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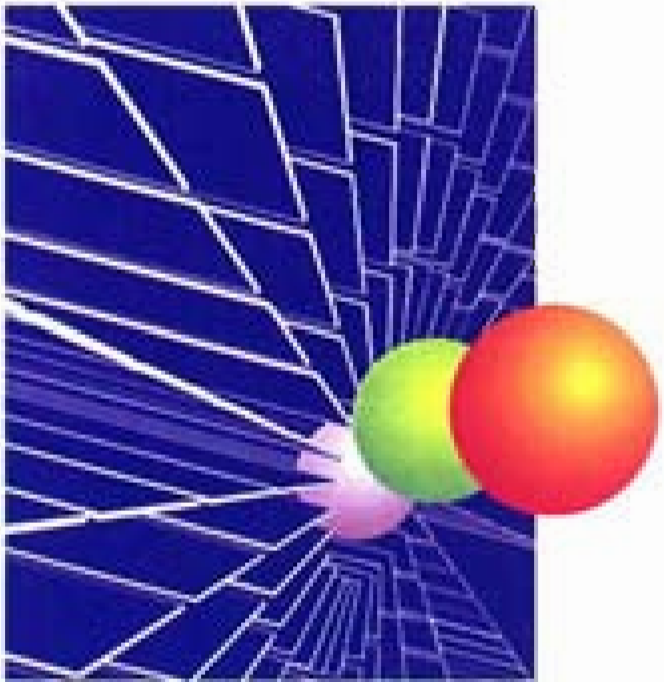
Research, Development and Technology Division

RDT 99-008

Determination of High Performance Concrete (HPC) Characteristics

RI 97-046



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16. Abstract

Two companion bridges were built on Missouri Route 21 over Route M in Jefferson County. The prestressed girders in the northbound bridge were fabricated with high performance concrete (HPC) with a design strength of 10,000 psi. The prestressed girders in the southbound bridge were fabricated with conventional concrete with a design strength of 5,000 psi. Various characteristics of the HPC and conventional concrete were determined and compared. These characterictics include: compressive strength, chloride permeability, freeze-thaw durability and an analysis of the air void systems. Both the HPC and the conventional concrete exceeded the design strength. Chloride permeability was very low for the HPC, and low to moderate for the conventional concrete. The HPC exhibited poor freeze-thaw resistance, while the conventional concrete showed moderate to excellent freeze-thaw resistance. Both the HPC and the conventional concrete had air void parameters outside of recommended ranges.

In addition to determining the above characteristics of each of the concrete mixes, a curing system similar to the "match-cure" system was evaluated. The test results of specimens cured with the curing system are believed to be more representative of the concrete in the girders than member-cured specimens.

Curing temperatures were collected at many locations in the girders. The temperature data suggests some modifications to the steam curing process may be warranted to ensure a consistent curing condition for the entire girder.

This study has shown that HPC can be produced with locally available materials in Missouri and could possibly lead to improved bridge performance in the future.

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RESEARCH INVESTIGATION RI97-046

DETERMINATION OF HIGH PERFORMANCE CONCRETE (HPC) CHARACTERISTICS

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EXECUTIVE SUMMARY

The objective of this study was to determine the characteristics of high-performance concrete (HPC) used in prestressed I-girders and compare them with the characteristics of conventional concrete commonly used in prestressed I-girders. Two companion bridges were constructed. The northbound Missouri Route 21 bridge over Route M in Jefferson County was designed and built using HPC prestressed I-girders with design strength of 10,000 psi. The southbound structure was designed and built using conventional prestressed concrete I-girders with design strength of 5,000 psi. The bridges are subjected to similar environmental and traffic impacts, which will allow for a valuable comparison throughout their service life.

Three concrete mixes were used in the project. Each of these three mixes included a superplasticizer. One HPC mix was used for all of the girders in the northbound bridge. Girders for the southbound bridge were fabricated from two conventional mixes referred to in this report as CONV. I and CONV. II. The CONV. I and CONV. II mixes were basically the same with the exception of the coarse aggregate used.

The HPC mix had a water to cementitious materials (w/c) ratio of 0.243, which included 5.5% silica fume by weight of cement. The coarse aggregate was Plattin Limestone. The 28 day strength was 12,360 psi. The HPC had a very low permeability, but displayed poor freeze-thaw durability. It is felt the poor freeze-thaw durability may be attributed to the coarse aggregate used. Further study is warranted to determine the reason for the poor results.

The CONV. I mix had a w/c of 0.305. The coarse aggregate was Plattin Limestone. The 28 day strength was 9,270 psi. CONV. I had low permeability, but displayed marginal freeze-thaw resistance. The same coarse aggregate was used in this mix as in the HPC mix.

The CONV. II mix had a w/c of 0.328. The coarse aggregate was Derby Doe Run Dolomite. The 28 day strength was 6,850 psi. CONV. II has moderate permeability and excellent freeze-thaw resistance. The coarse aggregate used in this mix is different than that used in the HPC and CONV. I.

In addition to determining the characteristics of the HPC and conventional mixes, a MoDOT fabricated curing system was evaluated. The curing system, designed to provide a "match-cure", consisted of a converted refrigerator and a series of thermocouples. The temperature of the girder was monitored so that the temperature of specimens in the curing box could be maintained at that of the girder. For the HPC, the temperature of specimens was maintained within approximately 3°F of the girder. This "match-cure" resulted in compressive strength of the HPC 8.5% higher than that of a member-cured specimen at three days. At 28 days, the "match-cured" compressive strength was 10.7% higher than the member-cured. However, at 56 days the member-cured compressive strength was slightly higher (1.3%) than the "match-cured" compressive strength.

The study has demonstrated that HPC can be used in the fabrication of prestressed I-girders. Design strengths of 10,000 psi can be used to increase spans, increase beam spacing and utilize shallower girders. Increased resistance to chloride penetration (reduced permeability) is expected to lead to longer service life and reduced maintenance of the bridge. Good freeze-thaw resistance, while not observed in all of the mixes in this study, should also lead to reduced maintenance and longer service life. The varied freeze-thaw performance seen in this study will be investigated further in an attempt to explain the poor performance.

The two bridges will be monitored throughout their service life and periodic reports will be created documenting their performance.

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INTRODUCTION

As a member of the American Association of State Highway and Transportation Officials (AASHTO) High-Performance Concrete (HPC) Lead State Team, Missouri is committed to promoting the implementation of HPC technology, in highways and highway structures.

Early attempts to improve concrete focused on increased compressive strength. The term "high-strength concrete" was frequently used. However, increased strength alone does not necessarily improve the concrete's performance or durability. Enhanced performance of concrete is a critical consideration when evaluating future maintenance costs or life-cycle costs of a highway or bridge.

The term "high-performance concrete" (HPC) is now often used. The American Concrete Institute (ACI) has recently defined HPC as:

> concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices.

High-performance concrete is concrete in which certain characteristics are developed for a particular application and environment. Examples of characteristics that may be considered critical for an application are:

ease of placement	density
compaction without segregation	heat of hydration
early age strength	toughness
long term mechanical properties	volume stability
permeability	long life in severe environments[1]

Advantages of using HPC in bridge design include:

longer spans	increased durability
increased beam spacing	improved mechanical properties
shallower members	

Longer spans, increased beam spacing and shallower members all result in less required material. Less material, depending on the cost of the constituents, could result in a lower initial cost of the bridge. The increased durability of the bridge members results in longer life, fewer repairs and lower overall maintenance costs. This potential savings in both initial and maintenance costs make HPC very attractive to owners throughout the concrete industry.

This report details Missouri's first HPC bridge project. The HPC was used to fabricate prestressed I-girders for a bridge in Jefferson County. The bridge is located on northbound Route 21 over Route M. Using the higher strength concrete (10,000 psi) in the bridge design allowed one line of girders to be eliminated, decreasing the number of girders required from 24 to 20. The reduction in the number of girders resulted in less material needed for fabrication and less time required to place fewer girders. While the primary goal of the HPC was to achieve a design strength of 10,000 psi, improved freeze-thaw durability and improved resistance to chloride penetration were also desired. The special provisions contained in *Appendix A* detail the HPC mix requirements.

OBJECTIVES

The objective of this study was to determine the characteristics of high-performance concrete used in prestressed I-girders and compare them with the characteristics of conventional concrete commonly used in prestressed I-girders. MoDOT Central Laboratory personnel determined the following characteristics:

- compressive strength
- modulus of elasticity
- permeability
- freeze-thaw durability
- air void system parameters

In addition to the above research, MoDOT also evaluated the use of a curing box, which was fabricated by personnel from the Research, Development and Technology division (RDT). The curing box allowed test specimens to be cured at a temperature closer to the actual internal girder temperature than is achieved with conventional curing of test specimens alongside the girder.

The University of Missouri - Columbia also participated in research for this project. The results of the university research will be contained in the report, "Instrumentation and Monitoring of High Performance Concrete Prestressed Girders" to be published in the future.

DISCUSSION OF PRESENT CONDITIONS

MoDOT is currently responsible for maintaining approximately 900 prestressed concrete bridges. The bridges are designed for a life span of 75 years, although these bridges have not been in service long enough to determine the actual life span. In recent years (June 1996 through May 1999) prestressed concrete bridges have accounted for 60% of the new bridges awarded by the Missouri Highway and Transportation Commission. Using conventional concrete mixes to construct these bridges requires more material than would be required if they were constructed of higher strength HPC. HPC allows the bridges to be designed with longer spans, fewer beams and shallower members. Increased service life and reduced maintenance are additional benefits of bridges constructed of HPC with enhanced durability characteristics. There exists a need to analyze this type of construction and identify materials and processes that lead to economical, longer lasting bridges. Due to the large number of prestressed concrete bridges being designed and built, even relatively small cost savings, either in initial costs or maintenance costs per bridge, will lead to large savings to MoDOT and to the Missouri taxpayer.

PROJECT COSTS AND BENEFITS

The use of HPC in the I-girders resulted in the elimination of one line of girders in the bridge superstructure. Only twenty girders, instead of the original twenty-four were needed for the HPC bridge. As expected, the initial costs of the HPC I-girders were higher than the conventional I-girders. As can be seen in Table 1, the cost for fabricating and placing the twenty HPC girders was $181,425.00. The cost for fabricating and placing the twenty-four conventional girders was $160,638.00. The HPC bridge had a length of 281' while the conventional bridge was 289' long. Comparing the initial costs, on the basis of cost per foot of bridge length, shows the HPC cost was 16% higher than the conventional to fabricate and place the required girders.

Overall benefits of HPC should be demonstrated by the significant long term savings realized as a result of improved durability and less maintenance and repair required over a longer service life. This project showed that HPC in structures is a viable concept in Missouri, although additional investigation is needed to address the freeze-thaw durability issue.

TECHNICAL APPROACH

In a previous study, MoDOT worked with four prestress fabricators in the area to determine the feasibility of producing 10,000 psi concrete with locally available materials. The study showed all four fabricators were able to produce such concrete.

The decision was made to use a high performance concrete design on the prestressed I-girders of a bridge in Jefferson County in eastern Missouri. A companion bridge was constructed of conventional concrete. This will allow a good comparison between the HPC and conventional concrete. The bridges are subjected to the same environmental and traffic conditions. The HPC bridge is on northbound Missouri Route 21 over Route M and the conventional bridge handles the southbound traffic. The preliminary design of the four span northbound bridge included six lines of conventional strength MoDOT Type 6 girders. Two HPC design options were reviewed. The first retained six lines of girders, but used shallower MoDOT Type 4 girders. *(See Figure 1)*

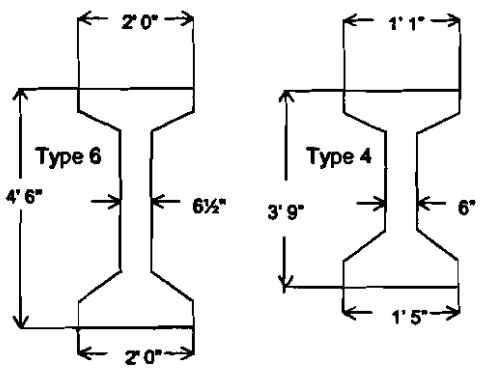

Figure 1

The second made use of the MoDOT Type 6 girders, which allowed for the reduction of one line of girders. The number of girders required for this bridge was reduced from 24 to 20. Each option resulted in less material than would have been required with the conventional design. The second option was chosen, due to the limited redesign required. A comparison of the chosen design and the preliminary design can be seen in *Figure 2.*

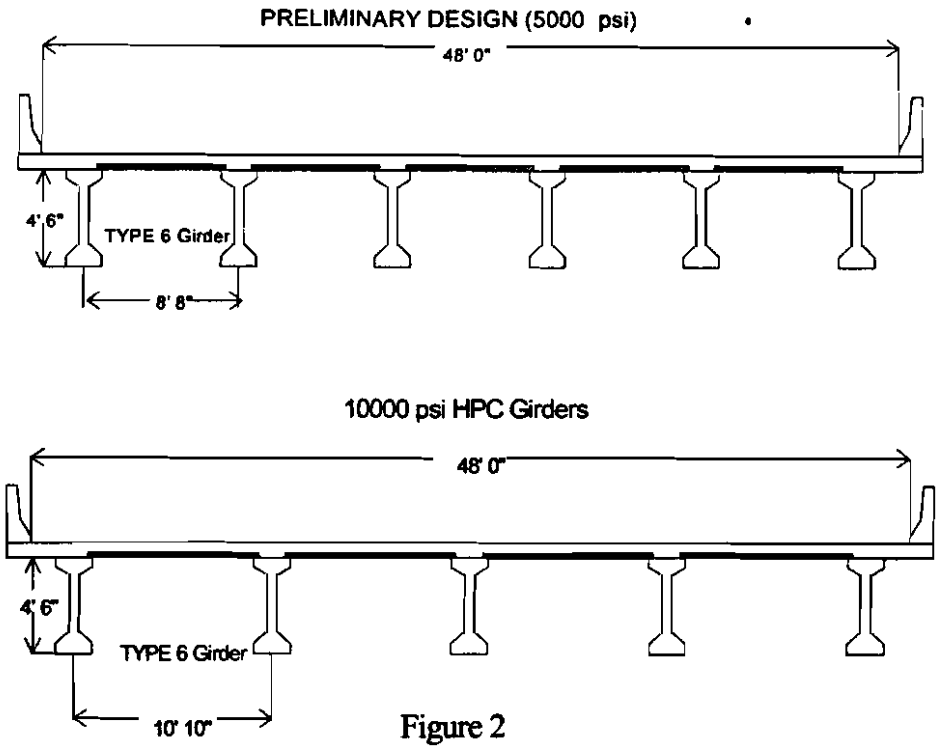

Figure 2

Egyptian Concrete Company of Bonne Terre, Missouri was awarded the fabrication contract for the prestressed I-girders, both HPC and conventional. The special provisions *(Appendix A)* of the job required the fabricator to design the HPC mix and submit the design to MoDOT for approval. The provisions limited variation from the approved mix design.

The approved mix proportions for the HPC and the conventional concrete (CONV. II) can be seen in Table 2. A third mix was also incorporated into the conventional bridge and is represented by CONV. I. This mix was designed as a conventional mix, but incorporated the pavement quality coarse aggregate that was specified for the HPC. Test results and properties of all three mixes will be compared and discussed.

Thermocouples were placed as shown in *Appendix C* at various locations in the HPC girder to monitor heat of hydration and curing temperatures. The temperatures were compared to the internal temperature of a thermocouple instrumented reference cylinder in the curing box. Depending on the temperatures inside the girder and the temperature of the reference cylinder in the curing box, steam could be manually introduced in the curing box to raise the temperature of the test specimens. The door of the curing box could be opened to lower the temperature of the test specimens in the curing box. This system is similar to the "match cure" system used by others to monitor and regulate the temperatures of test cylinders in an effort to match internal temperatures of the girder during curing. On this project the temperature of the reference cylinder in the curing box

was initially 6.1°F cooler than the temperature of the center of the girder (92°, 85.9° respectively). When the steam curing of the girder was started, the process of adjusting the temperature in the curing box began. Temperatures were recorded every fifteen minutes until steam curing ended. For the HPC girder, 86% of the observations showed a difference between the temperature at the center of the girder and the temperature of the control cylinder in the curing box of less than 2°F. Ninety-five percent of the observations showed a difference of less than 3°F.

Standard specifications require moist curing of the girders until design strength (10,000 psi HPC, 5,000 psi CONV. I and CONV. II) is attained. The fabricator chose to continue the steam curing until design strength was achieved, rather than move the girders at release strength (5,500 psi HPC, 4,000 psi CONV. I and CONV. II) and provide additional moist curing in the yard. The design strength of the HPC and CONV. I girders was achieved at approximately 3 days. The design strength of CONV. II was achieved at 1 day . The member temperatures were monitored around the clock and curing box temperatures maintained until the design strength was reached. The test specimens were then transported to the MoDOT Central Laboratory and cured in limewater until testing.

During the fabrication of the HPC girders on July 24, 1998, all of the HPC test specimens were formed. There were 27 - 6"x12" cylinders made for compressive strength (ASTM C39) testing at 1, 3, 5, 7, 14, 21, 28, 56 and 365 days. Six 6"x12" cylinders were made for modulus of elasticity (ASTM C469) testing at 28 and 56 days. Two 4"x8" cylinders were made chloride permeability (AASHTO T277) testing at 56 days. Six 3.5"x4.5"x16" beams were made for freeze-thaw durability (ASTM C666 Procedure B) testing. Two 6"x12" cylinders were also collected for air void analysis (ASTM C457).

The next girders poured would be used in the conventional bridge and were made from the conventional concrete mix with the Plattin Limestone coarse aggregate (CONV. I). These girders were fabricated on August 18, 1998. Test specimens were formed from this mix for all of the above noted tests. It should be noted that there were only 18 - 6"x12" cylinders made for compressive strength testing to be performed at 1, 3, 5, 7, 28, and 56 days. The same numbers of specimens were made for the other tests as outlined above.

The remaining conventional girders were then fabricated. On August 28, 1998, the remaining test specimens were formed from the conventional mix with the Derby Doe Run Dolomite coarse aggregate (CONV. II). The same numbers of test specimens were fabricated as above for all tests except the compressive strength. For this mix, 15 - 6"x12" cylinders were made for compressive strength testing at 1, 3, 7, 28, and 56 days.

The testing described above was completed at the appropriate age and the results are discussed later in this report.

Both the HPC bridge and the conventional bridge were erected in the fall of 1998 and opened to traffic on November 3, 1998. Periodic inspections will be performed on both of the bridges to assess and compare their performance throughout their service life.

RESULTS AND DISCUSSION

Compressive Strength (ASTM C39)

Compressive strength data was collected for several ages of the HPC mix. The compressive strength of the HPC passed the design strength (10,000 psi) within three days. Note the two conventional mixes also reached their design strength (5,000 psi) within three days. Table 3 shows the actual compressive strength measurements for all three mixes. The compressive strength of the HPC was 14,520 psi at the age of 1 year. These specimens were all cured in the curing box for the duration of steam cure of the girders. The girders were steam cured until they attained design compressive strength. They were then moved to the yard. The cylinders were then transported to the lab and cured in lime-water until testing.

The average compressive strengths at various ages for the three mixes are represented graphically for comparison in *Figure 3*.

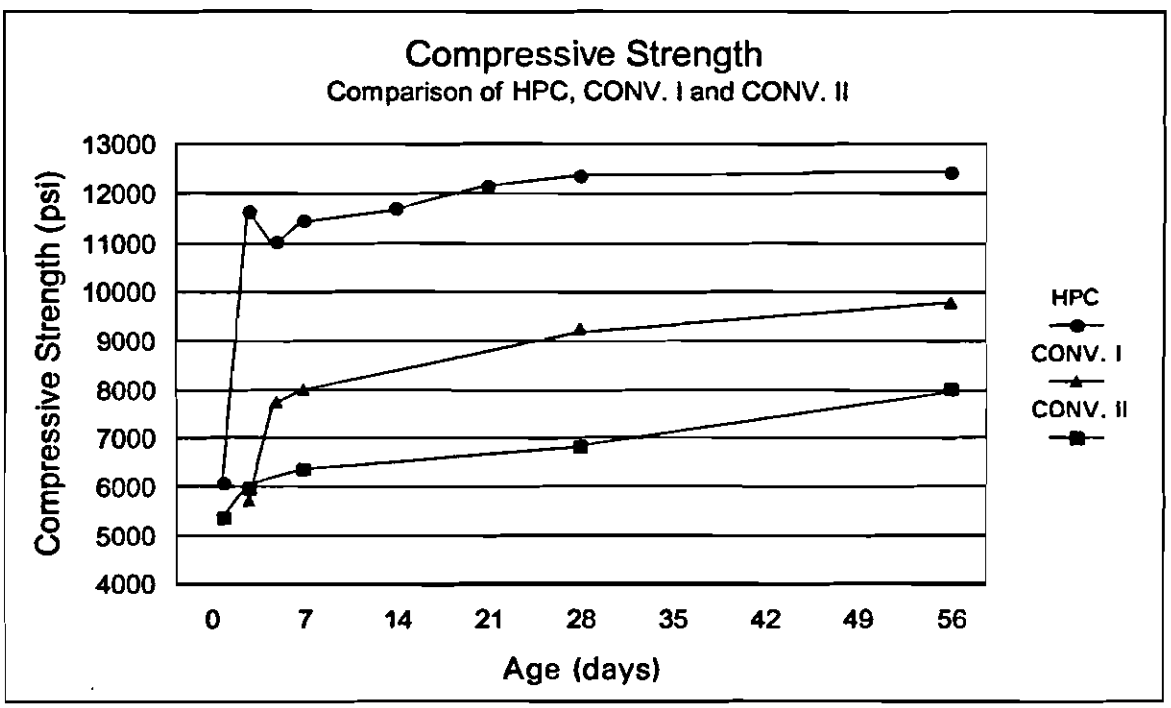

Figure 3

The above compressive strength data was compared to data the plant inspectors had collected from HPC cylinders that were initially cured next to the girder. The comparison of HPC cylinders "match cured" and those member cured is shown in *Figure 4*. At three days, the compressive strength of the cylinders that were initially cured in the curing box was 8.5% higher (11550 psi vs. 10640 psi) than those initially cured alongside the girder. At 28 days, the cylinders initially cured in the curing box showed a compressive strength 10.7% higher (12270 psi vs. 11080 psi) than the cylinders initially cured alongside the

girder. However, at 56 days, those cylinders initially cured in the curing box had a compressive strength slightly lower (12320 psi vs. 12480 psi, 1.3%) than the cylinders initially cured alongside the girder. These results are similar to other research that has concluded compressive strength is typically underestimated at release but overestimated at later ages if ASTM moist-cured or member-cured cylinders are used for strength verification.[2]

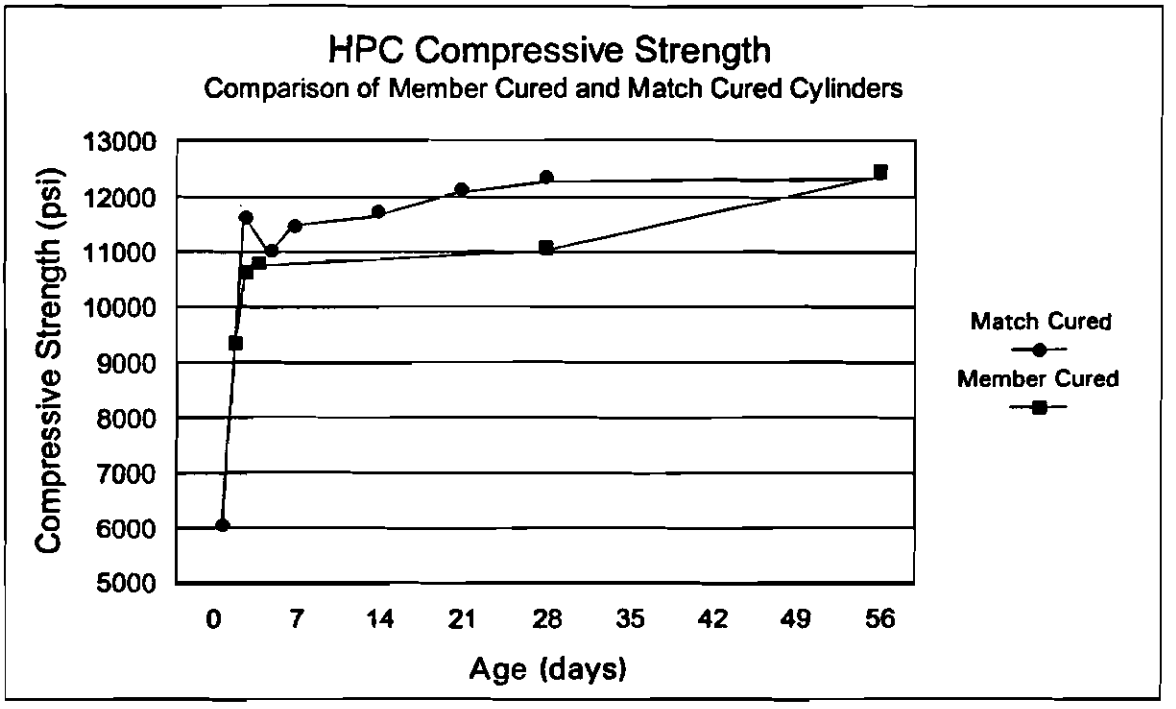

Figure 4

Modulus of Elasticity (ASTM C469)

Several specimens were formed for modulus of elasticity testing. However, the data recorded for this investigation and subsequent calculations of modulus of elasticity are invalid, due to an error in the procedure for collecting measurements for ASTM C469. The procedure has since been reviewed and corrected.

Chloride Permeability (AASHTO T277)

One of the original goals of this investigation was to produce a HPC with a very low permeability. Inclusion of silica fume in concrete has been shown to reduce it's permeability.[3,4] When used as an admixture in concrete, the silica fume reacts with the free lime during hydration of the cement, forming a new cementitious compound, calcium silicate hydrate (CSH). The resultant binder matrix has a denser microscopic pore structure leading to a more impermeable concrete.[4]

Table 4 shows the results of the Electrical Indication of Concrete's Ability to Resist Chloride (AASHTO T277) test for the three mixes included in this study. Only the HPC mix contained silica fume. The amount of silica fume used in the HPC is 5.5% by weight. While the CONV. I and CONV. II mixes did not include any silica fume, the results from the test show a low and a moderate permeability, respectively. One could say these results are reflective of the relative amount of air in each of these conventional mixes. The CONV. I mix has 4.4% air in the hardened concrete, and CONV. II has 5.9%. A discussion of the air void system will be presented later in this report. It should also be noted that CONV. I has a slightly lower (0.305 vs. 0.328) water to cementitious materials ratio, which may have contributed to a lower permeability than CONV. II.

Freeze-Thaw Durability (ASTM C666 Procedure B)

To ensure a long, low maintenance life of the bridge, the HPC specifications were written to achieve high strength durable concrete. Freeze-thaw resistance is a significant characteristic of durable concrete. Pavement quality coarse aggregate was required for the I-girders rather than the standard masonry quality coarse aggregate with the intention of enhancing the durability of the HPC mix. Approved pavement quality coarse aggregates meet higher quality standards and are considered more sound than the masonry aggregates. The fabricator chose to use a Plattin Limestone as the coarse aggregate for the HPC and the CONV. I. Derby-Doe Run Dolomite was selected as the coarse aggregate for the CONV. II mix. Table 5 shows the physical properties for the two coarse aggregates.

The freeze-thaw test specimens were initially cured in the curing box until design strength was reached. The specimens were then transported to the MoDOT Central Laboratory and placed in lime-water. The specimens were cured in lime-water until aged 35 days, when the freeze-thaw testing began.

Table 6 includes the freeze-thaw durability data for each of the three mixes used in this study. It can be seen that the HPC mix was unable to reach the standard 300 cycles before it's relative dynamic modulus of elasticity reached 60% of it's initial relative dynamic modulus of elasticity.[5] The CONV. I mix had a relatively low durability factor of 66, although 300 cycles were completed. Finally, the CONV. II mix showed an excellent resistance to freezing and thawing with a durability factor of 99. Observation and comparison of these results obviously warrants concern, since the HPC mix, designed to have enhanced freeze-thaw durability, actually resulted in significantly poor test results. These poor test results occurred despite very low permeability of the HPC.

An apparent correlation exists between the freeze-thaw durability factor and the weight change of the test specimens. *(Refer to Table 6)* The CONV. II beams lost weight during the freeze-thaw testing and had an excellent freeze-thaw durability factor of 99. The CONV. I beams gained weight during the freeze-thaw testing and had a low durability factor of 66. The HPC beams gained significantly more weight in the freeze-thaw tests than the CONV. I beams, and had a significantly lower durability factor of 50. These

results are typical of other freeze-thaw testing performed in the MoDOT Central Laboratory. Generally, all specimens lose some weight when initially subjected to the freeze-thaw test. The beams that perform well, meaning they have high durability factors, continue to lose weight throughout the freeze-thaw test. Beams that perform poorly generally gain weight, due to the absorption of water, after the initial weight loss observed during the freeze-thaw test.

Likewise, a similar correlation exists between the freeze-thaw durability factor and the length change of the test specimens. The general trend is that the higher percentage length changes in the beams, the lower the durability factor. This expansion is caused by deterioration of the beams, leading to poor freeze-thaw durability.

After completing the freeze-thaw tests, the beams were subjected to center point loading until failure, as in the flexural strength test. Visual inspection of the CONV. II specimens showed no apparent coarse aggregate failure. However, the HPC and the CONV. I specimens did show evidence of coarse aggregate failure, indicating freeze-thaw failure of the aggregate. Analysis of the air void system was also performed and is discussed below, but the visual inspection of specimens seems to warrant further evaluation of the Plattin Limestone durability.

The curing conditions of the test specimens may have also contributed to the poor freeze-thaw test results of the HPC. Some research has indicated an exaggerated negative effect caused by the limited drying permitted in ASTM C666, on the freeze-thaw durability of concretes with low water to cementitious materials ratios.[6] Following the 35 day wet curing, any water not used for hydration becomes detrimental freezable water in the freeze-thaw test specimens.

Air Void System Analysis (ASTM C457)

Improvement in freeze-thaw durability is usually brought about by the presence of minute air bubbles dispersed uniformly throughout the cement paste portion of the concrete. Air bubbles larger than 0.04 in. are referred to as entrapped air and offer little resistance to the harmful effects of freezing and thawing in concrete. Entrained air bubbles, however, are smaller and more closely spaced, and offer significant resistance to the harmful effects of freezing and thawing of concrete. The presence of these air bubbles is known as the concrete's air void system and is typically measured by the percent of air in the hardened concrete.

The structure of the air void system is considered to be a good indicator of the concrete's ability to resist the detrimental effects of freezing and thawing conditions. Evaluation of the air void system's characteristics can be determined in accordance with ASTM C457, Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. The cement paste in concrete is normally protected against the effects of freezing and thawing if the spacing factor, as defined in ASTM C457, is 0.008 in. or less. It is also recommended that the specific surface of the air voids be between 600 $in.^2/in.^3$

and 1100 in.^{2}/in.^{3}, and that the number of air voids per inch of traverse be significantly greater than the numerical value of the percentage of air in the concrete.[7]

Table 7 shows the spacing factor for each of these three mixes exceeds 0.008 in. The specific surface for the HPC is within the recommended 600 - 1100 in.^{2}/in.^{3}, but the CONV. I and the CONV. II specific surface is well below 600 in.^{2}/in.^{3}. Finally the number of voids per inch for each mix is not significantly greater than the numerical value of the percentage of air in the mix.

According to the standard recommendations, the air void systems in these mixes, with exception of all the air void sizes and the HPC specific surface, are not sufficient for frost resistance. However, note that each of the three mixes includes a superplasticizer (or high range water reducer). Much research has been done on the effects of these admixtures on the concrete's air void system and its resistance to freezing and thawing.[8] The air void systems in concrete containing superplasticizers generally develop larger air bubbles with larger spacing factors.[9] The spacing factor above which significant internal damage occurs in a standard freeze-thaw test has been determined for different concretes in a number of studies. For concretes with water-cement ratios of 0.30 and 0.25 containing superplasticizers, the experimentally determined critical spacing factors are approximately 0.016 in. and 0.030 in., respectively. Data from these tests show that properly air-entrained superplasticized concrete can be freeze-thaw durable at spacing factors greater than the ACI recommended maximum of 0.008 in.[9]

The freeze-thaw testing completed for this study somewhat correlates to the references above. The CONV. II mix, with a spacing factor of 0.018 in., still achieved excellent freeze-thaw durability. The HPC and CONV. I mix have a smaller amount of air in the hardened concrete than the CONV. II, however it is thought to be sufficient. The HPC and CONV. I have smaller bubbles and smaller spacing factors than the CONV. II, but performed poorly in the freeze-thaw tests. Again, it is felt the poor freeze-thaw results of the HPC and CONV. I mixes are more attributable to the aggregate than to the air void system. Further investigation should be done to confirm this theory.

The approved design fresh air content for the HPC was 4.5%. Special provisions required the actual fresh air content to be not less than, and not more than 3.5% above, that designated in the approved mix design. The design air content for the CONV. I and CONV. II was 6%, while specifications required the actual fresh air content to be maintained between 4.5% and 8.0%.

Curing Temperatures

As discussed earlier, one of the objectives of this study was to evaluate a curing system similar to the commercially available "match-cure" system. The goal of "match-curing" is to cure test specimens at the same temperature vs. time parameters as the actual bridge girder. The emphasis in this study was on the HPC mix. All of the test specimens from the three mixes were cured in the curing box. However, no comparisons were made between tests of "member-cured" and "match-cured" specimens, except for the HPC

compressive strength, which is shown in Figure 4. The comparison of the girder curing temperature to the "member-cured" and "match-cured" cylinder temperatures is contained in *Appendix D*. The data from the HPC and the CONV. II mix show that the "member-cured" specimens cured at a lower temperature than the girder. The CONV. I "member-cured" specimens apparently cured at a temperature higher than that of the girder and the "match-cured" specimens. In any case, the temperature of the "match-cured" specimens was maintained closer to the girder temperature than were the "member-cured" specimens. It is felt the "match-cured" specimens yielded test results more representative of the concrete in the girders, than did the "member-cured" specimens.

An observation was made concerning curing temperatures at the mid-span of the concrete girders. In the HPC girder, a significant temperature difference of about 20° F was recorded between the top of the girder and the bottom of the girder. It is not determined if this temperature gradient has any detrimental effect on the curing of the girder. Such a temperature gradient was not observed in either the CONV. I or the CONV. II girders. *Appendix E* includes the temperature data from the top, center and bottom of the mid-span of each girder.

Appendix F includes temperature data with respect to the location of the steam source. The steam source at the prestress plant was located on the north end of the casting bed. In the HPC girder, there seemed to be a relationship between curing temperature and the location of the steam source. The temperature of the north end of the girder increased faster and attained a higher peak temperature than did the south end. However, the CONV. I and CONV. II reflected an opposite effect, in that the north end cured at a lower temperature than the south end.

It seems that in the case of HPC, changes may be considered to the curing process to provide a consistent curing environment throughout the girder.

CONCLUSIONS

1. The materials and knowledge exist to produce high strength concrete for use in bridges in Missouri. As bridge designs are optimized to make full use of higher strengths, a reduction in material required will be realized, along with possible lower initial costs.

2. The use of silica fume in concrete with low w/c ratios appears to have a positive effect on the concrete's ability to resist the penetration of chlorides. The lessons learned in this study for producing low permeable concrete should lead to larger benefits in bridge deck applications.

3. It has been determined in the lab, that a highly freeze-thaw durable concrete (CONV. II) can be produced, using superplasticizers and good quality aggregate.

4. The HPC produced in this project exhibited poor freeze-thaw resistance despite its very low permeability. These results warrant further study of such mixes.

5. The use of superplasticizers appears to have an effect on the air void system of concrete, resulting in larger air bubbles with larger spacing factors. It does not appear to be detrimental to the freeze-thaw durability of the concrete, provided sufficient air is present.

6. The use of the curing system used in this study that was able to match the actual temperatures occurring in the bridge member resulted in higher compressive strengths than the member cured specimens at early ages, and slightly lower compressive strengths than the member cured specimens at older ages.

7. Inconsistent curing conditions were observed over the length and height of the girders. The system currently in place to provide steam curing resulted in an inconsistent curing environment.

RECOMMENDATIONS

1. Based on the savings in material and production time, MoDOT should seek to build additional prestressed bridges with high performance concrete. The bridge design for this material should be reviewed and optimized in order to take full advantage of the strength characteristics.

2. MoDOT should pursue the use of HPC in other applications, such as in bridge decks. HPC designed for enhanced durability could lead to longer lasting bridge decks, requiring less maintenance.

3. The freeze-thaw durability of Plattin Limestone should be evaluated. At least the specific source used on this project should be tested to determine if its inclusion on the approved pavement quality aggregate list is appropriate.

4. Results of the use of the curing box should be shared with fabricators and district inspectors, so that they may benefit from the more representative compressive strength data achieved, especially at release. The more representative compressive strength data may allow an increase in girder production rates.

5. MoDOT should continue to field monitor both the HPC and the conventional bridge for comparison of performance and correlation with the results found in this laboratory study.

IMPLEMENTATION

The two bridges that were constructed on this project will be monitored throughout their life. Maintenance and repairs will be tracked to assess the actual life cycle costs of the HPC bridge versus the conventional bridge. Any long-term benefits such as reduced maintenance or longer life will be documented and considered for specification revisions.

MoDOT is currently pursuing other HPC projects. Observations made during this study can be considered in these future projects. These future projects will add to MoDOT's experience, allowing improved HPC to be produced.

The specific issue of poor freeze-thaw durability exhibited by the HPC in this study will be further investigated. Factors that will be studied will include the hardened air content of the HPC and the freeze-thaw durability of Plattin Limestone.

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Table 1
Comparison of HPC and Conventional Girder Costs

Bridge	Bridge Length (feet)	# of Girders	Total Girder Length (feet)	Bid Price Girders in-place
HPC	281	20	1405	181,425.00
Conventional	289	24	1734	160,638.00

Table 2
Mix Proportions (per cu. yd.)

	HPC	CONV. I	CONV. II
Water (lbs)	219	219	237
Type 1 Cement (lbs)	852	719	722
WR Grace Force 10,000 (lbs) Silica Fume	50	N/A	N/A
w/c	0.243	0.305	0.328
Fine Aggregate (lbs) *Class A – Mississippi River Sand*	905	1189	1193
Coarse Aggregate (lbs) *Gradation E – ¾" maximum*	1977 *Plattin Limestone*	1781 *Plattin Limestone*	1769 *Derby Doe Run Dolomite*
Daravair 1400 (oz/sack) Air entraining agent	0.50	0.24	2.46
Daratard 17 (oz/sack) Water reducing retarder	2.83	4.70	N/A
Daracem 19 (oz/sack) High range water reducer	23.57	14.08	N/A
ADVA Cast (oz) High range water reducer	N/A	N/A	8.47
Fresh Air Content (%)	4.80	5.80	4.50
Slump (in)	7.75	7.75	8.00

Table 3
Compressive Strength
AGE

Mix Type	Cyl. or Avg.	1 day	3 days	5 days	7 Days	14 days	21 days	28 days	56 days	365 days
HPC	1	6050	11497	10860	11860	11840	12000	12270	12350	14450
	2	6120	11769	11180	11090	11620	12310	12450	12540	14590
	3	6010	11379	11590	11320	11990	11630	12100	12080	14530
	AVG.	**6090**	**11630**	**11020**	**11480**	**11730**	**12160**	**12360**	**12450**	**14520**
CONV. I	1		5550	7960	7830			8990	10050	
	2		5840	7510	8190			9540	9540	
	3		5720	7860	7810			9240	10290	
	AVG.	**	**5700**	**7740**	**8010**	*	*	**9270**	**9800**	*
CONV. II	1	5220	5920		6400			6770	7884	
	2	5450	6000		6360			6920	8158	
	3	5520	6050		6630			6720	7569	
	AVG.	**5340**	**5960**	*	**6380**	*	*	**6850**	**8020**	*

* - data was not or will not be collected for this age
** - specimens were still in plastic state

Table 4
Ability to Resist Chloride

Mix Type	Specimen # or Mix Average	Charge Passed (Coulombs)	Chloride Ion Penetrability
HPC	97-15 1A	114	Very Low
	97-15 1B	128	
	97-15 1C	135	
	97-15 2A	91	
	97-15 2B	97	
	97-15 2C	102	
	AVG.	**111**	
CONV. I	97-15 3A	1239	Low
	97-15 3B	1124	
	97-15 3C	1226	
	97-15 4A	1067	
	97-15 4B	1200	
	97-15 4C	1045	
	AVG.	**1150**	
CONV. II	97-15 5A	3518	Moderate
	97-15 5B	3044	
	97-15 5C	2662	
	97-15 6A	2629	
	97-15 6B	3229	
	97-15 6C	3233	
	AVG.	**3053**	

Table 5
Coarse Aggregate Properties

	Specific Gravity	Absorption %	Unit Weight lbs/cu. ft.
Plattin Limestone	2.62	1.4	97
Derby Doe Run Dolomite	2.62	2.6	96

Table 6
Freeze-Thaw Durability

Mix	Beam #	# of Cycles	Relative Modulus	Durability Factor	Weight. Chg. (grams)	% Length Change
HPC	FT-1	282	59.0	56	56	0.12
	FT-2	192	59.9	38	56	0.09
	FT-3	252	58.3	49	54	1.05
	FT-4	246	59.6	49	58	1.07
	FT-5	282	57.2	54	59	1.13
	FT-6	282	57.6	54	54	1.06
	AVG			**50**	**56.2**	**0.75**
CONV. I	FT-7	306	84.2	65	32	0.95
	FT-8	306	87.2	67	30	1.06
	FT-9	306	91.1	70	16	0.37
	FT-10	306	81.7	63	36	0.86
	FT-11	306	81.4	62	29	0.07
	FT-12	306	88.7	68	30	0.67
	AVG			**66**	**28.8**	**0.66**
CONV. II	FT-13	300	99.5	100	-61	0.10
	FT-14	300	99.5	100	-61	0.09
	FT-15	300	100.0	100	-59	0.11
	FT-16	300	98.6	99	-61	0.44
	FT-17	300	98.2	98	-58	0.29
	FT-18	300	99.1	99	-58	0.11
	AVG			**99**	**-59.7**	**0.19**

Table 7
Summary of Air Void Analysis
ASTM C457 - Procedure A

Mix Type	Spec. # or Mix Avg.	Fresh % Air	Hardened % Air	Average Air Void (in.)	Voids Per Inch	Spacing Factor (in.)	Specific Surface ($in^2./in^3.$)
HPC	97151	4.8	3.588	0.00706	5.08	0.01283	566.86
	97152	4.8	3.657	0.00613	5.97	0.01144	652.92
	AVG.		**3.623**	**0.00660**	**5.53**	**0.01214**	**609.89**
CONV. I	97153	5.8	4.122	0.00842	4.89	0.01506	474.95
	97154	5.8	4.707	0.00815	5.78	0.01350	491.06
	AVG.		**4.415**	**0.00829**	**5.34**	**0.01428**	**483.01**
CONV. II	97155	4.5	6.348	0.01306	4.86	0.01926	306.38
	97156	4.5	5.404	0.01118	4.84	0.01771	357.93
	AVG.		**5.876**	**0.01212**	**4.85**	**0.01849**	**332.16**

Appendix A

HIGH PERFORMANCE CONCRETE MSP-97-04B

1.0 Description of MSP-97-04B. This specification covers materials and construction requirements for producing and placing a high performance concrete mixture for precast, prestressed bridge units

1.1 Unless otherwise stated, specification section references are from the version, in effect at the time of this contract, of the Missouri Standard Specifications for Highway Construction and its supplements.

1.2 All materials and construction procedures shall meet the requirements listed in Sec 705 except as noted herein.

2.0 Concrete Mixture Requirements.

2.1 The maximum water cement ratio by weight, including all cementitious materials (cement, fly ash, silica fume, ground granulated blast furnace slag) and water components, is not limited for the submitted design.

2.2 The minimum cement factor, including all cementitious materials, shall be 6.4 sacks per cubic yard with no specified maximum.

2.3 The minimum design air content of the mortar portion (all non-coarse aggregate components) of the mixture shall not be less than 8.0 percent. Based on the mortar content, the 8.0 percent figure shall be converted to a percentage total air content for the total mixture which shall be shown in the submitted design and used as the minimum allowable air content for the plastic concrete.

2.4 Slump shall not exceed 8 inches.

2.5 The mix shall provide 10,000 psi ultimate strength at 56 days. Release strength shall be 5,500 psi. Strengths may be obtained earlier under accelerated curing.

2.6 Chloride permeability at design strength shall not be greater than 1000 coulombs when tested in accordance with AASHTO T 277. This test shall be performed on the mixtures submitted for approval, however is not required for subsequent testing unless materials or curing procedures are changed.

3.0 Materials. Precaster selected and engineer approved combinations of coarse aggregate, fine aggregate, water reducer (high or low range), other approved additives, cement, fly ash, ground granulated blast furnace slag (GGBFS), or silica fume may be used. No proprietary mixtures will be allowed. All materials shall be compatible and approved. A statement from each supplier of silica fume or GGBFS and all other admixtures (not fly ash) including air entrainment shall be provided, listing and identifying all materials to be used, with indicated supplier concurrence that their material is compatible and recommended for use with those listed.

3.1 Coarse aggregates shall meet the requirements of Sec 1005.1 for pavement aggregate quality.

3.2 Silica fume material and usage shall meet applicable portions of Sec 505.30 concerning material and mixing and shall be added in accordance with manufacturer's recommendations.

3.3 Repulpable sacks may be used for addition of cementitious materials, provided it is established by trial batches or other experimental batches that there is absolutely no distinguishable sack residue in the final product. Separate silos or bagging operations are preferable.

3.4 Cementitious material content shall be limited as noted in Sec 501.13 and 505.30, including maximum 15 percent fly ash and 25 percent GGBFS, except as noted herein. Silica fume and GGBFS may be intermixed, with a statement of compatibility and recommendation from the supplier. Type III cement may be used. Replacement of cement with other cementitious material shall not exceed 25 percent total by weight.

3.5 High range water reducers may be used and shall be previously approved for use in accordance with Sec 1054.

3.6 With approval of the engineer, other gradations of coarse or fine aggregate may be used, however all quality requirements, including a maximum of 2.0 percent passing the No. 200 for fine and coarse aggregate, shall apply and the maximum aggregate size shall not exceed that of 1005, Grade E aggregate.

4.0 Mix Design. The precaster shall submit and specify the specific materials, mix design, designated slump, air content, water/cement ratio within the limits of this provision. Actual test results on concrete made and cured in accordance with the submitted design and intended procedures shall be included, including air, slump, and strengths of cylinders at 24 hour intervals up to 7 days minimum and 10,000 psi. Results of chloride permeability tests on concrete from those batches shall also be furnished. The above information will be required for each variation of water/cement ratio desired, as well as any major changes in material proportioning.

4.1 The precaster shall also designate the mixing sequence and mixing times. All concrete shall be placed within a maximum of 60 minutes from the beginning of mixing operations and no greater than 15 minutes later than the time designated by the contractor and used for the trial batch.

4.2 If other aggregate gradations than standard specifications are utilized, the precaster shall designate the intended gradation range, which will be used for inspection and quality control of the aggregates.

5.0 Equipment. The precaster shall be responsible for furnishing calibrated equipment for cylinder breaks either in the plant or by using an approved commercial laboratory. A minimum of 425,000 pound force machine will be required for 10,000 psi concrete. The equipment capacity should exceed the anticipated loading by 50 percent. Approved high strength sulfur compound designed for use in the 10,000 psi range shall be used for capping.

6.0 Construction Requirements.

6.1 Prior to starting project unit casting, the precaster shall make a minimum of a 3 cubic yard trial batch in the same manner as intended for the final units to demonstrate proper

batching, placement, finishing and curing of the concrete. The trial batch shall replicate all actual casting conditions including materials, times, equipment, and personnel. All required tests shall be performed and the concrete shall meet all specifications prior to start of initial casting. More than one trial batch may be required in the event that mix or process changes are necessary or specifications are not met. New trial batches will not be required for changes in water content for previously approved mix designs.

6.2 Mixture tests, sequencing, and times during production shall not exceed those limits specified by the precaster in the approved mix design or those listed herein.

6.3 Total mix air content shall not be less than that designated in the approved mix design, nor exceed that value by more than 3.5 percentage points.

6.4 Slump shall not exceed 8 inches and shall be within 2 inches of that specified in the approved mix design.

6.5 The water/cement ratio shall be within 0.020 of that specified in the approved mix design. If adjustments for water content beyond that are necessary, a previously tested and approved mixture shall be used.

6.6 Compressive tests for release and final design strengths shall be performed on 6 inch x 12 inch cylinders cured in the same manner as the precast, prestressed units as the final indicator of strength compliance. As an alternate, the precaster may use 4 inch x 8 inch cylinders for determining strength to release and final design strength to cease cure, provided companion made and cured 6 inch x 12 inch cylinders shipped to the MoDOT central laboratory for ASAP testing after the same curing time are of equal or greater value.

6.7 No redosage of high range water reducer or other additives shall be done. Additional mixing water may be added only once after the initial mixing process and prior to any consequential discharge, in which case an additional 30 revolutions at mixing speed is required. All subsequent concrete in that load not meeting the air, slump, or other requirements shall be discarded and the remainder of the load rejected. No retempering, waiting, or other measures shall be used to obtain specification compliance. These requirements shall not be used to modify the required maximum of 30 minutes between lifts.

6.8 Any repulpable sack residue identified in the final product will result in immediate rejection of the unit without recourse. No repair will be allowed.

Appendix B

WORK PLAN
Revised July 7, 1998

Date: November 5, 1997

Project Number: RI97-046

Title: Determination of High Performance Concrete (HPC) Characteristics

Research Agency: Research, Development & Technology Division

Principal Investigator: Tim Chojnacki

Objective: The objective of this study is to determine the following characteristics of high performance concrete produced under field conditions: compressive strength, modulus of elasticity, permeability, freeze-thaw durability, and air-void analysis. The high performance concrete evaluated in this study will be from Bridge A-5529 on the Rte. 21, Jefferson County project, Job No. J6S0704D. The project is scheduled to be let in December '97. A companion bridge, A-5530 will be built with a conventional concrete mix. For comparison purposes, this conventional mix will be evaluated using the same procedures as the high performance mix.

Background and Significance of Work: The production and application of high performance concrete has made significant progress over the last few years. Many states, including Missouri, are taking steps towards implementing this innovative approach to concrete with applications in highway structures. As part of those steps, Missouri will be constructing the state's first high performance concrete bridge project in the fall of 1997. This bridge will include prestressed girders designed and fabricated using high performance concrete with a minimum compressive strength of 10,000 psi. Since this is a considerably new approach to the design and construction of prestressed bridge girders, the determination of characteristics pertinent to the performance of the concrete is necessary for proper evaluation. These characteristics include those listed in the objective above.

Action Plan: The action plan for this project will initially include preparing for the fabrication of specimens in the field. Fabrication of specimens in the field will follow. Specimens will then be returned to the lab and placed under ideal curing conditions until testing. Testing will be coordinated so as to be carried out by the RD&T and Materials divisions. After testing, a report will be prepared and then disseminated among those with potential interest in the results. This may include the MoDOT divisions of materials and bridge, as well as, other transportation agencies including those in the AASHTO Lead State Program.

Literature Search: Information concerning high performance concrete will be collected from various sources. This includes publications and videos from the FHWA and other

state transportation agencies with experiences in high performance concrete and information collected from high performance concrete seminars and workshops.

Method of Implementation: Conclusions and recommendations found in this study will be shared with potential users through the dissemination of the final report and possibly presentations.

Anticipated Benefits: The benefits of conducting this study will be the progress made and technology gained as a result of MoDOT's research of high performance concrete.

Research Period: The research period for this study will be from November 1997 until July 1999.

Funding: This project will be funded by SPR 38 funds.

Procedure: The following are the procedures for this investigation.

November 1 - January 1: Locate and organize equipment needed for fabricating and initial curing of specimens in the field. The field location will be the prestress/precast producer fabricating the high performance concrete girders for the bridge project. Equipment needed includes both 6" x 12" and 4" x 8" cylinder molds, freeze-thaw beam molds, air-meter, slump cone, and curing box. The curing box will be used to provide housing for the first 24 hours of curing specimens in the field. The curing box will be constructed as a temperature-regulated housing unit that will allow heating and cooling as necessary so that the internal temperatures of the specimens curing will match the monitored internal temperature of the beam curing.

June 15 - August 31: Fabricate specimens in the field. This will include the following specimens:

High Performance Concrete

27 - 6"x12" specimens for compressive strength testing at 1, 3, 5, 7, 14, 21, 28, 56 days, and 1 year (three specimens will be averaged per date of testing) according to ASTM C 39 (AASHTO T 22).

6 - 6"x12" specimens for average static modulus of elasticity at 28 days and 56 days according to ASTM C 469.

2 - 4"x8" specimens for chloride permeability at 56 days according to ASTM C 1202 (AASHTO T 277).

6 - 3.5"x4.5"x16" freeze-thaw specimens for freeze-thaw durability according to ASTM C 666 (AASHTO T 161) Method B.

2 - 6"x12" specimens for air-void analysis according to ASTM C 457.

Conventional Mix Concrete for Comparison to HPC Test Results

18 - 6"x12" specimens for compressive strength testing at 1, 3, 7, 28, 56 days, and 1 year (three specimens will be averaged per date of testing) according to ASTM C 39 (AASHTO T 22).

6 - 6"x12" specimens for average static modulus of elasticity at 28 days and 56 days according to ASTM C 469.

2 - 4"x8" specimens for chloride permeability at 56 days according to ASTM C 1202 (AASHTO T 277).

6 - 3.5"x4.5"x16"freeze-thaw specimens for freeze-thaw durability according to ASTM C 666 (AASHTO T 161) Method B.

2 - 6"x12" specimens for air-void analysis according to ASTM C 457.

Specimens will be initially cured (during the cure period of the prestressed I-girders) in the curing box. Beyond the initial cure, the specimens will be cured and handled in accordance with ASTM C 31.

August 31 to October 1: Testing as indicated will be carried out and results analyzed. Testing for compressive strength will continue for 1 year after fabrication of specimens. Hence, additional time beyond October 1 will be necessary to complete the collection of this data.

October 1 to November 1: Results, with the exception of the 1 year compressive strength data, will be incorporated into a final report. At approximately 1 year, a report addendum will be completed to include additional compressive strength data.

Staffing: This investigation will require the following staffing.

1 - Research and Development Engineer, Tim Chojnacki
1 - Senior Materials Research Analyst, Ron Middleton
1 - Field Testing Technician
2 - Field Technicians

Equipment: In addition to the available in-house equipment (air-meter, slump cone, concrete molds, compressometer, etc.), the following equipment or materials will be purchased for the purpose of this study.

Temperature-Regulated Curing Unit:

Recycled freezer unit from state surplus	$ 300.00
100' - 1" steam hose or alternative	$ 300.00
Misc. items (PVC, valve, nipples, etc.)	$ 50.00

Modified arrow board trailer for hauling curing unit:

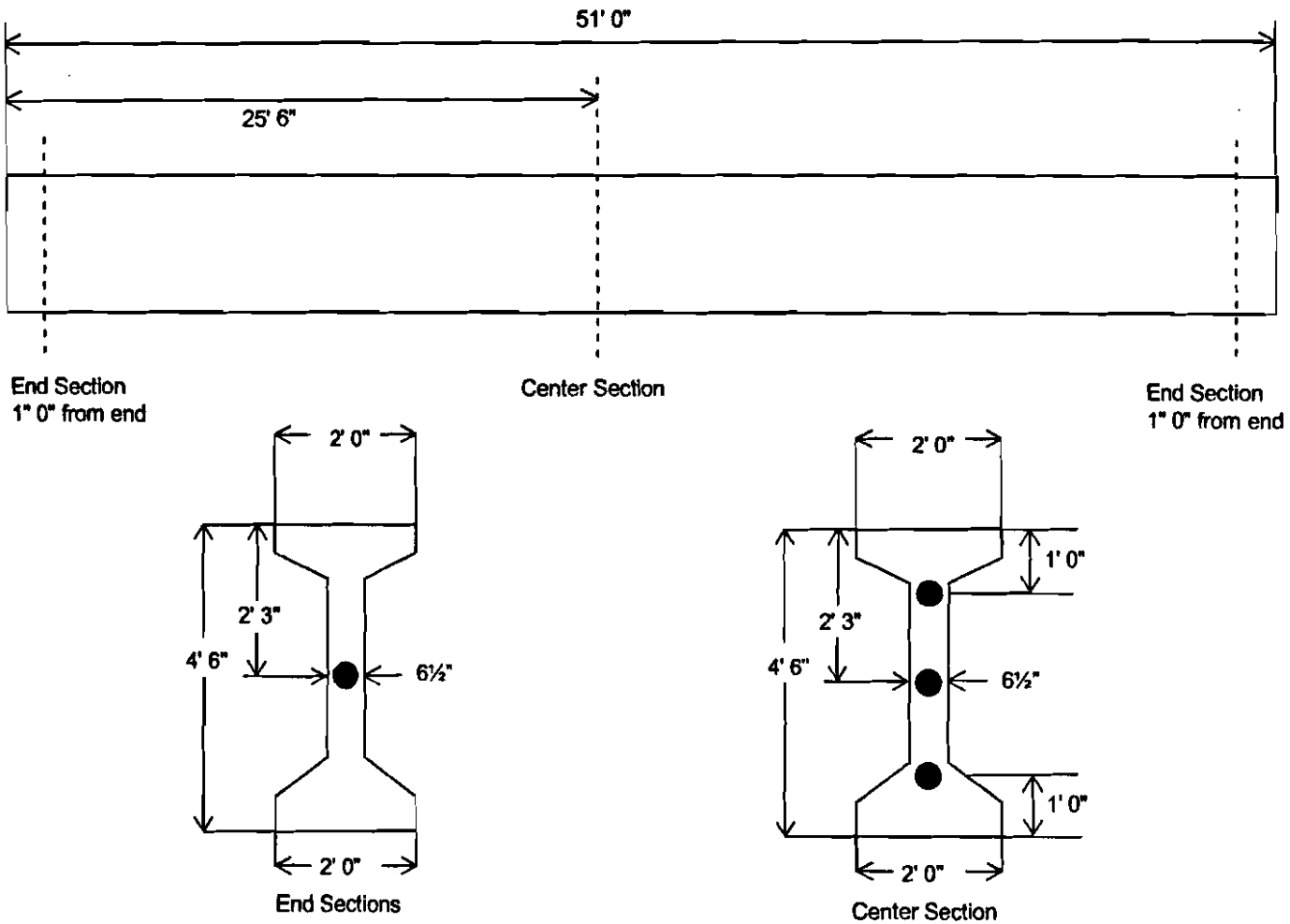
Materials	$ 20.00
Labor	$ 550.00
Equipment Total	$1220.00

Budget:

1 - Senior Research and Development Engineer (1 @ 1.5 months x $4162 x 1.693)	$10,569.00
1 - Senior Materials Research Analyst (1 @ 0.5 month x $3732 x 1.693)	$ 3,159.00
1 - Field Testing Technician (1 @ 2.5 months x $3002 x 1.693)	$12,706.00
1- Field Technician (1 @ 2 months x #2369 x 1.693)	$ 8,021.00
1- Field Technician (1 @ 1 month x #2369 x 1.693)	$ 4,011.00
Travel Expenses	$ 729.00
Equipment	$ 1220.00
Total	**$40,415.00**

Appendix C

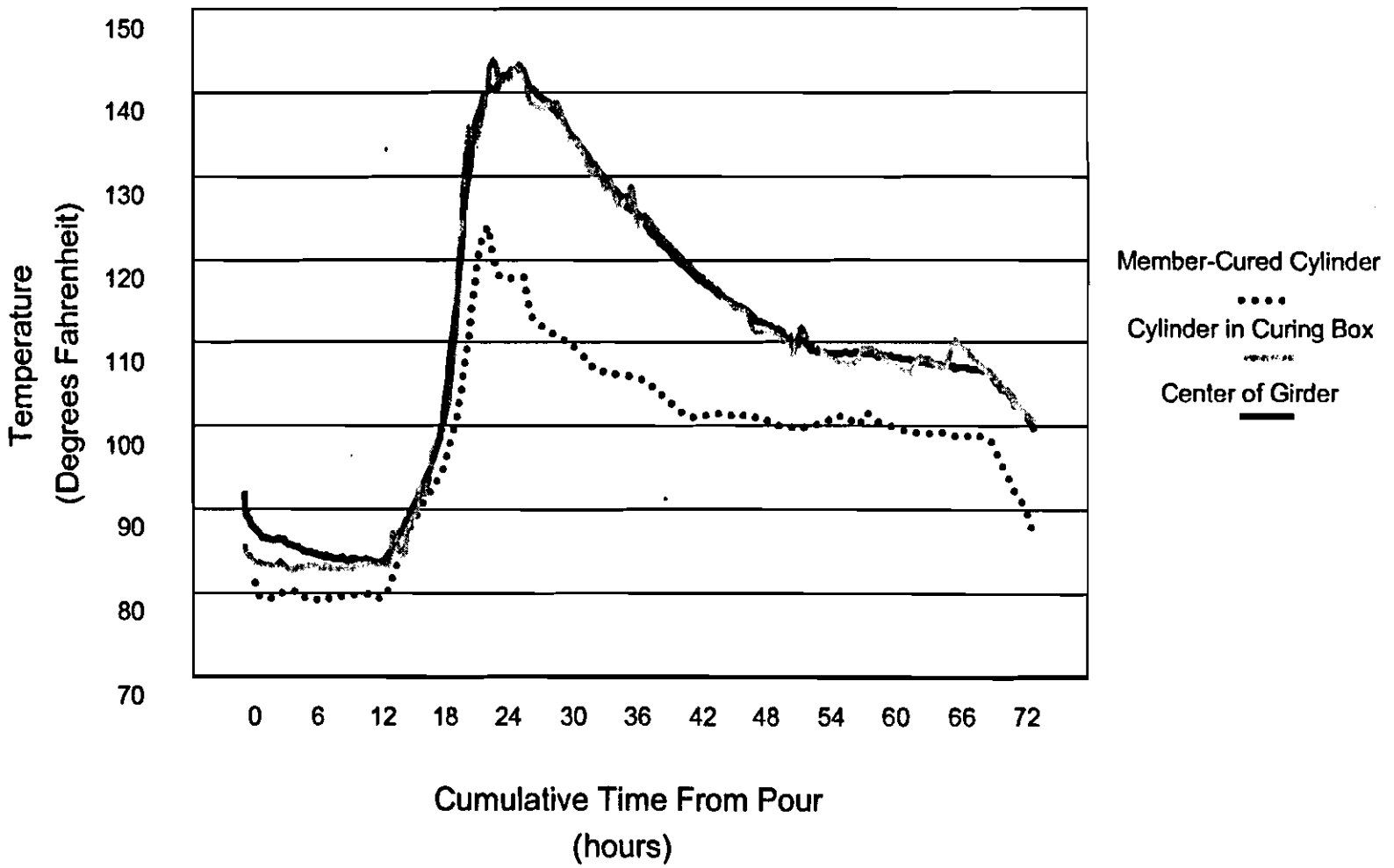
Location of MoDOT Thermocouples in I-Girder



Appendix D

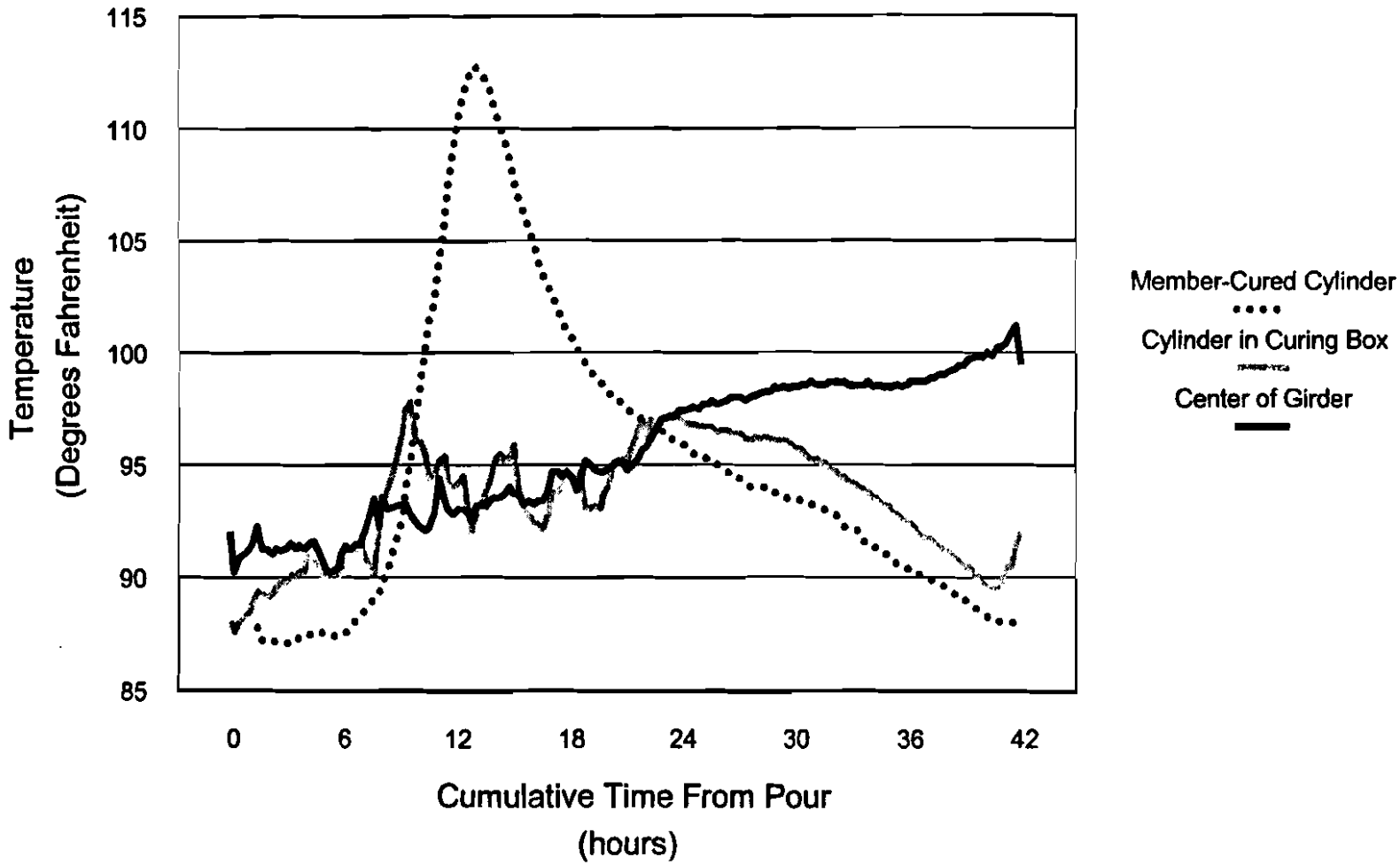
HPC

Girder Curing Temperature vs. Cylinder Curing Temperatures



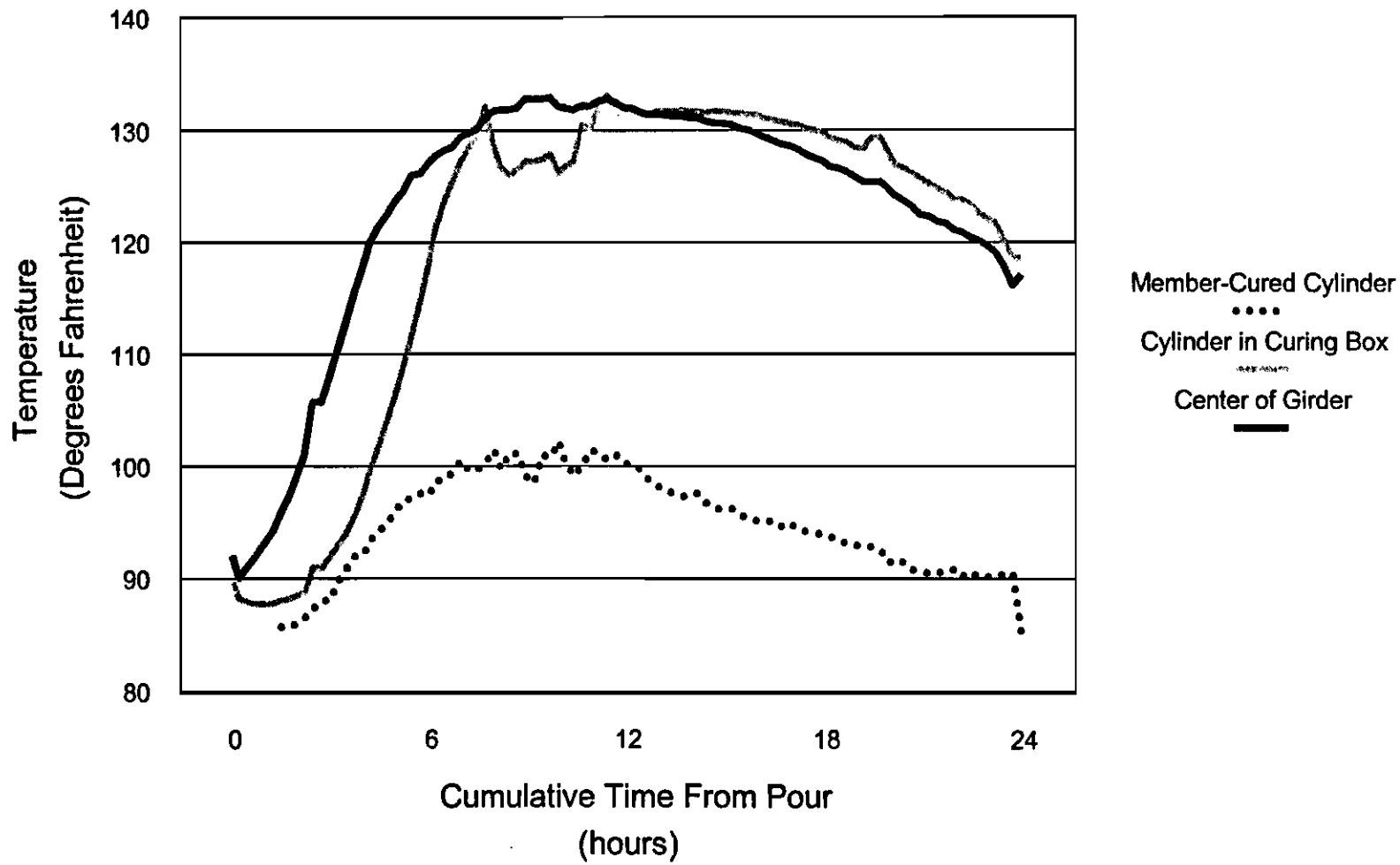
CONV. I

Girder Curing Temperature vs. Cylinder Curing Temperatures



CONV. II

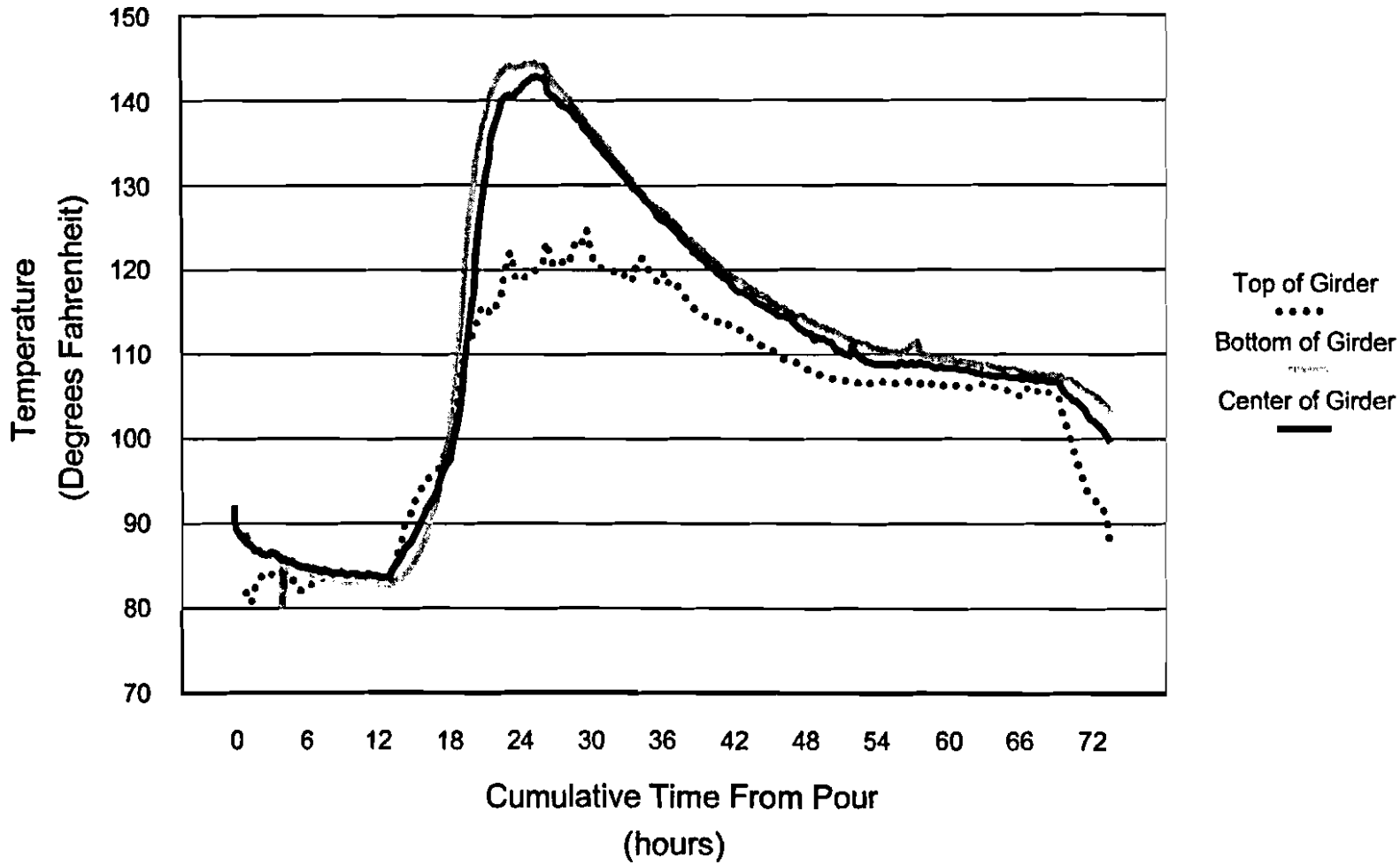
Girder Curing Temperature vs. Cylinder Curing Temperatures



Appendix E

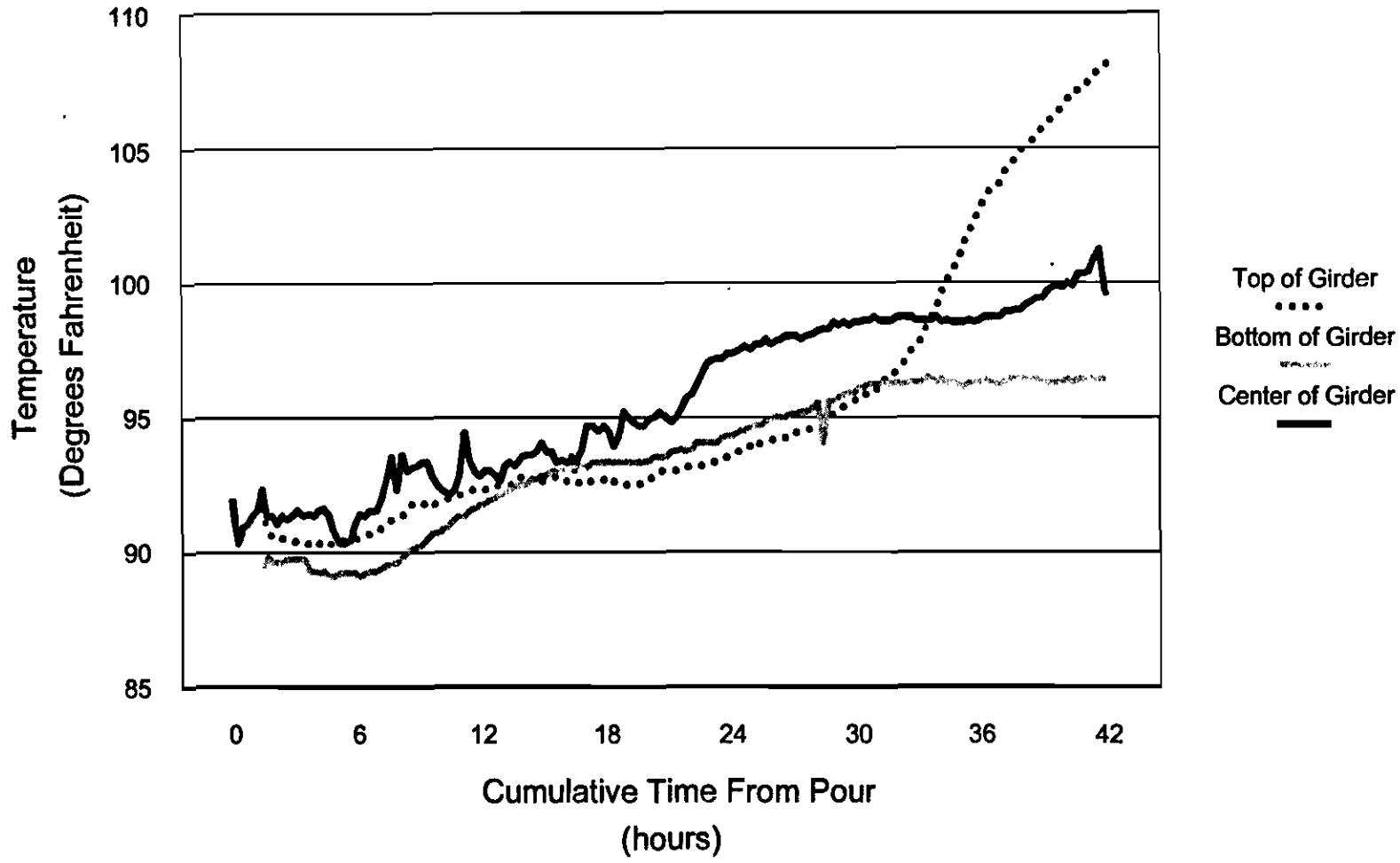
HPC

Girder Curing Temperatures at Mid-span



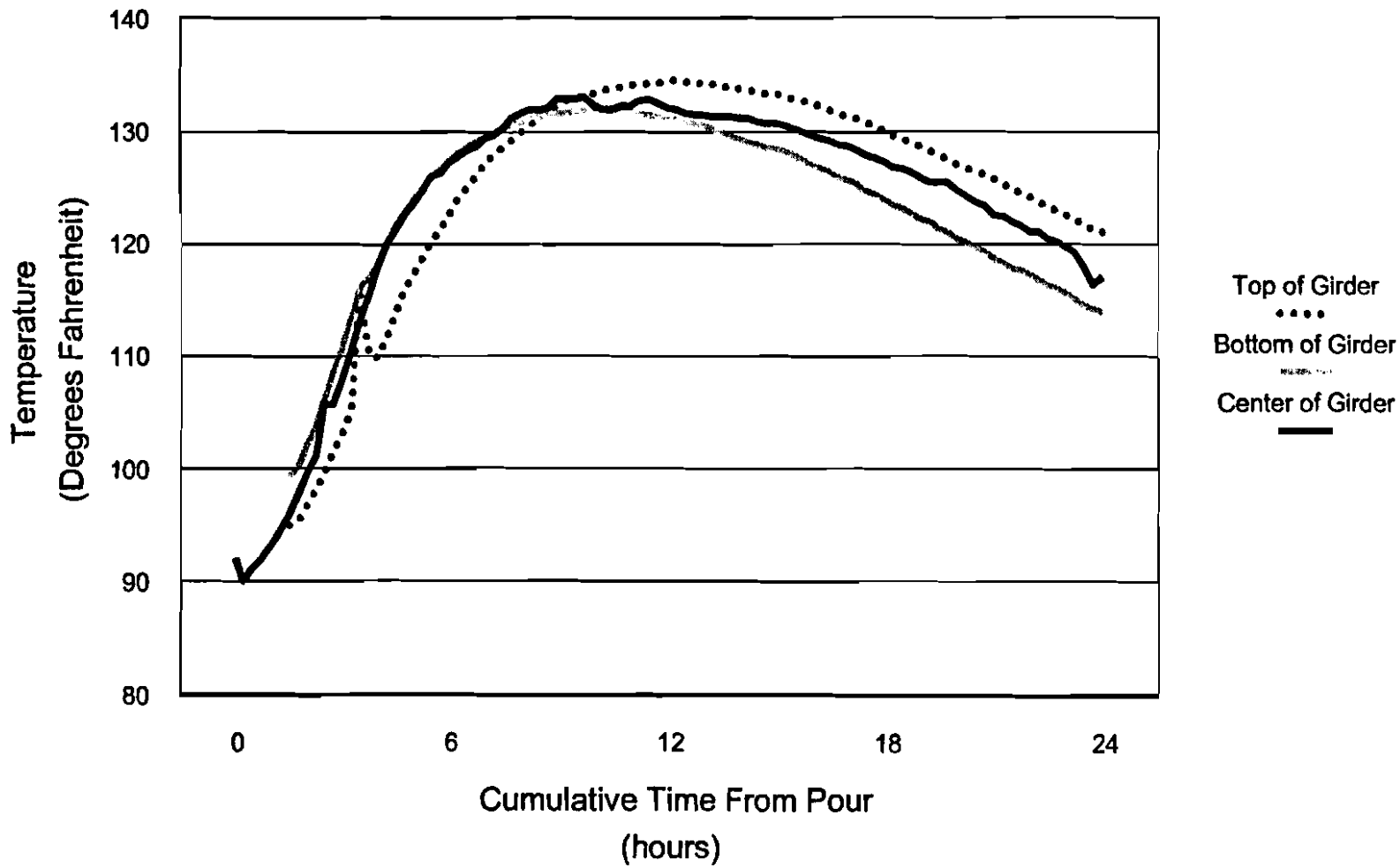
CONV. I

Girder Curing Temperatures at Mid-span



CONV. II

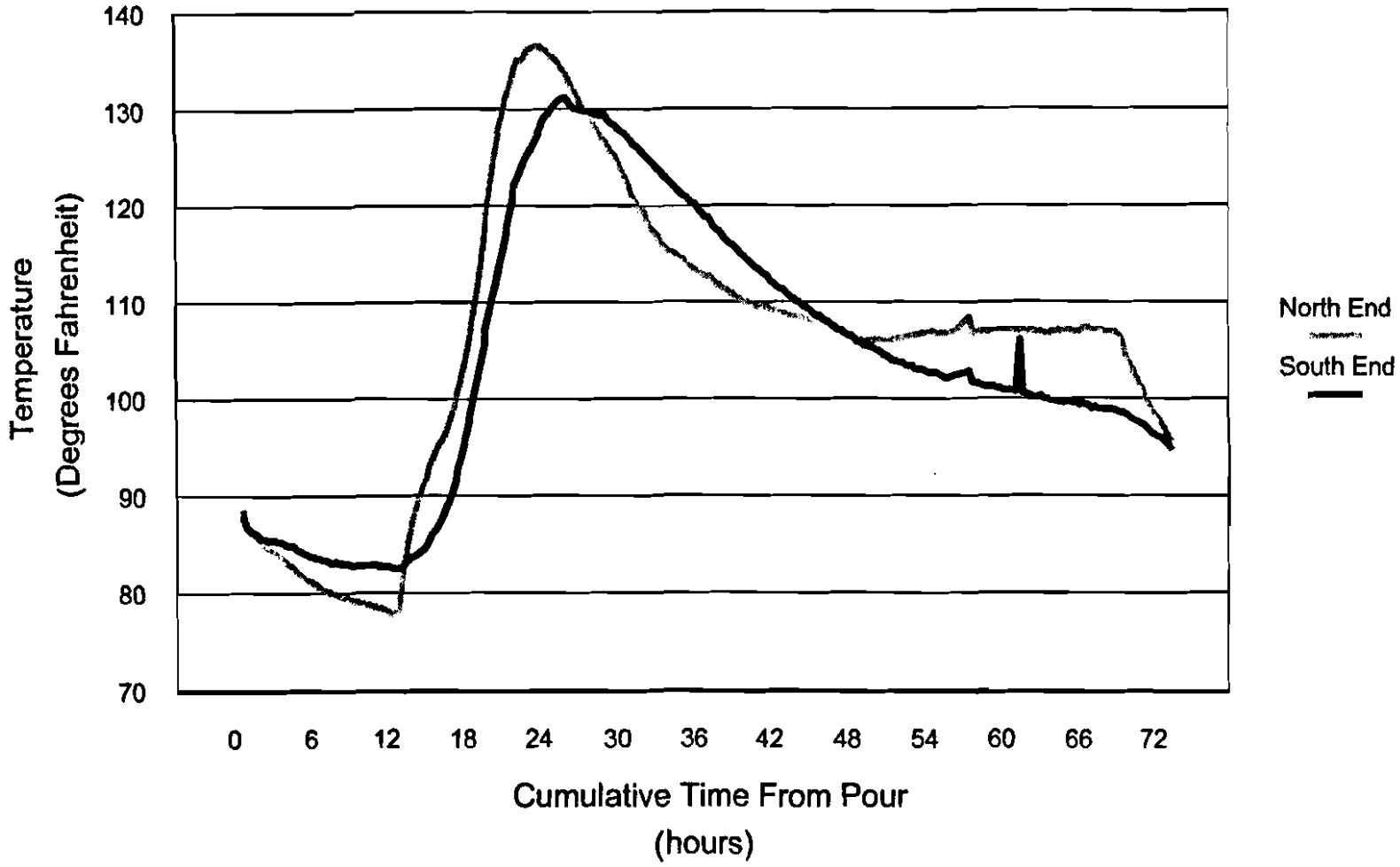
Girder Curing Temperatures at Mid-span



Appendix F

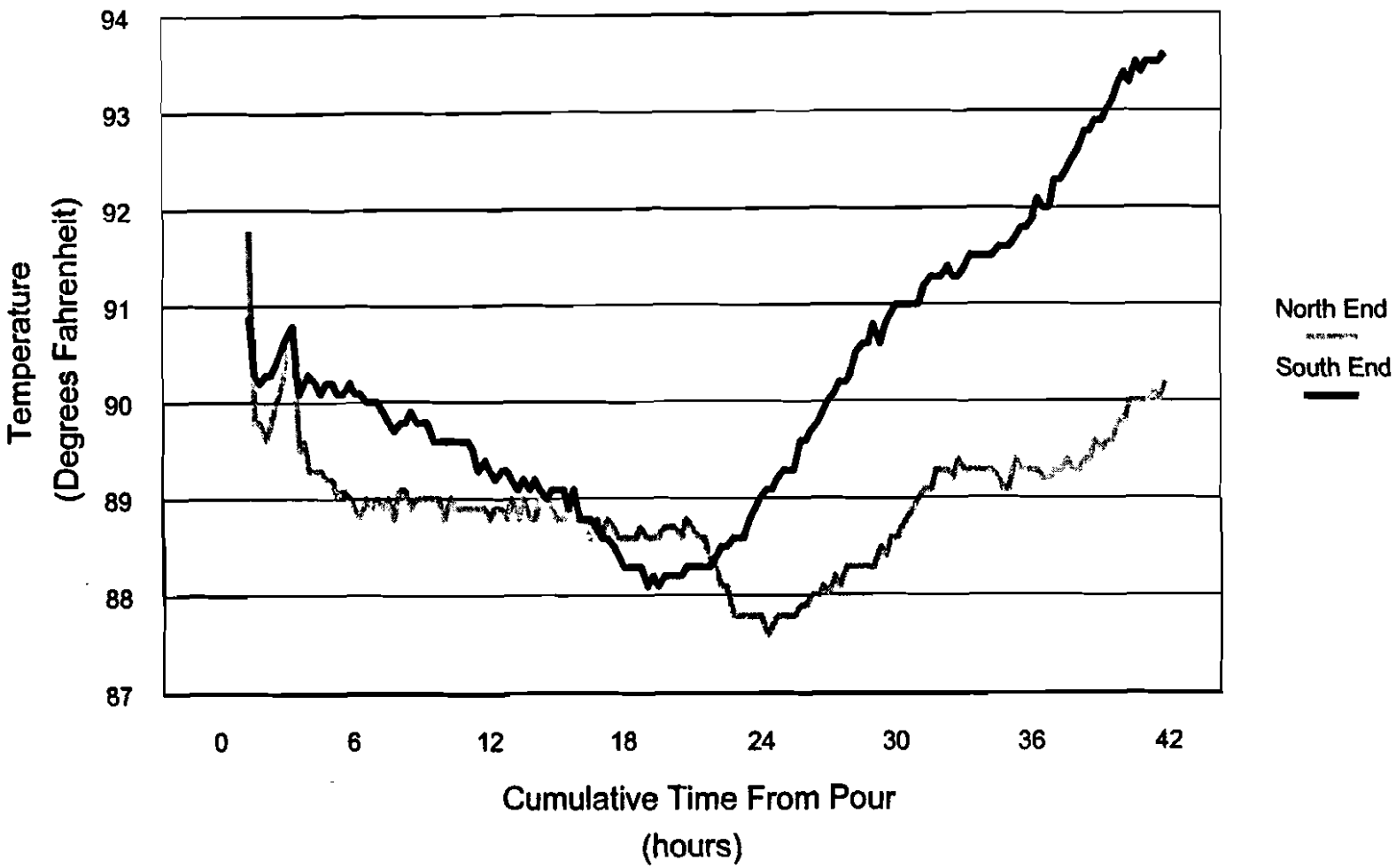
HPC

Curing Temperatures at Girder Ends



CONV. I

Curing Temperatures at Girder Ends



CONV. II

Curing Temperatures at Girder Ends