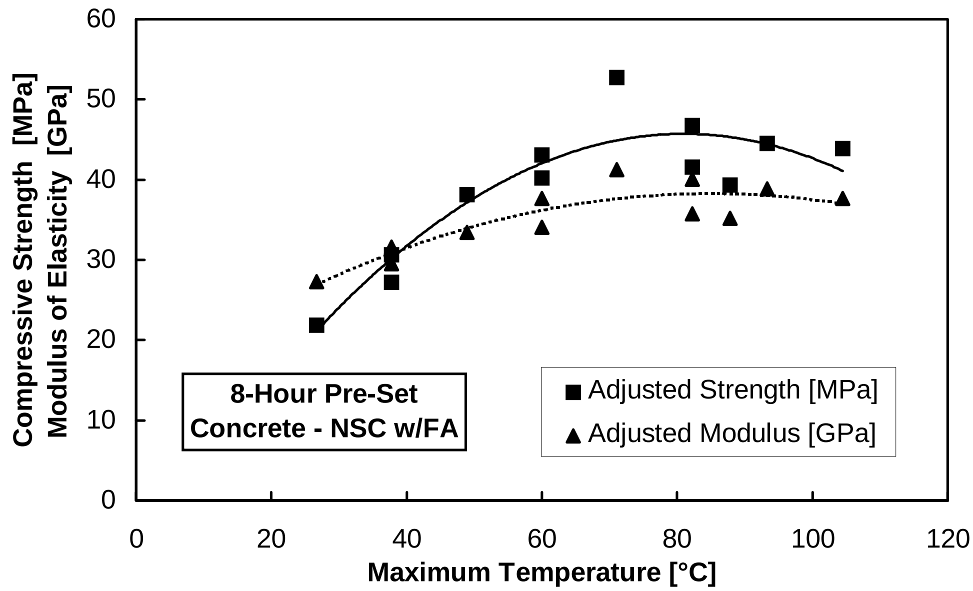

Figure 4.8 Release data for NSC with fly ash cured with an 8-hour pre-set period

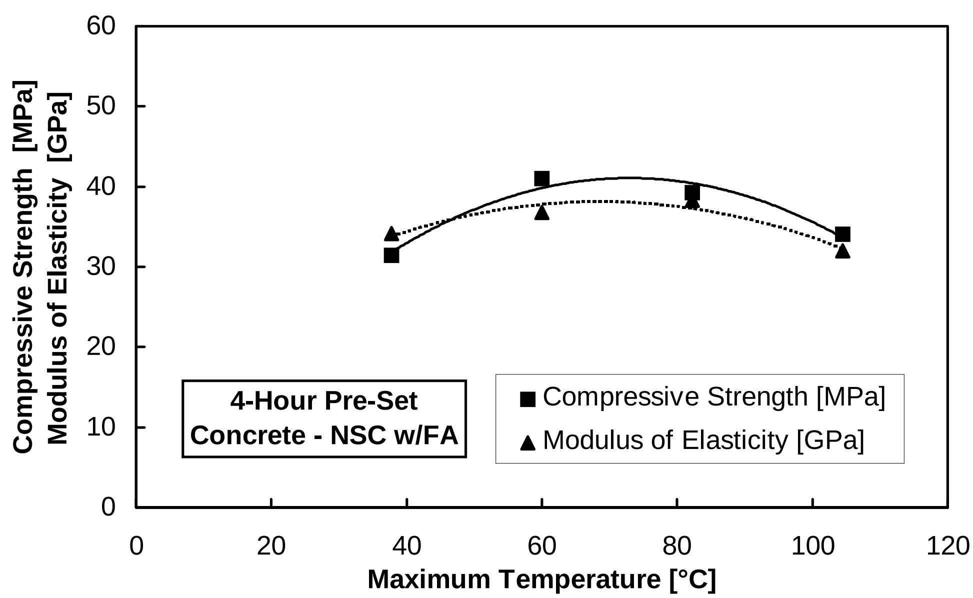

Figure 4.9 Release data for NSC with fly ash cured with a 4-hour pre-set period

In Figures 4.4 through 4.9, trendlines were added by fitting a second-order polynomial through the data using the least squares fit method. The solid curve represents the trendline through the compressive strength data, and the dashed line represents the trendline through the modulus of elasticity data. These trendlines will be used for comparison with the concrete characteristics collected from the field. The laboratory and field data can be found in tabular form in Appendix B.

4.4 DESIGN CHARACTERISTICS

Three design characteristics of each concrete type were evaluated in this research project: compressive strength, modulus of elasticity, and permeability. Once again, normalization of the data was performed when necessary to account for the differences in the same type of concrete mixed on different days.

The following figures display the compressive strength and modulus of elasticity data collected for the HPC mix.

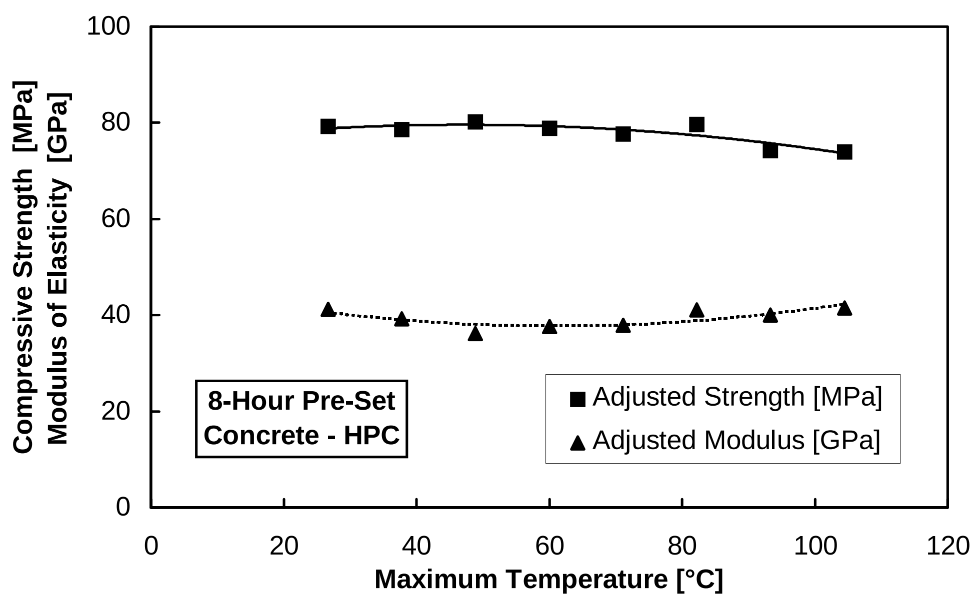

Figure 4.10 Fifty-six-day data for HPC match/air cured cylinders

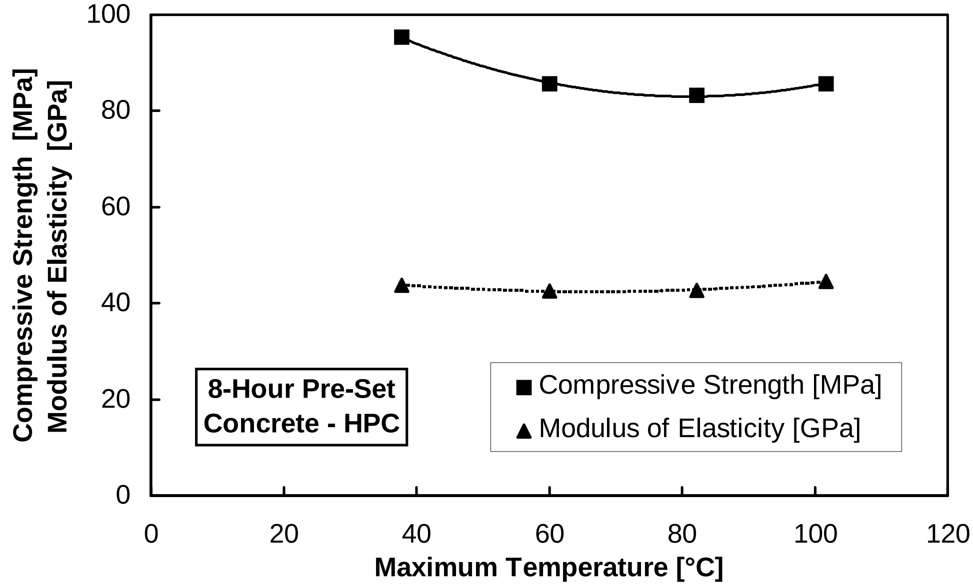

Figure 4.11 Fifty-six-day data for HPC match/moist cured cylinders

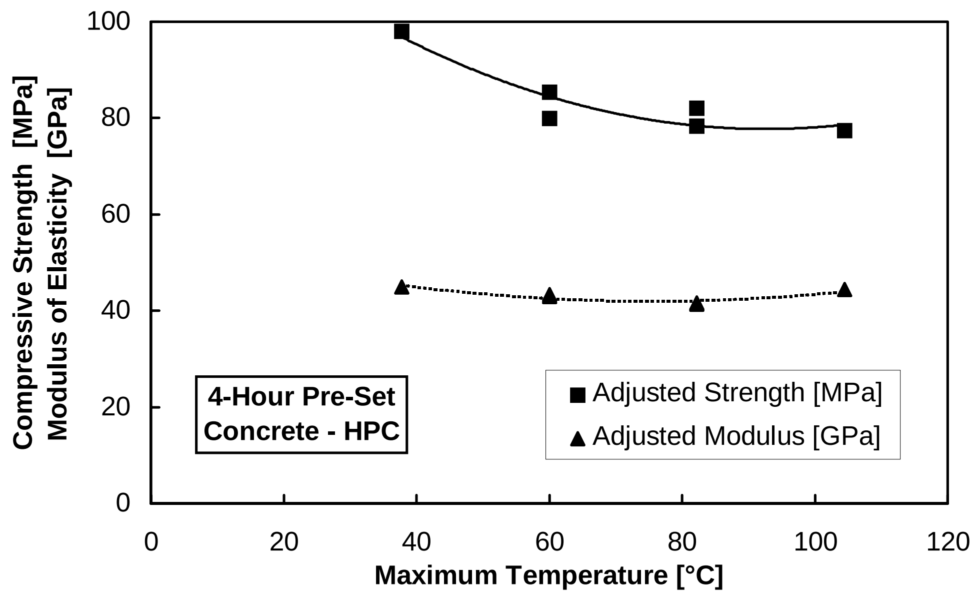

Figure 4.12 Fifty-six-day data for HPC match/moist cured cylinders with a 4-hour pre-set period

The effect of curing temperature on the design compressive strength and modulus of elasticity of normal strength concrete was also evaluated. The same procedure that was used to analyze the HPC mix was used to analyze both NSC mixes. Cylinders were both moist cured at 23° C (73° F) and air cured outside under cover at ambient temperatures. (A graph of the ambient curing temperatures can be found in Appendix C.) Furthermore, the effect of the 8-hour pre-set period and the 4-hour pre-set period was evaluated. The following figures display the results of the NSC testing.

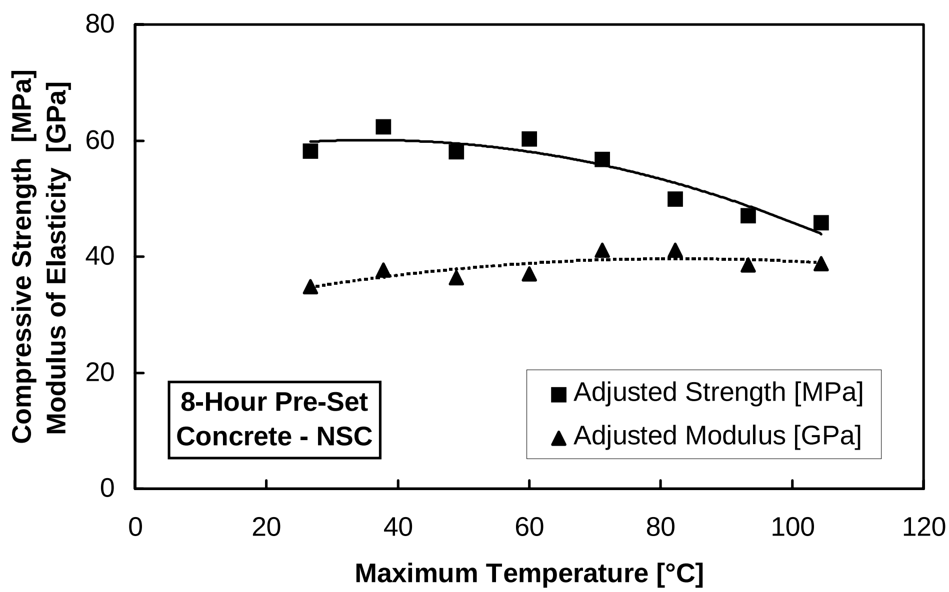

Figure 4.13 Twenty-eight-day data for NSC match/air cured cylinders

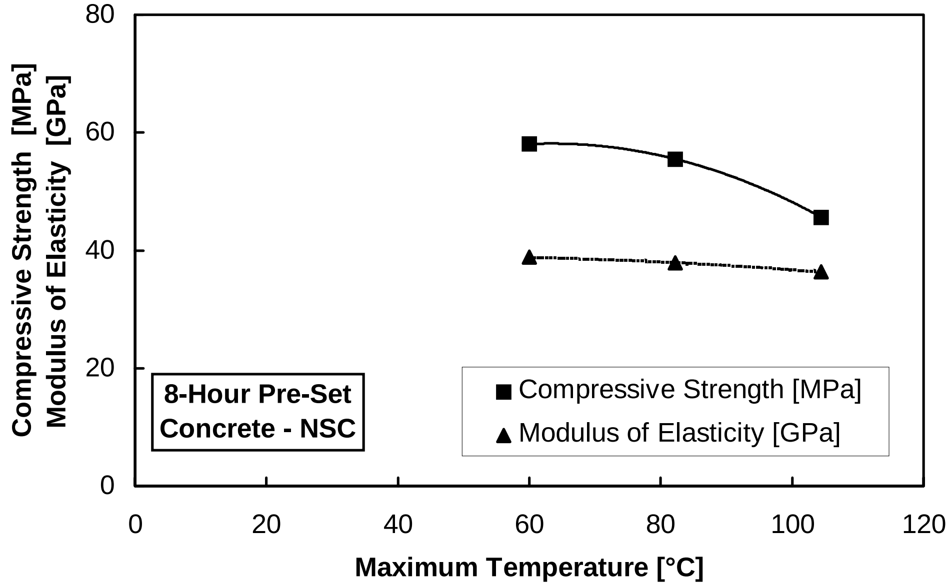

Figure 4.14 Twenty-eight-day data for NSC match/moist cured cylinders

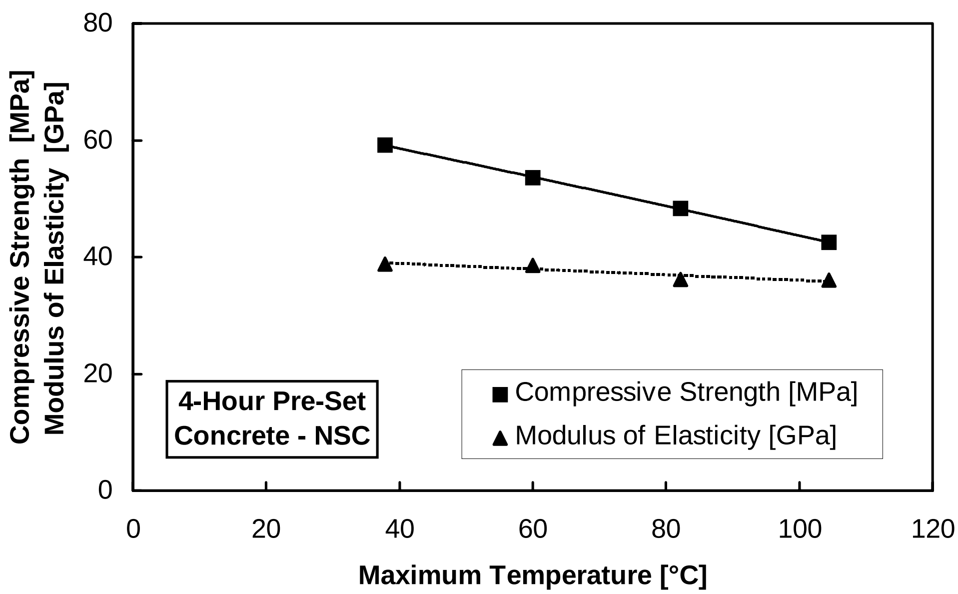

Figure 4.15 Twenty-eight-day data for NSC match/moist cured cylinders with a 4-hour pre-set period

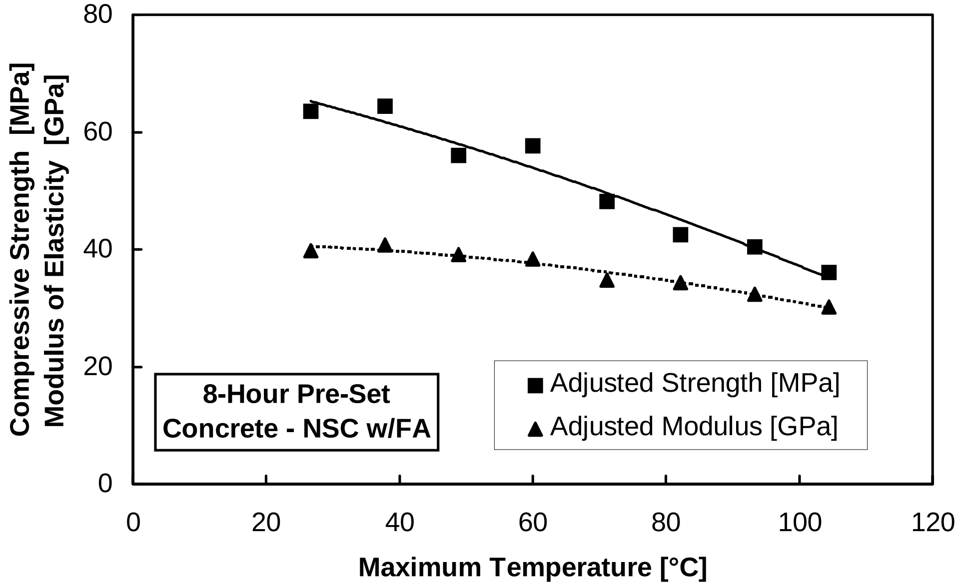

Figure 4.16 Twenty-eight-day data for NSC with fly ash match/air cured cylinders

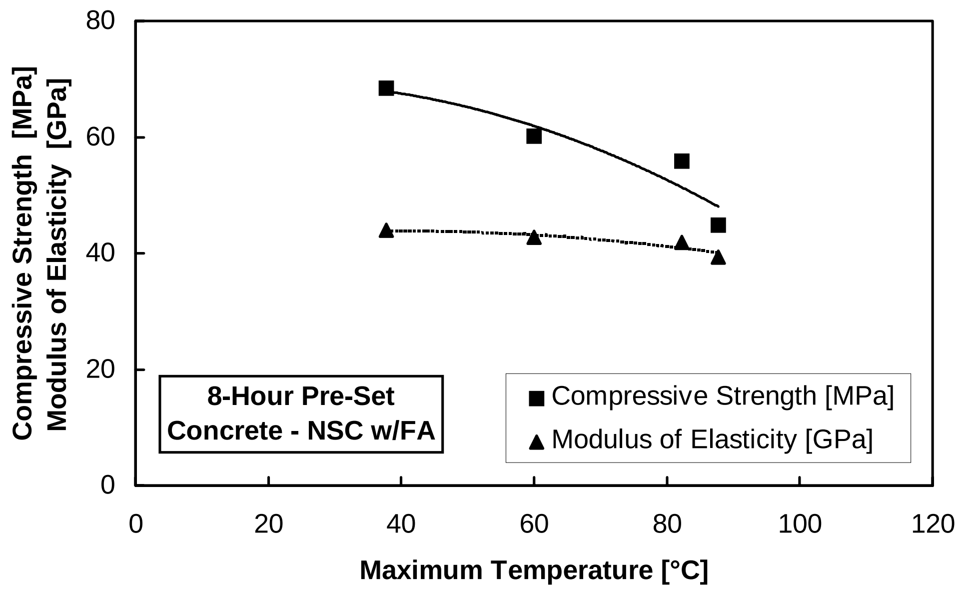

Figure 4.17 Twenty-eight-day data for NSC with fly ash match/moist cured cylinders

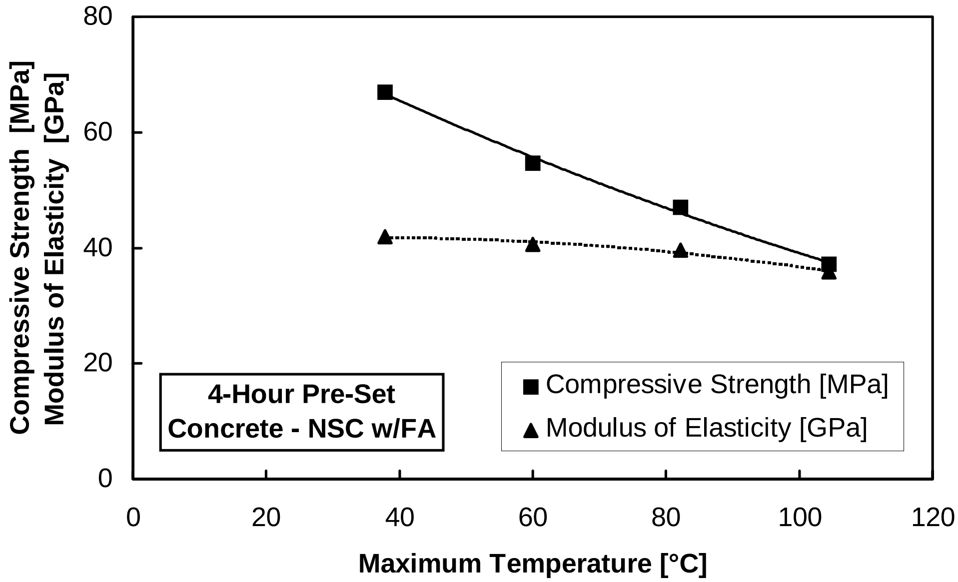

Figure 4.18 Twenty-eight-day data for NSC with fly ash match/moist cured cylinders with a 4-hour pre-set period

In Figures 4.10 through 4.18, trendlines were drawn using the procedure described in the release characteristics' section. Once again, these trendlines will be used to compare the results of laboratory testing with data collected from the field.

The final design characteristic analyzed was permeability. Specimens were cured in the laboratory using the model temperature profile and tested to determine the chloride ion penetrability as per ASTM C 1202-94 (Ref 12). Table 4.1 outlines the permeability results for the HPC mix. The cylinders were cured for 24 hours using the SURE CURE system and then air cured outside under cover at ambient temperatures until testing.

Table 4.4 Permeability data for HPC

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	56	580	Very Low
Match/Air	38	56	1070	Low
Match/Air	60	56	1410	Low
Match/Air	93	56	3100	Moderate
ASTM	-	90	370	Very Low
Match/Air	38	90	950	Very Low
Match/Air	60	90	910	Very Low
Match/Air	93	90	870	Very Low

(1) As per ASTM C 1202-94 (Ref 12)

The same procedure was used for both normal strength concrete without fly ash and normal strength concrete with fly ash. Tables 4.2 and 4.3 outline the data collected.

Table 4.5 Permeability data for NSC without fly ash

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	2100	Moderate
Match/Air	38	28	2700	Moderate
Match/Air	60	28	2700	Moderate
Match/Air	93	28	2830	Moderate
ASTM	-	90	1630	Low
Match/Air	38	90	1740	Low
Match/Air	60	90	2140	Moderate
Match/Air	93	90	2170	Moderate

(1) As per ASTM C 1202-94 (Ref 12)

Table 4.6 Permeability data for NSC with fly ash

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	4620	High
Match/Air	38	28	2900	Moderate
Match/Air	60	28	2580	Moderate
Match/Air	93	28	5910	High
ASTM	-	90	2660	Moderate
Match/Air	38	90	1740	Low
Match/Air	60	90	1830	Low
Match/Air	93	90	4230	High

(1) As per ASTM C 1202-94 (Ref 12)

Given the excellent permeability results obtained for the high performance concrete mix, no further testing was performed on that mix. However, we decided that further research was required on the two normal strength mixes. Thus, we examined the effect of moist curing after 24 hours of match curing using the SURE CURE system and the model temperature profile. This examination was performed for both the 8-hour pre-set period and the 4-hour pre-set period. Tables 4.7 through 4.10 document the results obtained.

Table 4.7 Permeability data for NSC without fly ash cured with an 8-hour pre-set period

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	3900	Moderate
Match/Moist	60	28	4190	High
Match/Moist	82	28	3820	Moderate
Match/Moist	104	28	5460	High
ASTM	-	90	1950	Low
Match/Moist	60	90	2790	Moderate
Match/Moist	82	90	2750	Moderate
Match/Moist	104	90	3240	Moderate

(1) As per ASTM C 1202-94 (Ref 12)

Table 4.8 Permeability data for NSC without fly ash cured with a 4-hour pre-set period

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	4410	High
Match/Moist	38	28	4940	High
Match/Moist	60	28	3950	Moderate
Match/Moist	82	28	5310	High
Match/Moist	104	28	6720	High
ASTM	-	90	2610	Moderate
Match/Moist	38	90	2660	Moderate
Match/Moist	60	90	2790	Moderate
Match/Moist	82	90	3840	Moderate
Match/Moist	104	90	3930	Moderate

(1) As per ASTM C 1202-94 (Ref 12)

Table 4.9 Permeability data for NSC with fly ash cured with an 8-hour pre-set period

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	3610	Moderate
Match/Moist	38	28	4120	High
Match/Moist	60	28	2150	Moderate
Match/Moist	82	28	2360	Moderate
Match/Moist	88	28	4790	High
ASTM	-	90	1620	Low
Match/Moist	38	90	1630	Low
Match/Moist	60	90	1140	Low
Match/Moist	82	90	1510	Low
Match/Moist	88	90	2870	Moderate

(1) As per ASTM C 1202-94 (Ref 12)

Table 4.10 Permeability data for NSC with fly ash cured with a 4-hour pre-set period

Cylinder Type	**Max. Temp. (°C)**	**Testing Age (days)**	**Charge Passed (coulombs)**	**Chloride Ion Penetrability[1]**
ASTM	-	28	4220	High
Match/Moist	38	28	3610	Moderate
Match/Moist	60	28	2060	Moderate
Match/Moist	82	28	2470	Moderate
Match/Moist	104	28	6190	High
ASTM	-	90	1670	Low
Match/Moist	38	90	1530	Low
Match/Moist	60	90	1140	Low
Match/Moist	82	90	1570	Low
Match/Moist	104	90	2810	Moderate

(1) As per ASTM C 1202-94 (Ref 12)

CHAPTER 5. ANALYSIS AND DISCUSSION

5.1 INTRODUCTION

This chapter analyzes and discusses the data presented in Chapter 4. Specifically, it examines the variation in member temperature profiles for different concrete types and member locations. Throughout this chapter, the internal concrete curing temperature is referred to as *curing temperature.* The effect of the member temperature profile on the release and design characteristics of concrete is also evaluated. Finally, we undertake a statistical analysis of the data to determine the validity of the conclusions drawn.

5.2 MEMBER TEMPERATURE PROFILES

Several member temperature profiles were monitored in the field for both high performance concrete and normal strength concrete. Figures 4.1 through 4.3 show typical member temperature profiles (several more profiles can be found in Appendix A).

As seen in Figures 4.1 through 4.3, the internal member temperature varies depending on the location within the member. Because of the large concrete mass, the highest temperature will generally occur in the end block of a section. The data from both the AASHTO Type IV beams and U-54 beams support this conclusion. On the other hand, the web is usually the coolest portion of the member, a result of its being so thin. The flange generally reaches a temperature that is between the end block and web. For the AASHTO Type IV beam, the top flange is usually slightly hotter than the bottom flange. As heat is generated in the lower portion of a member, it rises and supplies additional heat to the top flange. Given that both the hottest and coolest internal temperatures will be the most critical, the temperature in the end block and the web of a section should be monitored in most cases. Table 5.1 summarizes the heat generation measured in the field as a function of cementitious material content.

Table 5.1 Heat generation measured in the field

Beam Type	Steam Curing?	Temperature Location	Heat Generation (°C/60 kg cementitious/m^3)		
			High	**Low**	**Average**
U-54	No	Skewed End Block	6.2	5.3	**5.8**
U-54	No	Regular End Block	5.4	4.8	**5.1**
U-54	No	Web	3.8	0.3	**2.4**
U-54	No	Flange	3.7	0.5	**2.8**
U-54	Yes	Web	5.0	3.6	**4.4**
Type IV	No	End Block	4.8	2.0	**3.7**
Type IV	No	Web	4.1	1.3	**2.7**
Type IV	No	Top Flange	4.2	1.9	**3.2**
Type IV	No	Bottom Flange	3.2	2.8	**3.0**
Type IV	Yes	Web	5.4	4.4	**5.1**

It is generally accepted that the concrete temperature increases about 5.6 to 6.7° Celsius per 60 kilograms of cementitious material per cubic meter (10 to 12° Fahrenheit per 100 pounds of cementitious material per cubic yard). As seen in Table 5.1, this estimate is accurate only for the hottest locations in a member. The end block of the Texas U-54 girder, being very massive, generates very high internal heat. Table 5.1 also indicates that steam curing causes the heat generation values to increase. This is due to the additional heat supplied to the member by the steam. It should be noted that all of the field temperatures measured came from concrete containing fly ash. Since fly ash does not generate as much heat as cement, the heat generation values in Table 5.1 are lower than they would be if the mixes did not contain partial cement replacement with fly ash.

The difference in temperature between the actual concrete in the member and the quality-control cylinder can be quite significant. As seen in Figure 4.1, the web reached a temperature that was 22° C (40° F) hotter than the member cure cylinder, while the end block was 33° C (60° F) hotter. Figure 4.3 shows a case where the concrete in the end block was 44° C (80° F) hotter than the member cured cylinder. Figures 5.1 and 5.2 summarize the maximum and minimum differences between the concrete temperature in the member and the temperature of the member cured cylinder.

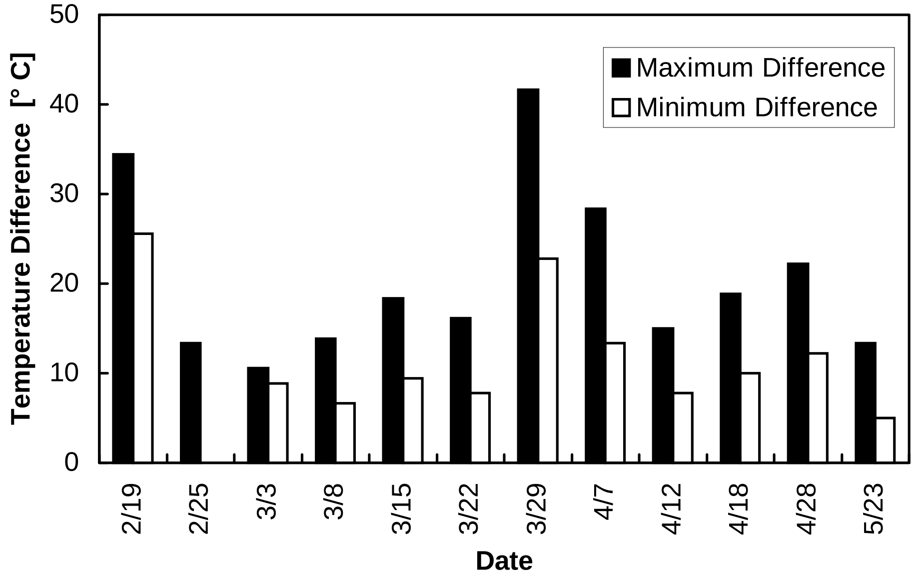

Figure 5.1 Difference between member concrete temperature and member cured cylinder for AASHTO Type IV girders

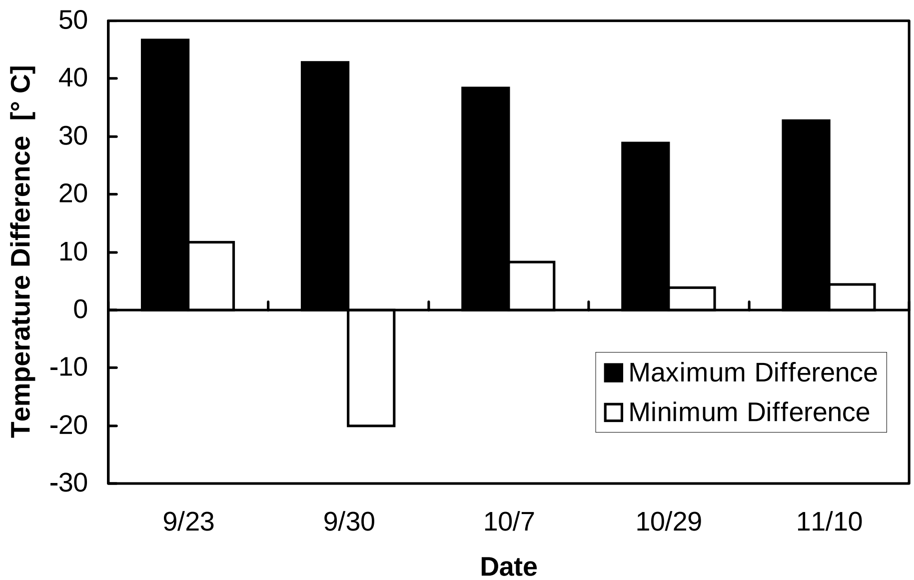

Figure 5.2 Difference between member concrete temperature and member cured cylinder for Texas U-54 girders

As shown in the previous figures, the temperature difference between the concrete in the member and the member cured cylinder is highly variable. For both girder types, the maximum difference was as high as 44° C (80° F), and the minimum difference ranged from 25° C to -20° C (45° F to -36° F). A minimum difference of negative 20° C (36° F) means that the member cured cylinder was 20° C (36° F) hotter than the lowest temperature in the member. Most importantly, in many cases the member cured cylinder reaches a temperature that is much different than the temperature of the concrete in the member. Given that this is a common occurrence in the precast concrete industry, it is perhaps time to start accounting for actual internal member temperatures.

The model temperature profile was developed from field temperature profiles for use in the laboratory. The intent of the model was not to predict member temperatures, but to represent a typical case. The following figure displays the fit of the model temperature profile to some typical field temperatures.

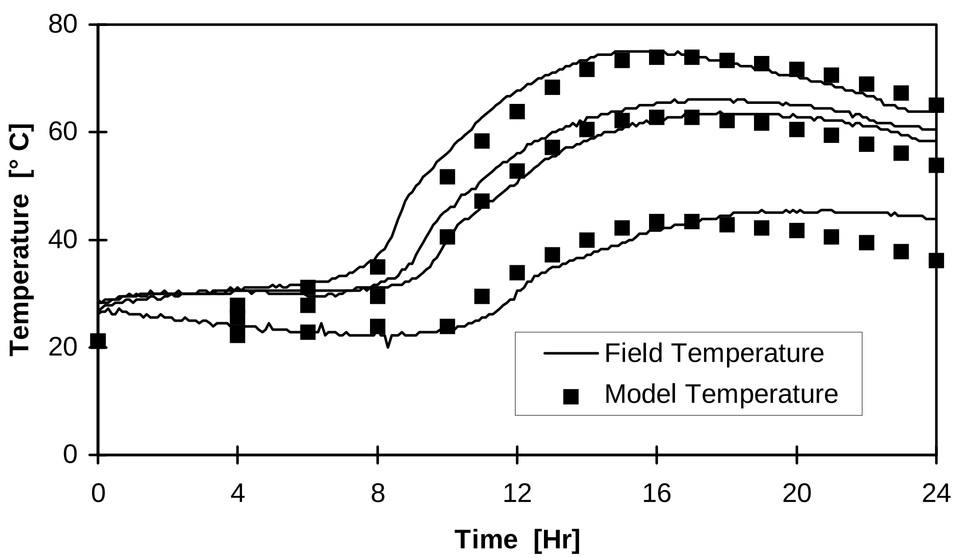

Figure 5.3 Model temperature profile fit

In Figure 5.3, the solid curve represents actual member temperatures recorded in the field, while the square dots represent the model temperature profile. As seen in the figure, the model fits the recorded field curves very well. The model temperature profile was used in the laboratory to cure specimens under typical field temperature conditions.

5.3 RELEASE CHARACTERISTICS

The effect of 24-hour curing temperature on the release characteristics of precast concrete is very dramatic. As seen in Figures 4.4 through 4.9 in the previous chapter, compressive strength and modulus of elasticity are affected by temperature in a similar manner. Both characteristics tend to increase with curing temperature up to approximately 71° C to 82° C (160° to 180° F). However, as curing temperature continues to increase, both compressive strength and modulus of elasticity start to decrease. This trend was observed for all three types of concrete tested and for both the 8-hour and 4-hour pre-set temperature profile models. The following figure, representing a typical case, displays these observations.

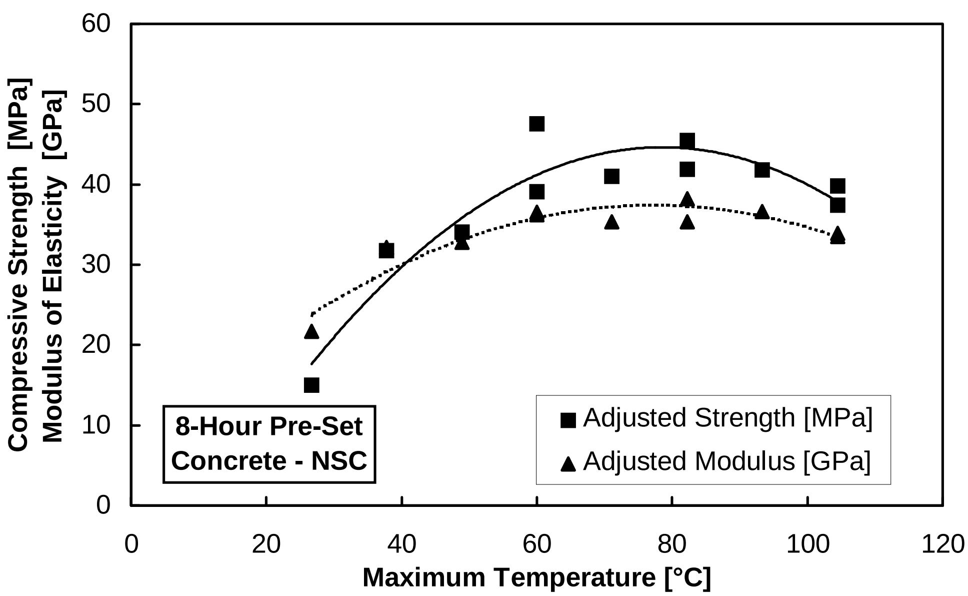

Figure 5.4 Typical case of release characteristics

There is a simple explanation why compressive strength and modulus of elasticity increase with curing temperature up to about 71° to 82° C (160° to 180° F). Referring back to concrete maturity theory, the maturity of concrete is basically the area under the time versus temperature profile. As curing temperatures increase, the maturity of the concrete also increases. Consequently, concrete that is cured at higher temperatures essentially ages quicker. Moreover, the concrete will gain strength quickly and reach a higher modulus of elasticity.

For temperatures above 82° C (180° F), the situation gets more complicated. Extremely high curing temperatures may affect the crystalline structure development of the concrete. Because cement hydration is accelerated by heat, extremely high curing temperatures may force the cement to hydrate too quickly. This could create concrete that is unable to develop the same crystalline structure it would at lower curing temperatures. Furthermore, the concrete would not fully develop to its potential strength and elastic modulus capabilities.

The situation continues to get worse for temperatures above 93° C (200° F). As curing temperatures approach the boiling point of water, free water in the concrete will start to vaporize. This could induce within the concrete internal stresses resulting from the pressure created by the vaporized water. These stresses could then cause microcracking, which would further decrease the compressive strength and modulus of elasticity of the concrete.

The release data collected in the laboratory compare relatively well with the data collected in the field. Figure 5.5 presents a comparison of compressive strength for the laboratory data and the field data.

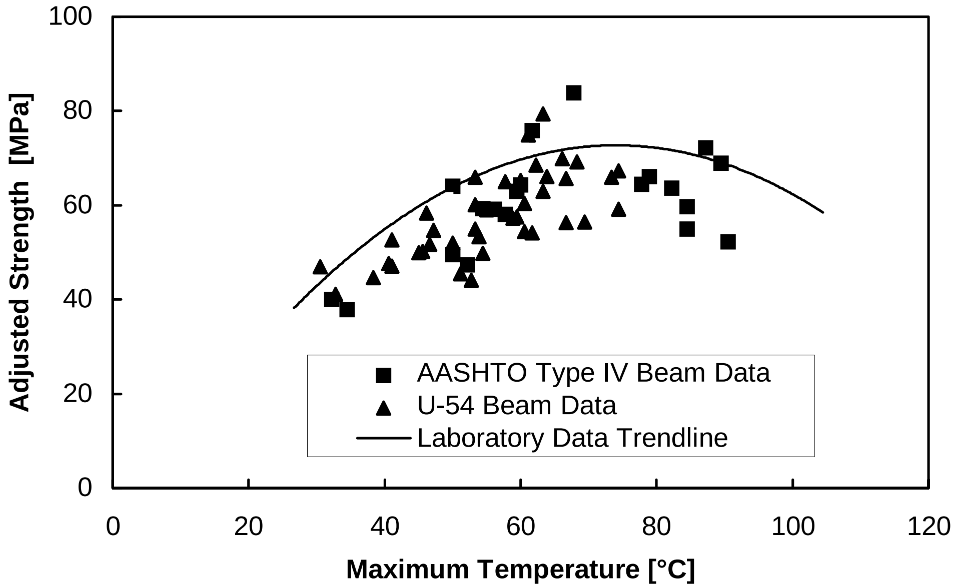

Figure 5.5 Comparison of compressive strength data for laboratory and field specimens

Figure 5.5 contains field data from both AASHTO Type IV beams and U-54 beams. The U-54 beam data were collected by Carlton at Texas Concrete in 1994, and the AASHTO Type IV beam data were collected in 1997 as part of this study. The same high performance concrete mix was used for both beams in the field as well as in the laboratory.

As seen in Figure 5.5, the laboratory trendline and the field data follow the same trend. For both data sets, compressive strength increases up to about 71° C (160° F) and then decreases above that temperature. Most importantly, the highest release strengths in the field came from specimens that were cured at about 71° C (160° F). Testing in the laboratory supports the conclusion that no further strength gain occurs when curing temperature exceeds about 71° C (160° F).

The laboratory trendline in Figure 5.5 does slightly overestimate the compressive strength of the field data. This is due to the fact that quality control in the laboratory is easier to monitor and maintain. Because of this, laboratory specimens are generally 5 to 15 percent higher in strength than specimens made in the field.

The modulus of elasticity data from the field and the laboratory trendline also fit very well. Because modulus data were not collected from the U-54 beams, field modulus values are available only for the concrete from AASHTO Type IV beams. Figure 5.6 shows a comparison of the laboratory and field modulus data for the HPC mix.

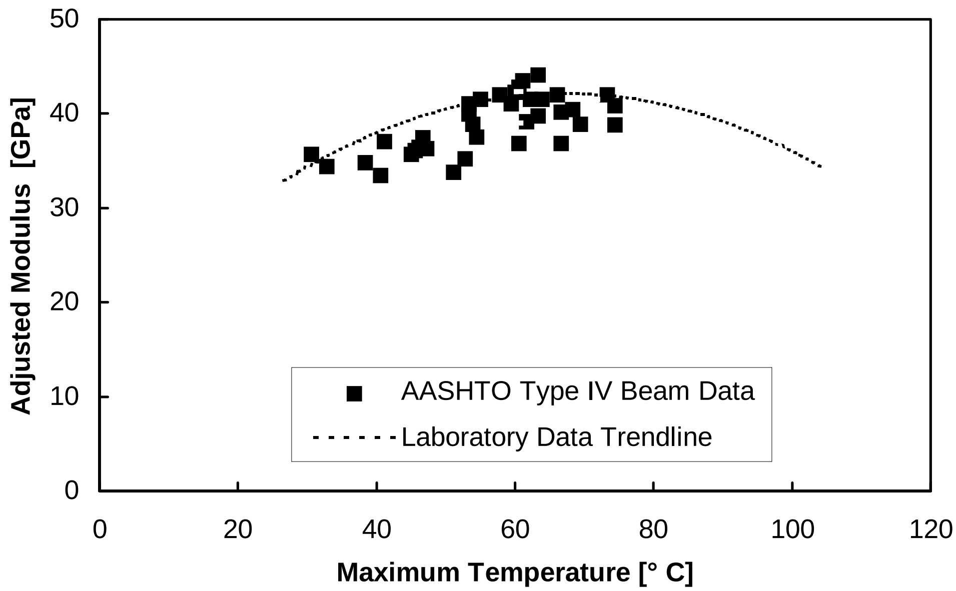

Figure 5.6 Comparison of modulus of elasticity data for laboratory and field specimens

As seen in Figure 5.6, modulus of elasticity values from the field increase with 24-hour curing temperature up to about 66° C (150° F). The field data appear to decrease after that temperature, though very little field data were available above 66° C (150° F). Based on the information collected, the field data and the laboratory data fit very well.

5.4 DESIGN CHARACTERISTICS

Research was undertaken on the design characteristics of three concrete mixes: high performance concrete, normal strength concrete without fly ash, and normal strength concrete with fly ash. The effect of the curing temperature profile on compressive strength, modulus of elasticity, and permeability was also evaluated.

5.4.1 Compressive Strength

The effect of 24-hour curing temperatures on the 56-day design compressive strength of HPC can be seen in Figures 4.10 through 4.12. All three figures show that compressive strength decreases as maximum curing temperature increases. The drop in strength is slightly greater on the 4-hour pre-set curve shown in Figure 4.12. For that case, the average strength of the cylinders cured at 104° C (220° F) is about 20 percent less than that for the cylinders cured at 38° C (100° F). In Figure 4.11, the 8-hour pre-set case has only a 10 percent drop in strength from the 38° C (100° F) cylinders to the 104° C (220° F) cylinders. Figure 5.7 displays the difference between the 8-hour pre-set and the 4-hour pre-set strength trendlines for the moist cured specimens.

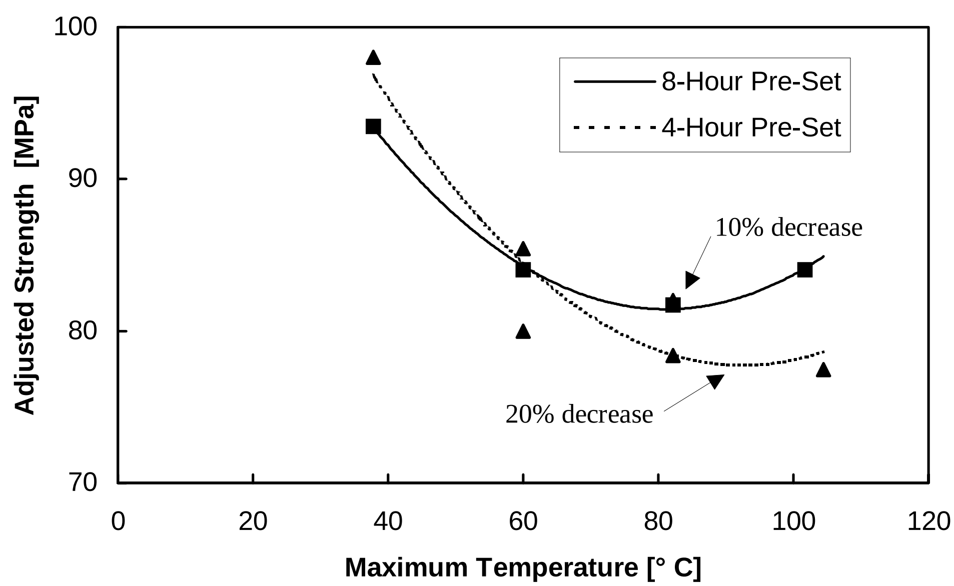

Figure 5.7 Compressive strength decrease of 8-hour and 4-hour pre-set specimens for the HPC mix

The reasons for the continual decrease in compressive strength is probably a result of the factors discussed in section 5.3. As curing temperature increases, hydration of the cement accelerates. Such action could result in concrete that hardens too quickly to develop the strong and dense crystalline matrix it is capable of developing. The fact that the 4-hour pre-set curve is affected the most seems to support this theory. Furthermore, any microcracking that occurred as a result of vapor pressure in the first 24 hours will also affect the long-term strength of the concrete. Both of these factors most likely contribute to the decrease in compressive strength observed.

Figures 4.13 through 4.18 display the effect of curing temperature on the 28-day compressive strength of the two normal strength concrete mixes. As seen in these figures, the results were even more dramatic than those observed for the high performance concrete mix. Although both normal strength mixes showed significant strength reduction, the normal strength mix with fly ash appears to be the most affected.

The normal strength mix without fly ash experienced a larger drop in design compressive strength than did the high performance mix. In Figure 4.15, the specimens cured with a 4-hour pre-set period experienced almost a 30 percent drop in average strength from the cylinders cured at 104° C (220° F) to the cylinders cured at 38° C (100° F). The 8-hour pre-set cylinders in Figure 4.14 experienced a 20 percent drop in strength. As seen with the HPC mix, the 4-hour pre-set period produced a decrease in design compressive strength larger than that for the 8-hour pre-set period.

As seen in Figures 4.16 through 4.18, the normal strength concrete with fly ash was the mix most affected by maximum curing temperature. There is a 45 percent drop in compressive strength shown in Figures 4.16 and 4.18. This is by far the largest decrease in compressive strength observed for the three mix types evaluated.

For the normal strength mix with fly ash, the effect of the pre-set period appears to be less dramatic than what was seen in the previous two mixes. Figure 5.8 displays the difference in strength loss for the 8-hour and 4-hour pre-set periods.

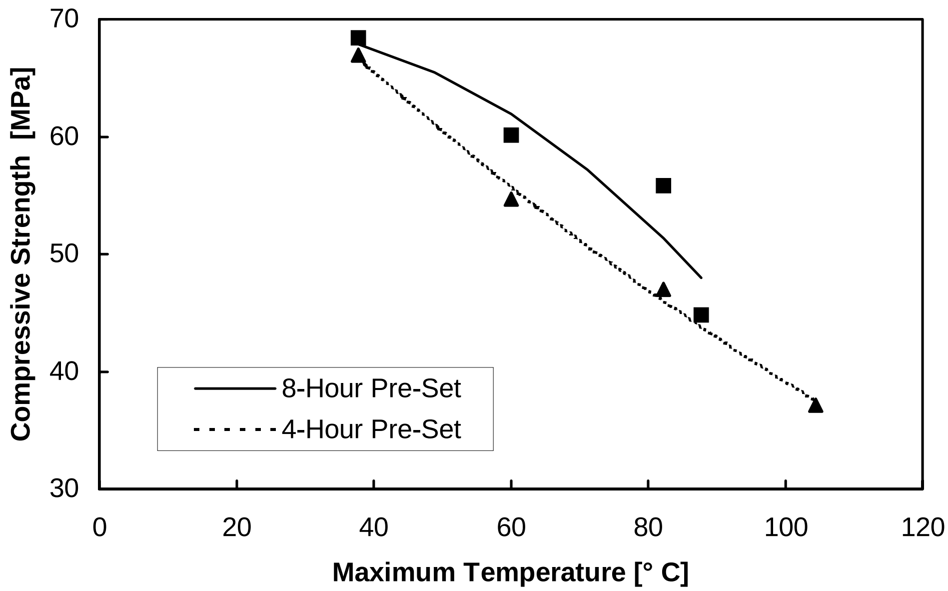

Figure 5.8 Compressive strength decrease of 8-hour and 4-hour pre-set specimens for the NSC mix with fly ash

In Figure 5.8, the two trendlines appear to be decreasing at a similar rate. The 8-hour pre-set curve is slightly more bowed, so the effect of curing temperature on those specimens was not as significant at lower curing temperatures. However, at higher temperatures both trendlines are decreasing at about the same rate. When compared with the other two mixes analyzed, the difference in strength between the 8-hour and 4-hour pre-set specimens is not as large.

The effect of maximum curing temperature on the compressive strength of normal strength concrete is very similar to the effect on high performance concrete. However, NSC seems to experience a larger decrease in strength as curing temperature increases. This response is most likely due to the lower cement content and higher water-cement ratio in the normal strength concrete mixes. Since the cement particles are separated by a larger distance in the normal strength mixes, the cement matrix is less dense. As curing temperatures increase, cement hydration is accelerated. This leads to the formation of a weak cement matrix. Therefore, the lower the cement content and higher the water-cement ratio, the more the concrete will be affected by high curing temperatures. Figure 5.9 displays the effect of curing temperature on the design strength for the three mixes.

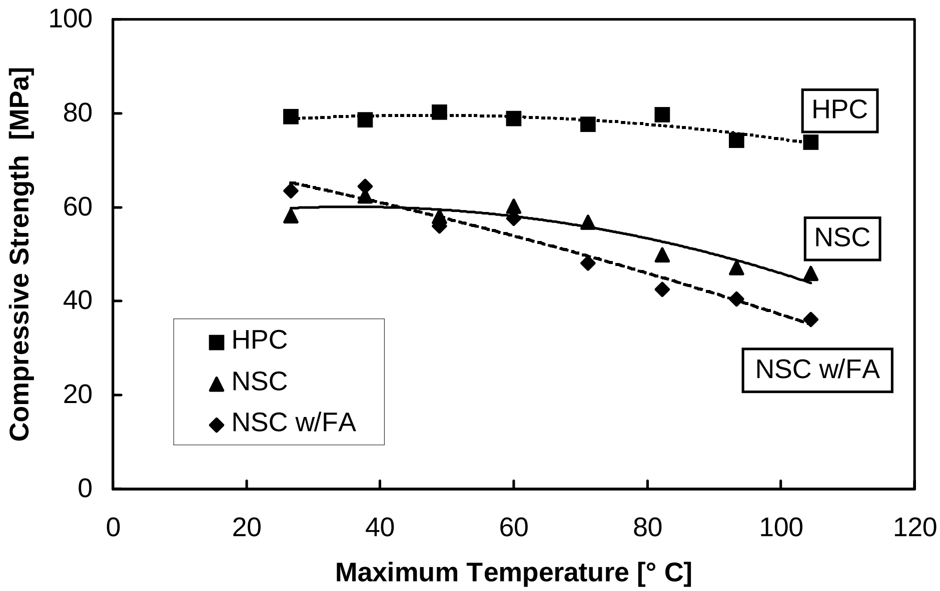

Figure 5.9 Compressive strength decrease for the three mixes evaluated

The laboratory data collected for design compressive strength compare very well with the HPC data collected in the field. A comparison can be made between field specimens and laboratory specimens cured under the same conditions. This means that moist cured cylinders from the field are compared with moist cured cylinders from the laboratory. The same comparison can be made for air cured specimens. Figure 5.10 compares air cured specimens from the field with the laboratory trendline, while Figure 5.11 compares moist cured specimens. In both figures, the laboratory trendline extends beyond the field data because a wider range of temperatures were cured in the laboratory.

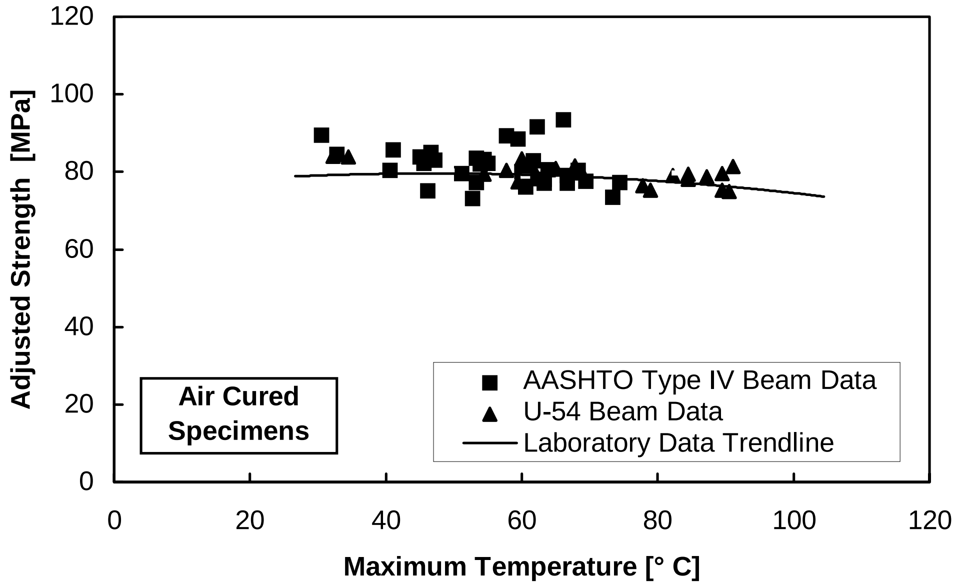

Figure 5.10 Comparison of air cured design strength data from the laboratory and field

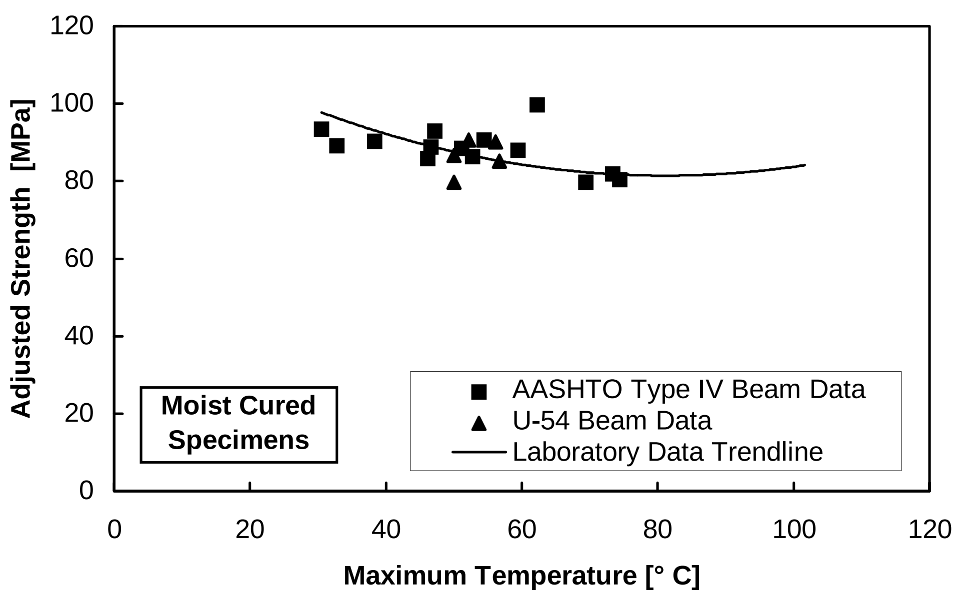

Figure 5.11 Comparison of moist cured design strength data from the laboratory and field

5.4.2 Modulus of Elasticity

We also evaluated the effect of the curing temperature profile on the design modulus of elasticity of concrete. Figures 4.10 through 4.18 display the laboratory modulus data for all three concrete mixes analyzed. The dashed line in each figure represents the trendline through the modulus data.

For the high performance concrete mix, the modulus of elasticity values varied only slightly over the entire range of curing temperatures. This can be seen in Figures 4.10 through 4.12. The following figure displays a typical case of the variation of elastic modulus with curing temperature for the HPC mix.

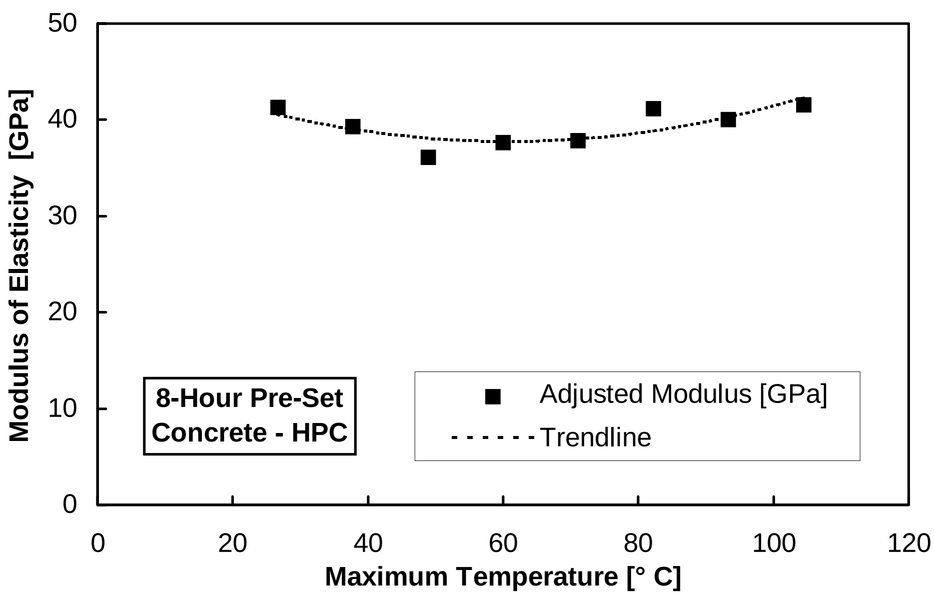

Figure 5.12 Typical variation of design modulus with curing temperature

In Figure 5.12, the modulus trendline varies less than 10 percent over the entire range of curing temperatures. However, the bowl-like shape of the trendline was not expected. For temperatures below 60° C (140° F), the modulus trendline decreases with curing temperature in much the same was as did compressive strength. This fits the expected behavior insofar as modulus of elasticity and compressive strength generally vary in a similar manner. For temperatures above 60° C (140° F), the increase in modulus was not predicted. This can perhaps be attributed to the accelerated hydration of the concrete at very high curing temperatures. If the concrete is cured rapidly, it may be very stiff at the low levels of loading used to determine the elastic modulus. This would be analogous to baking bread dough very quickly at very high temperatures. The baked bread might feel very hard to the touch, but it would crumble under less pressure than would properly baked bread. This same phenomenon could be occurring in the concrete cured at very high curing temperatures. The concrete is stiffer, as reflected by the increase in modulus, but also very brittle, as reflected by the decrease in compressive strength.

The modulus of elasticity data obtained from the field compare very well with the laboratory data. Figure 5.13 displays this comparison for HPC specimens that were air cured outside under cover until testing. Because no modulus data were collected from the U-54 beam concrete, field data were available only from the AASHTO Type IV beam concrete. The laboratory trendline extends beyond the field data because a wider range of temperatures were cured in the laboratory.

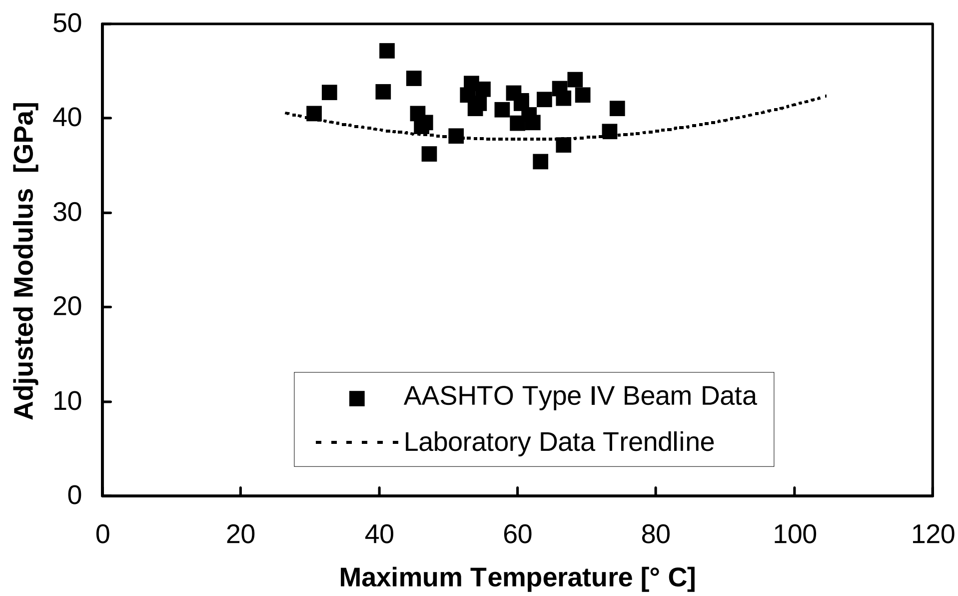

Figure 5.13 Comparison of modulus of elasticity data from the laboratory and field

The effect of curing temperature on the elastic modulus of normal strength concrete was also evaluated. For the NSC mix without fly ash, Figures 4.13 through 4.15 in Chapter 4 display the modulus data collected. Similar to those results for the HPC mix data, these show little variation in modulus over the entire range of curing temperatures. Figure 4.13 shows a slight increase in modulus as curing temperature increases. This can perhaps be attributed to the same phenomenon used to explain the increase in HPC modulus at high curing temperatures. As hydration is accelerated, the cement matrix forms more quickly and is stiffer. Or perhaps the increase is simply a result of the normalization process creating slightly shifted values. Regardless of the correct explanation, the change in modulus is small enough to be disregarded.

The modulus data for the NSC mix with fly ash can be seen in Figures 4.16 through 4.18 in Chapter 4. The data tend to fit the expected form because they vary in a manner similar to that seen for compressive strength. In all three figures, the modulus decreases as curing temperature increases. Because this is also the case with compressive strength, the data tend to support the idea that the modulus of elasticity of concrete is a function of the concrete compressive strength.

5.4.3 Permeability

The final long-term concrete characteristic evaluated was permeability. The ASTM C 1202-94 "coulomb test" was run on specimens from all three types of concrete (Ref 12). Because we obtained excellent permeability results for the high performance concrete mix, no further testing was undertaken. However, the two normal strength concrete mixes required further research.

The permeability results for the HPC mix can be found in Table 4.1. All of the specimens were air cured outside except for the ASTM specimen, which was moist cured. As seen in the table, the amount of charge passed at 56 days increases as curing temperature increases. However, at 90 days all of the specimens have reached a chloride ion penetrability in the very low range. This is simply a result of the high performance concrete mix design. Because of the low water-cement ratio and the high cement and fly ash content, the concrete develops a dense crystalline matrix. This is reflected in the excellent permeability results obtained.

The two normal strength concrete mixes did not test anywhere near as well as did the HPC mix. Once again, the specimens tested were air cured outside under cover until it was time to test them. Figures 5.14 and 5.15 display the permeability data for the two NSC mixes.

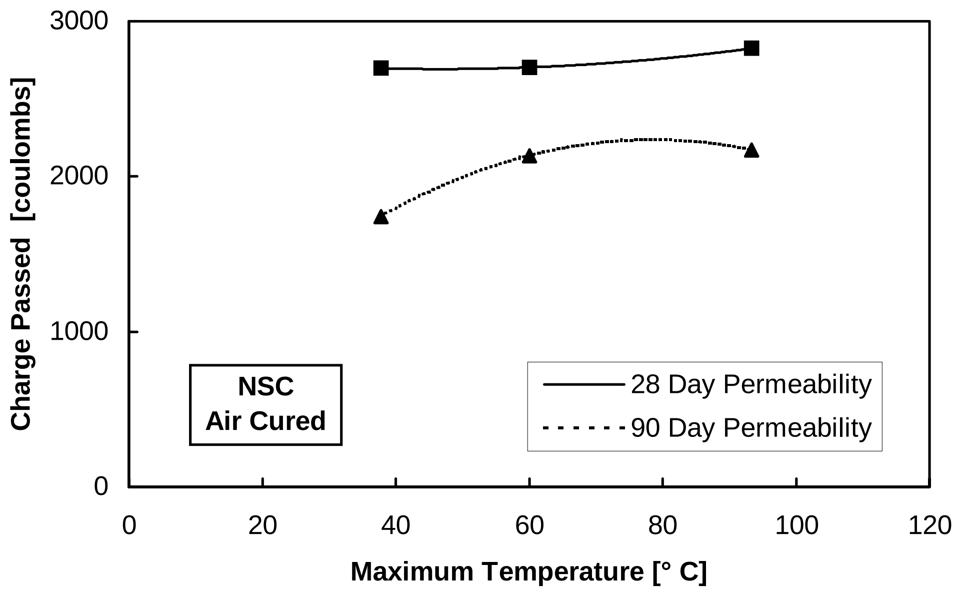

Figure 5.14 Permeability data for air cured NSC without fly ash

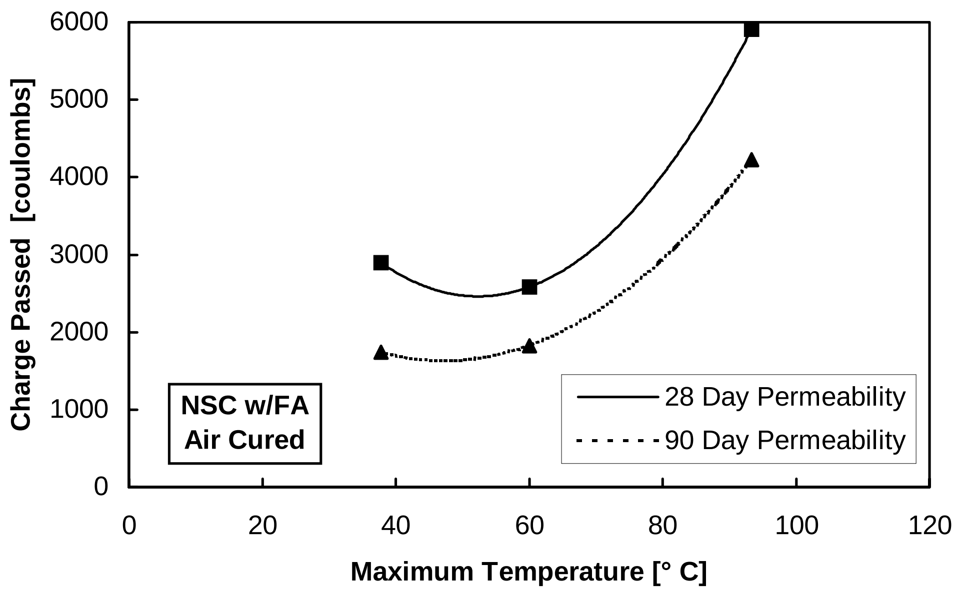

Figure 5.15 Permeability data for air cured NSC with fly ash

Figure 5.14 shows that curing temperature has only a slight effect on the permeability of air cured NSC without fly ash. At both 28 and 90 days, permeability increased with curing temperature. However, the increase was small, and the permeability of all the specimens are comparable.

As shown in Figure 5.15, the effect of very high curing temperatures on permeability is much worse for NSC with fly ash. That mix experienced a dramatic increase in levels of charge passed at both 28 days and 90 days for the specimen cured at 93° C (200° F). It appears that permanent damage was done to the concrete during curing, and the resulting chloride ion penetrability is in the high range after 90 days according to ASTM C 1202-94 (Ref 12).

The effect of the pre-set period on the permeability of NSC was also evaluated. The specimens were match cured in the laboratory using both the 8-hour and 4-hour pre-set temperature profile models. After 24 hours of match curing, the cylinders were moist cured at 23° C (73° F) until testing at 28 and 90 days. Figures 5.16 and 5.17 contain the 90-day permeability data for both NSC mixes.

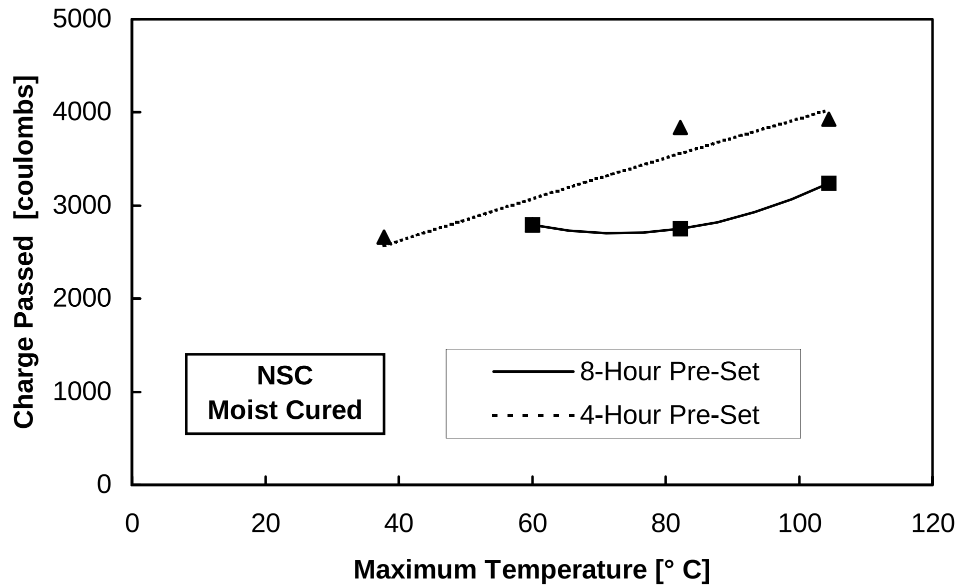

Figure 5.16 Permeability data for moist cured NSC without fly ash

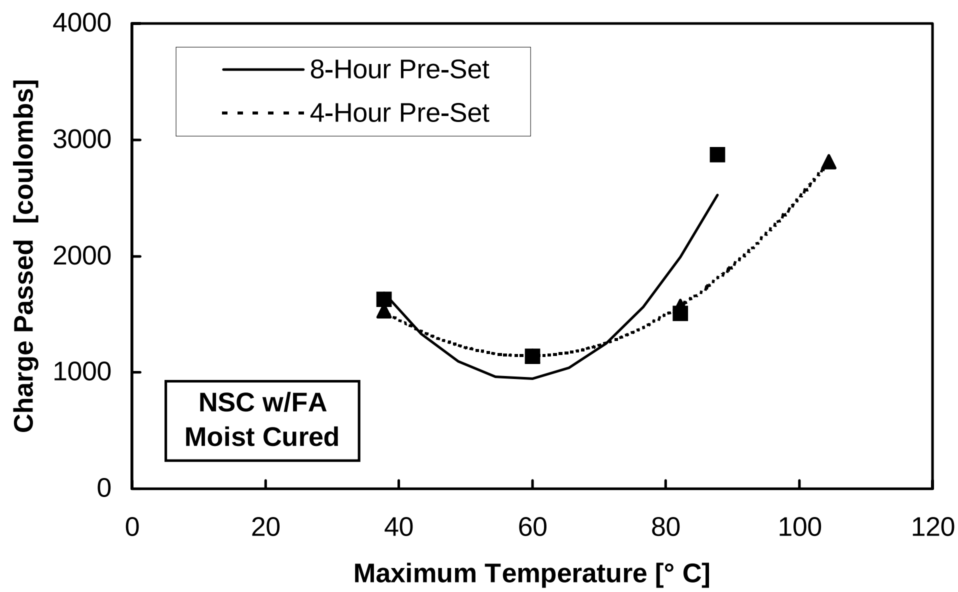

Figure 5.17 Permeability data for moist cured NSC with fly ash

Figure 5.16 shows that NSC without fly ash is damaged only slightly when the pre-set period is reduced from 8 hours to 4 hours. There was only a 90 coulomb difference between the best two permeability values for the different pre-set periods. However, the pre-set period does have an effect on the optimum curing temperature. The specimen cured at 82° C (180° F) tested best for the 8-hour pre-set period, and the 38° C (140° F) specimen tested best for the 4-hour pre-set period.

The permeability results for the NSC mix with fly ash are very similar to the mix without fly ash. In Figure 5.17, the trendlines through the two data sets are almost identical. For both the 8-hour and 4-hour pre-set period, the specimens cured at 60° C (140° F) have the lowest charge passed values. The specimens cured at 82° C (180° F) show very little increase in charge passed, but the specimens cured at 104° C (220° F) show definite damage to the permeability of the concrete.

Because of the bowl-like shape of the trendlines in Figures 5.16 and 5.17, it appears that some heat curing will help the permeability of NSC at 90 days. This trend can also be seen in Figure 5.15 for the 90-day permeability data of air cured specimens. It appears that temperatures as high as 60° C to 71° C (140° F to 160° F) do not significantly affect the permeability of NSC. However, for temperatures above 82° C (180° F), all of the NSC tested showed significant permeability damage.

5.5 STATISTICAL ANALYSIS

A statistical analysis was performed on the raw data collected in the laboratory to determine the validity of any conclusions drawn from the data. Since most of the data reported in Chapter 3 was obtained by averaging two test specimens, a paired T-test was run on the data. The T-test is used to determine the likelihood that two samples from the same two underlying populations have the same mean. Basically, the test looks at the variance in the two test specimen values averaged to obtain a single data point. If the variances are large over the range of curing temperatures from a single mix date, the T-test indicates that the data are less reliable. If the variances are small, the data are more reliable. The T-test was used to evaluate the trends and conclusions drawn from the data collected.

Most of the raw data collected on this research project produced very good T-test results. However, the data from four of the seven laboratory mixes tested for permeability did produce poor T-test results. This is perhaps a reflection of the high variability of the ASTM C 1202-94 permeability test (Ref 12). The data in the following tables produced poor T-test results:

Table 4.5 — Permeability Data for NSC without Fly Ash

Table 4.6 — Permeability Data for NSC with Fly Ash

Table 4.7 — Permeability Data for NSC without Fly Ash cured with an 8-hour Pre-Set Period

Table 4.8 — Permeability Data for NSC without Fly Ash cured with a 4-hour Pre-set Period

There is a statistical significance to the poor T-test results calculated from these data. At the 95 percent confidence level, the two sample sets averaged to produce the data in those tables have different means. In other words, the two sample sets have significant variances in permeability values. Therefore, the conclusions drawn from those data sets are less reliable.

CHAPTER 6. CONCLUSIONS

6.1 SUMMARY

This research project investigated the use of match cure technology in the precast concrete industry. Match cure technology is a method of curing quality-control specimens that are more representative of the actual concrete in the member. This method involves curing specimens at the same temperature profile the member experiences over the same period of time. The resulting match cured specimens more accurately reflect the characteristics of the concrete they were made to represent. Moreover, the precaster can use the technology to produce the best quality concrete possible.

The experimental program was broken down into three components, in which both high performance concrete and normal strength concrete were evaluated. The first component involved collecting temperature data from precast concrete members in the field. The second component involved an investigation into the effect of curing temperatures on the 24-hour release characteristics of precast concrete. The final component looked at the effect of curing temperatures on the design characteristics of precast concrete.

6.2 CONCLUSIONS

The following conclusions can be drawn from the research performed:

1. In the precast concrete industry, specimens that are match cured are more representative of the concrete in the member than are the current quality-control specimens cured next to the member.
2. For both the AASHTO Type IV girder and the Texas U-54 girder, the hottest internal concrete temperatures generally occurred in the end block, while the lowest temperatures usually occurred in the web.
3. The prediction that concrete temperatures increase about 5.6 to 6.7° Celsius per 60 kilograms of cementitious material per cubic meter (10 to 12° Fahrenheit per

100 pounds of cementitious material per cubic yard) is valid only for the hottest locations of precast concrete members.

4. In the precast concrete industry, the temperature difference between the concrete in the member and the quality control cylinders cured next to the member was highly variable. This difference was as high as 44° C (80° F).
5. The 24-hour compressive strength and modulus of elasticity of concrete tended to increase with curing temperature up to about 71° C (160° F). This trend was observed for high performance concrete and normal strength concrete.
6. For temperatures above 82° C (180° F), the 24-hour compressive strength and modulus of elasticity start to decrease as curing temperature increases.
7. For temperatures above 49° to 60° C (120° to 140° F), the design compressive strength of concrete decreased as curing temperature increased. This decrease was most dramatic for normal strength concrete with fly ash and least dramatic for high performance concrete.
8. The length of the pre-set period had a significant effect on the design compressive strength of concrete. A 4-hour pre-set period caused a decrease in design strength that was 10 to 20 percent larger than an 8-hour pre-set period.
9. The design modulus of elasticity of high performance concrete was affected very little by curing temperatures. Normal strength concrete tended to be affected more, and the effect was similar to the decrease in compressive strength that was also observed.
10. The permeability of high performance concrete was affected very little by curing temperature.
11. For normal strength concrete, heat curing as high as 60° to 71° C (140° to 160° F) decreased the 28-day permeability when compared to specimens cured at lower temperatures.
12. Curing temperatures above 71° to 82° C (160° to 180° F) resulted in higher 28-day permeability values for normal strength concrete. The damage was worse for NSC with fly ash when compared to NSC without fly ash.

6.3 RECOMMENDATIONS

Current procedures for curing quality control specimens in the precast concrete industry produce specimens that are subjected to curing temperatures that can be very different than the actual concrete in the member. As shown in this research project, variations in curing temperature can dramatically affect the characteristics of concrete. This creates a situation in the precast concrete industry where the characteristics of the quality-control specimens differ substantially from those of the concrete they were made to represent. The use of match cure technology is an excellent way to close the gap between quality control specimens and in-place concrete. Therefore, match cure technology should be used for curing quality-control specimens within the precast concrete industry.

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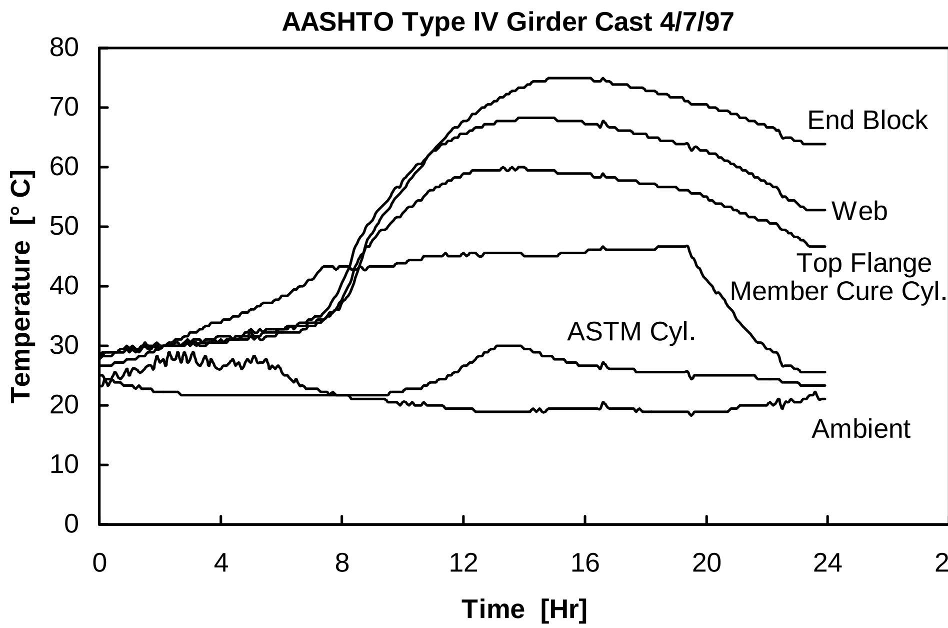
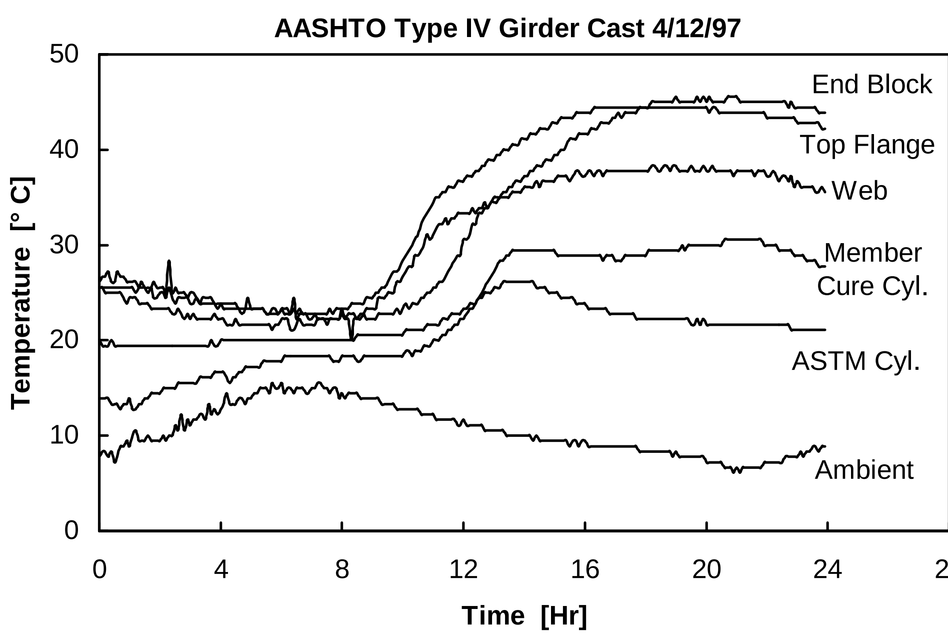
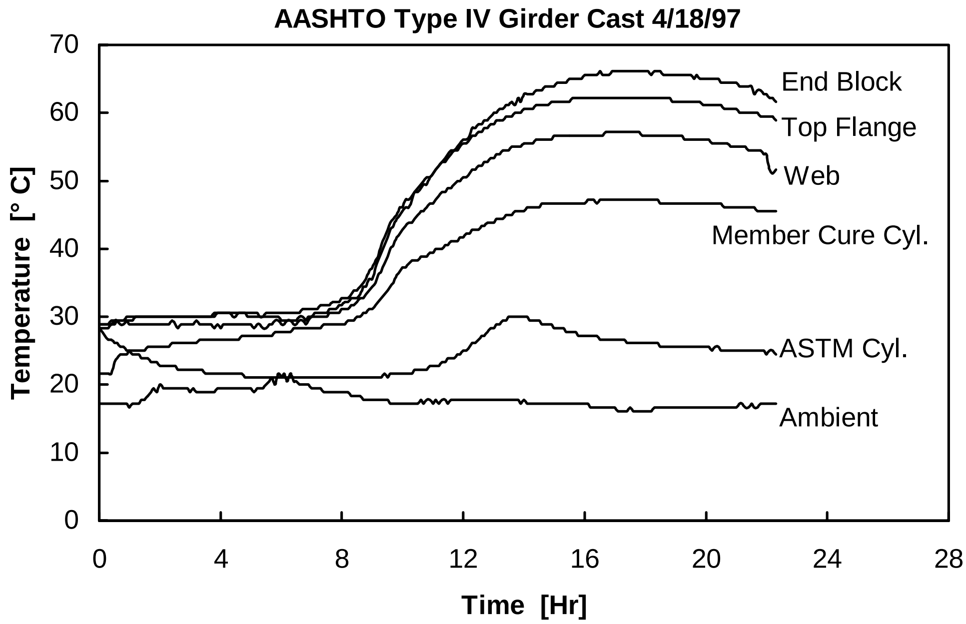
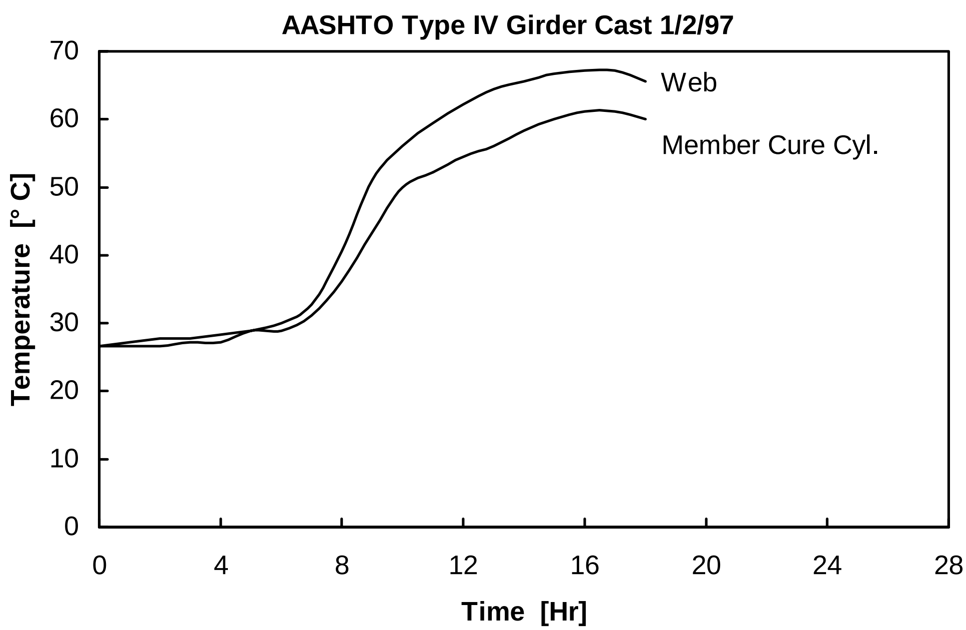
17. ASTM Designation C 469-94, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," *ASTM Standards*, V. 04.02, American Society for Testing and Materials, Philadelphia, PA, 1996.

APPENDIX A: FIELD TEMPERATURE PROFILES


AASHTO Type IV Girder Cast 4/7/97
Temperature [° C]
Time [Hr]
End Block
Web
Top Flange
Member Cure Cyl.
ASTM Cyl.
Ambient
0
10
20
30
40
50
60
70
80
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 4/12/97
Temperature [° C]
Time [Hr]
End Block
Top Flange
Web
Member
Cure Cyl.
ASTM Cyl.
Ambient
0
10
20
30
40
50
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 4/18/97
Temperature [° C]
Time [Hr]
End Block
Top Flange
Web
Member Cure Cyl.
ASTM Cyl.
Ambient
0
10
20
30
40
50
60
70
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 1/2/97
Temperature [° C]
Time [Hr]
Web
Member Cure Cyl.
0
10
20
30
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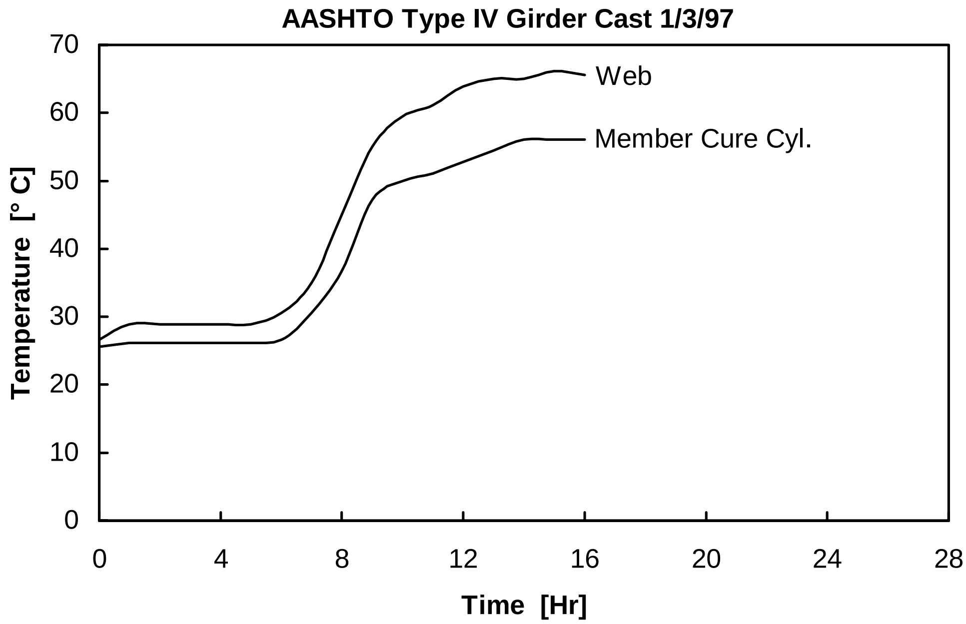
60
70
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 1/3/97
Web
Member Cure Cyl.
Temperature [° C]
Time [Hr]
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10
20
30
40
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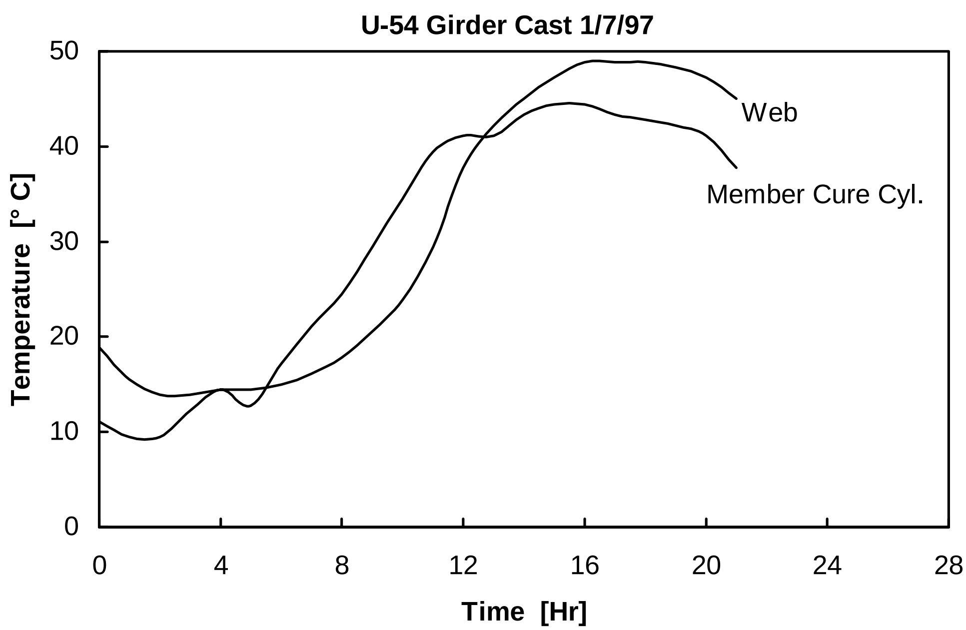
12
16
20
24
28


U-54 Girder Cast 1/7/97
Web
Member Cure Cyl.
Temperature [° C]
Time [Hr]
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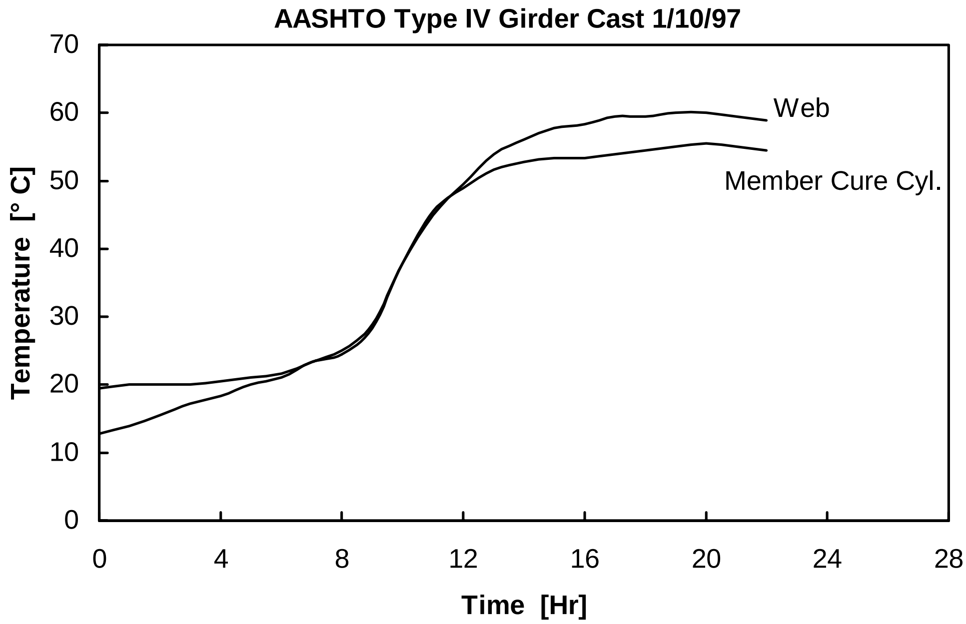
20
30
40
50
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 1/10/97
Temperature [° C]
Time [Hr]
Web
Member Cure Cyl.
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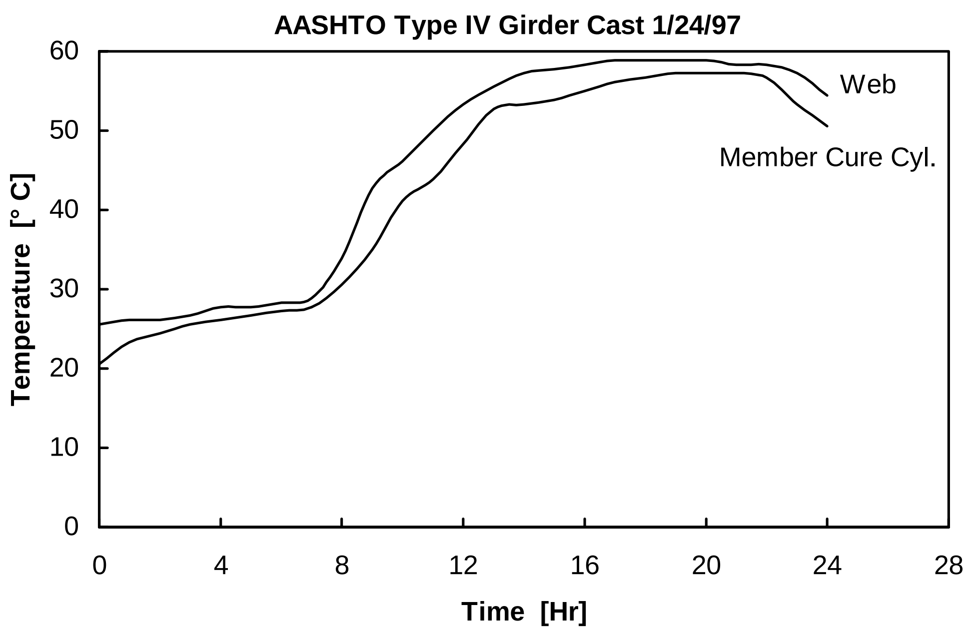
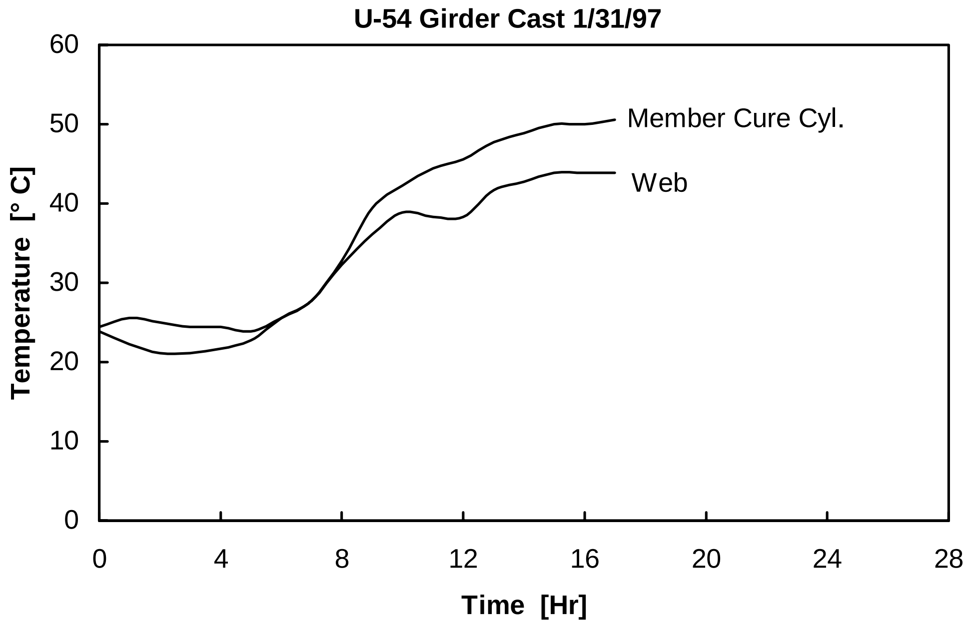
10
20
30
40
50
60
70
0
4
8
12
16
20
24
28


AASHTO Type IV Girder Cast 1/24/97
Temperature [° C]
Time [Hr]
Web
Member Cure Cyl.
0
10
20
30
40
50
60
0
4
8
12
16
20
24
28


U-54 Girder Cast 1/31/97
Member Cure Cyl.
Web
Temperature [° C]
Time [Hr]
0
10
20
30
40
50
60
0
4
8
12
16
20
24
28

APPENDIX B: FIELD AND LABORATORY DATA

Concrete: HPC **Date:** 2/19/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
1	52.1	68.5	68.5	83.2	76.0	74.3	74.3
7	83.4	75.0				80.2	
28	99.8	89.5	87.7	94.8	92.2	91.6	
56	105.1	94.5	93.7	94.4	95.6	96.4	101.0

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
1	36.2	38.9	38.9	43.6	45.0	43.6	43.6
7	46.6	39.5				42.1	
28	45.0	45.8	44.6	43.0	42.4	42.9	
56	44.7	44.5	43.0	41.9	41.4	43.0	47.2

Concrete: HPC **Date:** 2/25/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW
1	51.4	59.2	59.2	74.7		65.4
7	85.5	85.6		86.7		86.5
28	102.9	96.2	101.4			
56	109.8	98.6	107.8	102.2		104.9

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW
1	39.4	38.2	38.2	46.9		42.3
7	43.8	41.6		43.3		42.1
28	45.8	45.6	47.1			
56	46.2	44.1	46.1	45.0		48.6

Concrete: HPC **Date:** 3/3/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*	SF*
1	43.0	68.6	68.6	82.5	77.8		82.5	77.8
7	90.5	83.2		89.4	90.1			
28	105.6	90.9	93.8	97.0	96.3			
56	110.6	95.4	101.6	96.4	96.5		100.2	100.5

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*	SF*
1	35.5	41.2	41.2	45.4	44.8		45.4	44.8
7	45.3	43.0		41.5	42.5			
28	48.7	43.2	46.9	44.3	44.3			
56	46.4	41.7	50.8	40.2	39.5		43.4	45.6

Concrete: HPC **Date:** 3/8/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SF*
2	64.7	80.9	80.9	84.7	90.1	83.4	90.1
7	83.2	91.0			98.2		
19	93.6	92.1					
28	96.0	94.0	91.7	90.9	94.7	88.9	
56	103.5	98.2	102.6	95.6	102.1	94.8	101.6

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SF*
2	40.3	43.8	43.8	45.8	48.1	45.5	48.1
7	45.7	46.6			47.6		
19	45.0	40.4					
28	43.4	40.3	42.3	41.3	42.5	44.3	
56	43.4	38.3	42.1	39.1	41.4	39.8	46.9

Concrete: HPC **Date:** 3/15/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	60.4	68.7	68.7	83.6	80.3	75.8	75.8
7	77.6	83.6				86.5	
28	91.6	94.3	92.3	90.6	90.9	87.5	
56	101.3	100.3	100.2	91.1	95.9	95.7	100.6

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	-	-	-	-	-	-	-
7	42.1	43.2				42.9	
28	47.6	45.2	46.5	58.6	43.4	43.9	
56	45.5	40.2	43.6	38.1	38.9	41.4	46.2

Concrete: HPC **Date:** 3/22/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
2	62.7	66.8	66.8	85.6	85.4	82.5	85.6
5	79.4	82.9		87.6			
28	98.3	94.8	94.0	90.3	90.6	90.9	
56	105.9	86.5	102.0	91.7	93.4	90.0	94.3

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
2	40.7	41.6	41.6	45.9	43.5	43.5	45.9
5	41.2	41.4		42.2			
28	41.9	39.2	42.5	38.5	42.4	37.9	
56	43.9	41.6	47.1	41.6	41.3	41.0	44.7

Concrete: HPC **Date:** 3/29/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	64.9	64.5	64.5	92.8		78.2	78.2
5		80.0				86.2	
28	104.7	97.2		100.2		97.4	
56	105.9	99.9	105.4			98.4	107.1

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	42.4	42.3	42.3	47.7		46.1	46.1
5		40.0				44.1	
28	49.4	44.3		43.9		41.0	
56	47.0	44.7	46.5			43.6	48.1

Concrete: HPC **Date:** 4/7/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
1	48.9	69.0	69.0	79.6	77.1	81.7	79.6
7	82.5	76.7		83.6			
28	94.0	85.5	89.4	87.2	90.0	89.5	
56	103.4	86.7	99.1	89.2	92.5	92.8	92.8

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
1	35.5	37.5	37.5	42.1	43.5	41.6	42.1
7	44.4	41.4		44.6			
28	41.2	40.7	42.3	37.1	37.3	37.3	
56	46.5	40.7	48.8	42.6	41.0	45.8	45.9

Concrete: HPC **Date:** 4/12/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	60.1	68.2	68.2	72.8	72.4	64.7	64.7
5	73.6	79.8				77.7	
7	78.1	82.2				80.5	
28	97.4	94.7	99.6	89.1		93.7	
56	100.6	100.3	104.8	92.2	94.0		101.4

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SW*
2	38.1	39.4	39.4	39.9	39.4	38.5	38.5
5	39.5	38.9				36.2	
7	39.8	43.0				40.2	
28	49.0	47.2	50.3	46.3		46.5	
56	46.6	42.1	43.7	42.1	46.0		53.4

Concrete: HPC **Date:** 4/18/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SF*
1	51.9	68.7	68.7	87.8	86.0	81.6	86.0
7	83.1	79.9			89.9		
28	95.8	89.1	91.1	91.8	92.7	91.7	
56	92.0	85.2	95.4	95.9	94.0	91.6	102.5

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SF*
1	34.2	36.0	36.0	41.6	41.2	41.6	41.2
7	42.5	35.2			39.2		
28	42.6	41.2	44.5	42.3	41.6	41.6	
56	44.8	36.2	45.7	43.2	39.6	40.9	46.7

Concrete: HPC **Date:** 4/28/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
1	53.4	58.6	58.6	85.0	84.7	81.3	85.0
7	83.6	84.6		89.3			
28	99.6	89.1	98.3	90.3	86.9	89.2	
56	105.6	93.7	104.2	86.6	90.8	90.8	96.4

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SB	SF	SW	SB*
1	35.2	34.5	34.5	42.8	41.0	40.5	42.8
7	40.1	37.6		39.7			
28	42.3	38.4	43.1	37.9	41.1	40.9	
56	47.9	40.7	45.2	41.3	39.8	37.9	43.2

Concrete: NSC **Date:** 5/23/97

Compressive Strengths (MPa)

Day	ASTM	MC	TxDOT	SBF	SW	SF	SF*
1	49.6	59.8	59.8	63.4	66.5	67.3	67.3
7	71.9	68.5				75.4	
28	85.0	79.2	76.3	81.4	81.9	77.6	79.9

Modulus of Elasticity (GPa)

Day	ASTM	MC	TxDOT	SBF	SW	SF	SF*
1	36.9	37.2	37.2	41.4	42.5	42.0	42.0
7	42.5	40.1				41.2	
28	40.4	39.6	41.5	37.5	38.8	41.0	42.7

Lab Testing

Concrete: HPC

Date: 7/14/97 ‖ **Date:** 7/22/97

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	35.7	30.5	47.2	53.7	62.3	37.0	59.4	60.4	54.4	45.6
28	82.2	69.1	72.8	66.7	77.2	77.5	71.2	71.6	66.5	52.7
56	86.1	76.1	75.6	77.1	75.8	84.4	73.2	75.0	69.9	69.6

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	4900	4600	5560	5780	6020	4760	5730	5770	5370	4090
28	7510	6970	5740	5520	5630	6760	5740	5850	5470	5230
56	6950	6400	6090	5600	5840	6570	5550	6030	5870	6090

Lab Testing

Concrete: HPC Mix #1M

Date: 2/3/98 ‖ **Date:** 2/3/98

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	102 °C
1	36.5		47.6		64.2	36.5		67.9		65.8
28	88.0		89.8		79.9	88.0		78.1		81.2
56	91.4		95.3		85.6	91.4		83.3		85.6

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	102 °C
1	34.6		37.0		39.2	34.6		41.1		40.1
28	44.8		47.5		47.2	44.8		43.4		43.2
56	44.7		43.8		42.6	44.7		42.7		44.5

Lab Testing

Concrete: HPC Mix #1P

Date: 2/5/98 || **Date:** 2/18/98

Compressive Strengths (MPa)

Day	ASTM		38 °C	60 °C	82 °C	ASTM		60 °C	82 °C	104 °C
1	35.3		50.1	65.2	66.4	33.9		63.4	60.9	60.0
28	79.8		83.4	76.7	73.6	81.6		72.7	69.6	67.2
56	83.4		91.2	79.5	76.3	87.8		78.3	76.7	75.8

Modulus of Elasticity (GPa)

Day	ASTM		38 °C	60 °C	82 °C	ASTM		60 °C	82 °C	104 °C
1	33.2	0.0	37.9	43.0	41.9	32.7	0.0	39.3	37.6	34.0
28	44.2	0.0	40.7	41.5	42.1	40.9	0.0	38.7	42.7	40.7
56	42.7	0.0	42.8	41.4	39.4	43.0	0.0	41.2	39.9	42.5

Lab Testing

Concrete: NSC (w/o FA)

Date: 10/2/97 || **Date:** 10/7/97

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	21.7	15.8	33.3	35.8	41.0	18.8	37.3	38.1	38.1	36.3
7	48.4	51.1	53.0	49.8	50.7	46.0	45.2	38.9	39.9	38.7
28	62.3	58.4	62.6	58.3	60.5	58.4	53.4	47.0	44.3	43.2

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	28.6	22.5	33.4	34.1	37.9	27.2	34.8	37.6	36.1	33.0
7	39.0	37.9	39.7	38.4	37.4	50.5	38.6	37.0	34.9	35.7
28	42.5	35.7	38.7	37.4	38.1	39.4	39.2	39.2	36.7	37.0

Lab Testing

Concrete: NSC (w/o FA) Mix #1M

Date: 2/10/98 **Date:** 2/10/98

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	25.2				36.8	25.2		38.9		36.3
28	59.0				58.1	59.0		55.5		45.6

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	29.6				33.9	29.6		33.4		33.6
28	38.8				38.8	38.8		37.9		36.3

Lab Testing

Concrete: NSC (w/o FA) Mix #1P

Date: 2/25/98 **Date:** 2/25/98

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	22.2		31.6		37.9	22.2		37.9		36.7
28	60.4		59.2		53.6	60.4		48.3		42.5

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	27.5		33.1		33.9	27.5		33.2		32.1
28	38.3		38.8		38.6	38.3		36.2		36.1

Lab Testing

Concrete: NSC (w/ FA)

Date: 11/6/97 | **Date:** 11/11/97

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	20.0	21.1	29.6	36.9	41.6	14.9	38.0	33.6	32.1	31.6
7	48.3	47.8	53.2	48.6	53.8	46.3	42.6	37.8	36.2	32.5
28	63.6	65.2	66.1	57.4	59.2	61.5	47.7	42.1	40.1	35.8

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	29.2	28.9	33.5	35.4	39.9	24.5	36.7	35.6	34.6	33.5
7	40.1	37.2	39.6	40.2	44.7	39.6	38.7	35.1	34.9	31.0
28	44.2	42.5	43.6	41.8	41.0	45.1	37.9	37.4	35.2	33.0

Lab Testing

Concrete: NSC (w/ FA) Mix #1M

Date: 2/13/98 | **Date:** 2/13/98

Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C		88 °C
1	21.2		27.9		41.3	21.2		42.7		40.4
28	68.8		68.4		60.1	68.8		55.8		44.8

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C		88 °C
1	29.9		31.9		36.9	29.9		38.7		38.1
28	42.0		44.0		42.7	42.0		41.9		39.4

Lab Testing

Concrete: NSC (w/ FA) Mix #1P

Date: 2/16/98 **Date:** 2/16/98

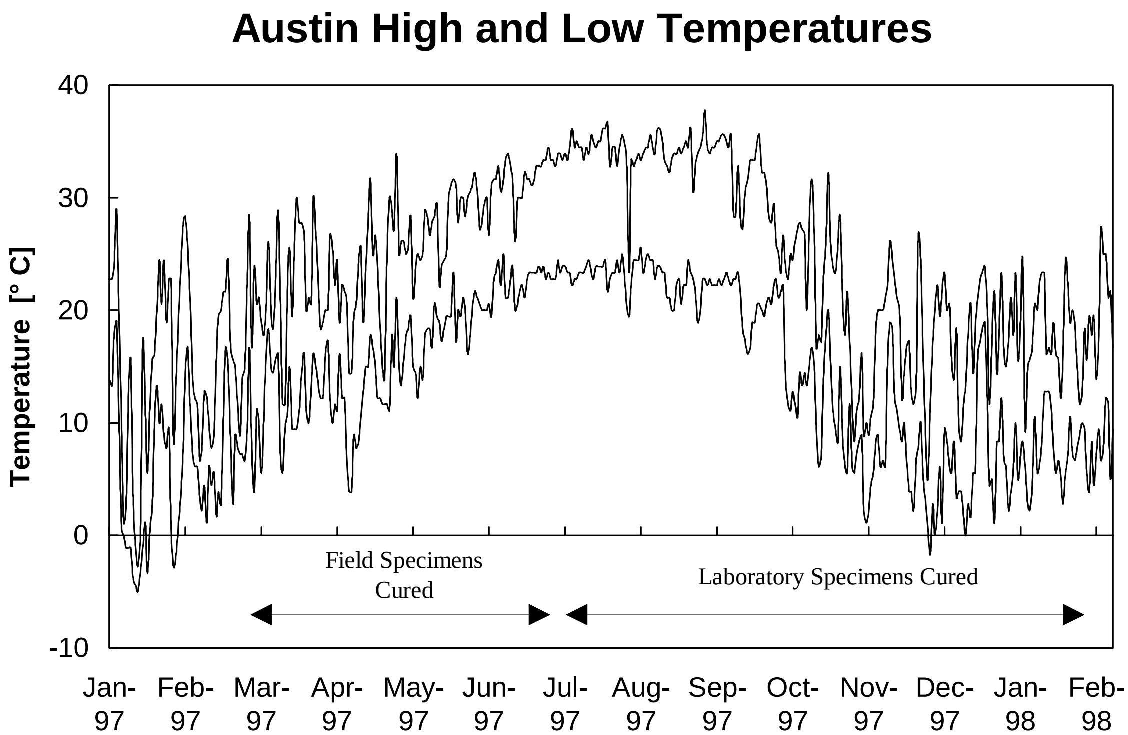
Compressive Strengths (MPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	21.4		31.4		41.0	21.4		39.2		34.1
28	65.6		66.9		54.7	65.6		47.0		37.2

Modulus of Elasticity (GPa)

Day	ASTM	27 °C	38 °C	49 °C	60 °C	ASTM	71 °C	82 °C	93 °C	104 °C
1	29.6		34.1		36.8	29.6		38.3		32.0
28	45.2		41.9		40.6	45.2		39.6		35.9

APPENDIX C: AUSTIN AMBIENT TEMPERATURES



Austin High and Low Temperatures
Temperature [° C]
40
30
20
10
0
-10
Field Specimens Cured
Laboratory Specimens Cured
Jan-97
Feb-97
Mar-97
Apr-97
May-97
Jun-97
Jul-97
Aug-97
Sep-97
Oct-97
Nov-97
Dec-97
Jan-98
Feb-98