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INDIANA DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

Volume I Final Report

FHWA/IN/JHRP-88/5 -1

PRODUCTION AND ENGINEERING PROPERTIES OF CONCRETE USED IN PRECAST PRESTRESSED I-BEAMS FOR THE STATE OF INDIANA

M.K. Kaufman and J.A. Ramirez

PURDUE UNIVERSITY

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Final Report

RE-EVALUATION OF THE ULTIMATE STRENGTH AND BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAM SECTIONS

March 23, 1988

TO: H. L. Michael, Director
Joint Highway Research Program

FROM: J. A. Ramirez

PROJECT: C-36-56W

FILE: 7-4-23

Attached is a copy of the first of two volumes of the Final Report of the HPR Part II study "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections". I have served as the Principal Investigator on this study, directed the project and have co-authored the report.

The research results reported in this first volume include recommendations to allow the use of concrete compressive strengths up to 6500 psi in the design of precast prestressed I-Beams in the State of Indiana. No modifications of the current design equations to determine the modulus of elasticity and the tensile strength are needed for the concrete currently being used in the fabrication of these members. This includes concretes with compressive strengths up to 9000 psi. The use of crushed limestone coarse aggregate is recommended in design situations where tensile stresses and deflections are critical. The recommendations are based on the results of an in-depth study conducted at a local precast plant, and a survey conducted in four other plants in the states of Indiana and Kentucky.

In the early stages of implementation it is suggested to continue the evaluation of concrete compressive strengths up to 28 days. During the winter months special attention should be given to the quality control and curing conditions for the mixes currently being used. The improper application of accelerated curing methods, and the unfavorable field curing conditions after transfer of the prestress force could lead to a reduction in the 28 day compressive strength of the concrete. During the winter months the current design mixes may need to be modified to achieve a 28 day compressive strength of 6500 psi.

The results of this study have been recommended for implementation in the State of Indiana. The use of high strength concrete in the design of prestressed I-Beams offers substantial benefits. The increased tensile strength of higher strength concretes is helpful in the service load design. Also, the increase in the modulus of elasticity results in better deflection control. The inherent relationship between higher strength concrete and better quality control makes high strength concrete attractive because of its improved long-term service performance. The qualities of high strength concrete are also proving themselves economically attractive in long span bridges. High strength concrete's comparatively greater compressive strength per unit weight and unit volume results in a reduction in dead load allowing lighter more slender bridges.

The results of this study and other findings should provide the necessary information so that designers can use higher concrete strengths to improve the economics and structural safety of bridges.

Sincerely,

Julio A. Ramirez

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16. Abstract

This report describes engineering properties and current production procedures of concrete for precast prestressed I-beams in the state of Indiana. Current production techniques used in precast plants to obtain higher strength concrete are evaluated. The results of this study indicate that proper quality control and the use of admixtures have facilitated the production of concrete with 28 day compressive strength exceeding 7000 psi. A survey of 5 precast plants in Indiana and Kentucky indicated that an increase in the 28 day compressive strength requirement could be specified without major changes or additional cost to the product. Data from a year around study with field cured specimens indicated that the current empirically derived expressions to determine modulus of elasticity and tensile strength could be used in concretes with compressive strength up to 9000 psi.

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Final Report

RE-EVALUATION OF THE ULTIMATE STRENGTH AND BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAM SECTIONS

Volume I
PRODUCTION AND ENGINEERING PROPERTIES OF CONCRETE USED IN PRECAST PRESTRESSED I-BEAMS FOR THE STATE OF INDIANA

by

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Purdue University
West Lafayette, Indiana
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PREFACE

This is the first of two volumes on the research project, "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections." This report summarizes information on the engineering properties of concrete used in precast plants manufacturing prestressed I-beams for the state of Indiana. A review of current design provisions and suggested recommendations in the use of high strength concrete for the fabrication of AASHTO I-girders are also included. The second report contains the results of nine tests on full scale Type I and Type II AASHTO I-Girders with concrete strengths over 6000 psi.

This work was conducted as Joint Highway Research Project No. C-36-56W. The study was carried out at the Purdue University Civil Engineering Structural Laboratory.

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LIST OF NOMENCLATURE AND ABBREVIATIONS

E_c	=	modulus of elasticity of concrete, psi.
f_c'	=	compressive strength of concrete, psi.
$\sqrt{f_c'}$	=	square root of compressive strength of concrete, psi.
f_{sp}'	=	tensile splitting strength of concrete, psi.
f_r'	=	modulus of rupture of concrete, psi.
w_c	=	unit weight of the concrete, lb per cu ft.
ϵ_o	=	strain in/in, corresponding to f_c'.
F	=	field cured concrete.
G	=	gravel coarse aggregate.
LS	=	limestone coarse aggregate.
RET	=	retarding admixture.
SUP,SUPER	=	superplasticizing admixture.
T,Tarp	=	tarpaulin cover placed during curing period prior to transfer of the prestress force.

ABSTRACT

This report describes engineering properties and current production procedures of concrete mixes for precast prestressed I-beams in the state of Indiana. Current production techniques used in precast plants to obtain higher strength concrete are evaluated. The results of this study indicate that proper quality control and the use of admixtures have facilitated the production of concrete with 28 day compressive strength exceeding 7000 psi. A survey of 5 precast plants in Indiana and Kentucky indicated that an increase in the 28 day compressive strength requirement could be specified without major changes or additional cost to the product. Data from a year around study with field cured specimens indicated that the current empirically derived expressions to determine modulus of elasticity and tensile strength could be used in concretes with compressive strength up to 9000 psi.

CHAPTER 1

INTRODUCTION

1.1 General

Indiana Department of Highways (IDOH) Standard Specifications[1] Section 707.04(c) requires that the concrete compressive strengths for precast prestressed concrete structural members reach a minimum strength of 4000 psi at the time of prestressing and 5000 psi for the 28 day compressive strength. Precasters use different combinations of high early strength cement, high range water reducers, accelerating admixtures and accelerated curing methods to reach the concrete strength required to transfer the prestress force to the structural members. The required transfer strength is typically reached in less than 24 hours, and the producer is able to re-use the casting beds on a daily basis. The 28 day requirement of 5000 psi is often reached in 2-3 days after the cast date. Actual 28 day concrete strengths greater than 6000 psi are common; however, the use of the higher strength concrete is not common practice in the design of bridges which use prestressed I-beams in the superstructure.

1.2 Problem Statement

As a result of the early strengths achieved at transfer, the 28 day compressive strength limit of 5000 psi is often reached in 2-3 days, and the evaluation of the concrete strength is usually not continued up to 28 days.

Hence, actual 28 day strengths are not known for typical concrete mixes used in the production of prestressed I-Beams. Also, the effects of the different year around curing conditions on the engineering properties of such mixes need to be evaluated.

High strength concrete is becoming increasingly available and its structural properties should be evaluated so the designer can use them to improve the economics, and structural safety of bridges.

1.3 Objectives of the Study

One of the main objectives of this research effort is to provide information on the engineering properties of typical concrete mixes used in the fabrication of prestressed I-Beams for the state of Indiana. This report contains information on the 28 day compressive strength of concrete mixes used in prestressed structural members. The information is gathered from a survey conducted on four precast plants in the states of Indiana, Kentucky, and from an in-depth study conducted at a Lafayette precast plant. The year around study conducted at the local precast plant includes information on the production as well as enginering properties of concrete mixes used in prestressed I-Beams.

The implications of allowing the use of higher 28 day design concrete strengths in pretensioned I-Beams for the state of Indiana are also discussed.

CHAPTER 2

LITERATURE REVIEW ON ENGINEERING PROPERTIES OF HIGH STRENGTH CONCRETE

2.1 General

The definition of high strength concrete varies depending on the geographical area. ACI Committee 363 focused their concern on compressive strengths greater than or equal to 6000 psi in the committee's "State-of-the-Art Report on High Strength Concrete." [2] Such limit was established because many current concrete structural design provisions were empirically derived using concrete strengths less than or equal to 6000 psi and the extrapolation of such design provisions to higher compressive strength concretes may be unjustified.

In this chapter a detailed review of the background of some of the engineering properties of higher strength concretes important to the precast industry is conducted. Specifically, the stress strain behavior in compression, the modulus of elasticity, modulus of rupture and splitting tensile strength are examined. Also, the effects of different curing techniques on the concrete strength are discussed.

2.2 Stress-Strain Behavior in Compression

Figure 1 shows the general stress-strain behavior of concrete loaded in uniaxial compression for different compressive strengths. The ascending part of the curve becomes steeper as the compressive strength increases. The corresponding strain at peak stress is approximately 0.002 in/in. The corresponding strain at peak stress is slightly higher for concretes with round river gravel coarse aggregate, as compared to concretes with crushed limestone.[3] The descending part of the curve is also steeper for the higher strength concrete.

Typically, smaller test specimens are used when evaluating material properties for high strength concretes. The smaller test specimen requires less material and the ultimate strength load is also smaller compared to that of a 6 x 12 inch cylinder. A reduction factor is usually applied to smaller specimens since they give higher compressive strengths as compared to the 6 x 12 inch cylinder. In the study conducted by Carrasquillo et al.[7] 4 x 8 inch cylinders were used to evaluate the compressive strength and modulus of elasticity. In this study it was found that the ratio between the 6 x 12 inch cylinders and the 4 x 8 inch cylinders was 0.9 for compression tests. In references 10 and 11 it was reported also that 4 x 8 inch cylinders will give higher compressive strengths than 6 x 12 inch cylinders.

2.3 Modulus of Elasticity

The value of the modulus of elasticity is important in calculations of deflections due to loads, prestress losses due to elastic shortening, and concrete stresses under service loads.

The modulus of elasticity or chord modulus of elasticity represents the

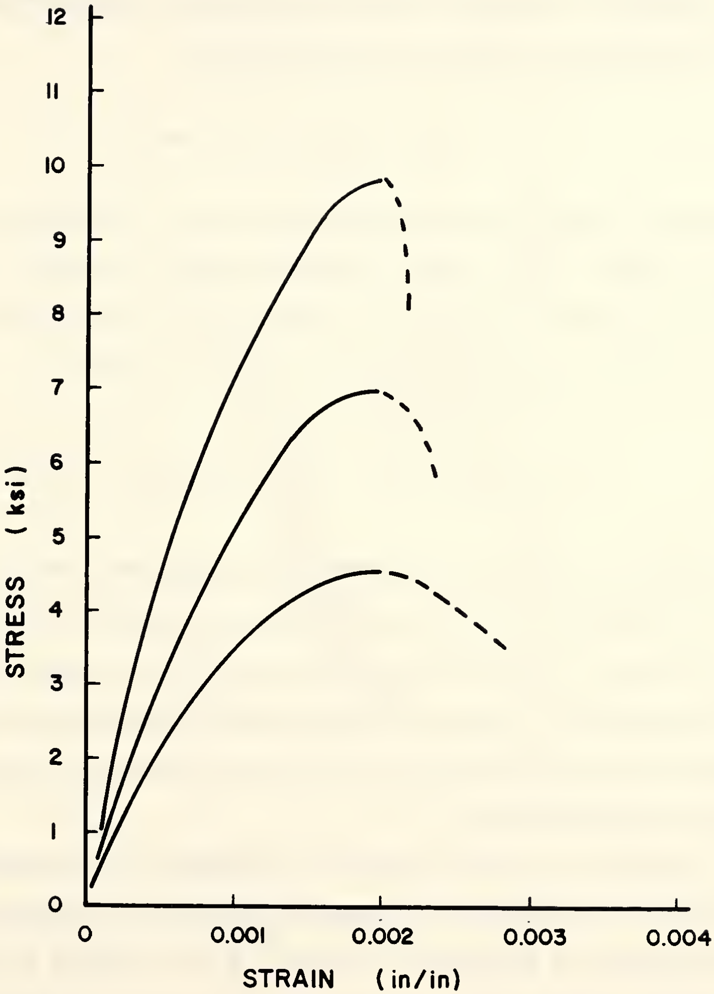

Figure 1 - Typical Stress-Strain Curves for Different Concrete Strengths.

slope of the concrete stress strain curve between 0 and 40% of the ultimate compressive strength as specified by ASTM Standard C469-83.[4] AASHTO Standard Specifications for Highway Bridges[5] recommend that the modulus of elasticity, for concrete consisting of unit weights between 90 and 155 pcf, be approximated using the following expression

$$E_c = 33\, w_c^{1.5} \sqrt{f_c'} \quad \text{(psi)} \tag{1}$$

where w_c is the unit weight of the concrete, and f_c' represents the compressive strength. This equation proposed by Pauw[6] was based on concretes with compressive strength up to 6000 psi. ACI Committee 363 has proposed the following equation for the modulus of elasticity:

$$E_c = [40000 \sqrt{f_c'} + 1.0 \times 10^6] \left(\frac{w_c}{145}\right)^{1.5} \quad \text{(psi)} \tag{2}$$

Equation (2) is valid for compressive strengths between 3000 psi and 12000 psi. Equation (2) was developed from work conducted by Carrasquillo et al.[7] In Figure 2 both equations are compared with test results obtained from several sources. The current design Equation (1) was shown to be mostly an upper bound of the test data for the modulus of elasticity in higher compressive strength concretes.

Equations (1) and (2) include the unit weight and compressive strength as the variables required to determine the modulus of elasticity. Actually, the modulus of elasticity is a function of such variables as compressive strength, elastic modulus of the aggregate and paste, aggregate and paste content, specimen size and shape, test method and moisture conditions of the test specimen.[6,7,8]

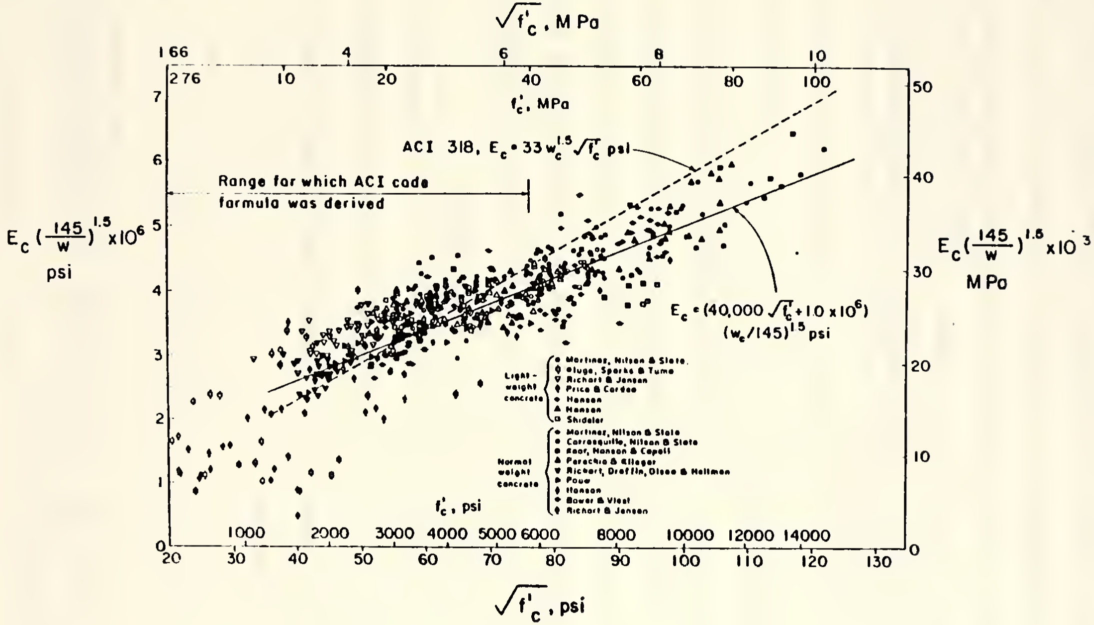

Figure 2 - Modulus of Elasticity versus Concrete Strength.

(From ACI Committee 363 State-of-The-Art Report on High Strength Concrete, Reference 2)

Thus the considerable scatter of the data in Figure 2 is not surprising.

Crushed limestone will produce a higher modulus of elasticity as compared to an equivalent mix using round river gravel as the coarse aggregate.[7] This is due to the stronger bond between the paste and crushed limestone. A moist cured cylinder will produce a higher modulus of elasticity and a lower compressive strength as compared to a cylinder cast with the same mix which is not moist cured.[9]

2.4 Modulus of Rupture

Flexural stresses in the extreme tension fiber quite often control the quantity of prestressed and mild reinforcing steel in the member. The limit value of the cracking moment is based on the extreme tension fiber allowable stress obtained from the modulus of rupture strength of the concrete. This value of moment is also used to determine the minimum amount of flexural reinforcement, and in shear calculations.

The modulus of rupture represents the tensile strength of the concrete when subjected to flexural stresses. Current design specifications[5] for highway bridges recommend that the modulus of rupture for normal weight concrete be estimated as

$$f_r' = 7.5 \sqrt{f_c'} \quad \text{(psi)} \qquad (3)$$

ACI Committee 363 recommends that the following equation be used to predict the modulus of rupture.

$$f_r' = 11.7 \sqrt{f_c'} \quad \text{(psi)} \qquad (4)$$

Equation (4) also was proposed by Carrasquillo et al.[7] The test specimens were 4 x 4 x 14 flexure beams. The coarse aggregate was crushed limestone.

2.5 Split Cylinder Strength

The split cylinder test is used as a measure of the direct tensile strength of the concrete. The state of stress in the split cylinder test is similar to that near the centroid of the web of a prestressed I-girder near a non-continuous support where flexural stresses are low and shear stresses are high. ACI Committee 363 recommends that the equation

$$f'_{sp} = 7.4\ \sqrt{f'_c} \quad \text{(psi)} \tag{5}$$

be used to predict the tensile splitting strength of concrete. Equation (5) was also proposed by Carrasquillo et al.[7] The test specimens were 4 x 8 inch cylinders with crushed limestone as the coarse aggregate.

2.6 Curing Procedures and Techniques

Curing of precast prestressed specimens in accordance to the Indiana Department of Highways Standard Specifications 707.07.[1] shall be done by wet or accelerated curing. Wet curing is accomplished by applying two layers of wet burlap to the exposed surfaces of the specimen. Two methods of accelerated curing are allowed, low pressure steam and radiant heat.

Four time periods are important in the process of accelerated curing using low pressure steam. They are the pre-steaming period, temperature rise period, period at maximum temperature and cooling period. The initial set of the concrete occurs during the pre-steaming period. The application of heat up to the desired peak curing temperature takes place during the temperature rise period. This peak curing temperature is maintained during the period at maximum temperature until the desired compressive strength is obtained. Next, the specimen is cooled to ambient temperature during the cooling period.

Indiana specifications[1] have the following requirements for the process of accelerated curing. During the time of initial set of the concrete only heat needed to maintain a minimum temperature of 50°F for the fresh concrete shall be applied. Initial set of the fresh concrete generally occurs in 2-4 hours. If retarders are used, the initial set time shall be increased to 4-6 hours. The rate of temperature increase inside the enclosure shall not exceed 40°F per hour during the temperature rise period. The peak temperature of the concrete surface shall not exceed 160°F during the curing period at peak temperature. No requirements are made as to the cooling period. The accelerated curing method using radiant heat is similar to the low pressure steam procedure except that wet burlap must be applied to the exposed surfaces of the concrete to reduce moisture loss. ACI Committee 517[12] is in general agreement with the Indiana specifications.

High steam curing temperatures result in higher early compressive strengths but, 28 day compressive strengths are generally lower. Hanson[13] found that application of steam prior to the initial set of the concrete can be quite detrimental to the compressive strength. Peak curing temperature between 150°F and 180°F are most effective in producing quality concrete. Rapid cooling rates should be avoided so as to reduce cracking in members due to effects of formwork restraints, and differential stresses due to different prestressing materials.

The optimum accelerated curing process can be quite different from one precast plant to another. Since, the ambient temperature, type of admixtures, size of specimen, method of heat application and the length of time of heat application varies for each plant, optimum accelerated curing schedules could be different.

2.7 Summary

When evaluating engineering material properties it is important to model the behavior of the material in its actual use. In other words, a comparison of deflections and cracking loads of full scale members should be made to test the validity of proposed equations for modulus of elasticity and tensile strength. The 6 x 12 inch cylinder in itself is just a model used to approximate the material behavior in the structure. In the Cornell study 4" x 8" cylinders were used to determine the compressive strength and the splitting strength, and 4" x 4" x 18" flexure beams were used to evaluate the modulus of rupture. The proposed equations for the modulus of rupture and split cylinder strength were developed based on the results of the smaller test specimens, and unlike the compression tests where the results were adjusted to correlate with those of 6 x 12 inch cylinders, no size effect was taken into account.

Concrete with crushed limestone showed a higher modulus of elasticity and tensile strength as compared to that with gravel. The concrete compressive strength is equivalent for both types of aggregate given the same mix proportions.

Two methods of accelerated curing are allowed in precast plants which produce prestressed structural members for the state of Indiana. During the winter months, the improper application of accelerated curing methods to fresh concrete and the unfavorable field curing conditions can result in detrimental effects to the 28 day compressive strengths.

CHAPTER 3

CONCRETE FOR PRECAST PRESTRESSED I-BEAMS IN THE STATE OF INDIANA

3.1 General

Five precast plants which produce prestressed members for the state of Indiana were surveyed to obtain information dealing with their concrete production. The survey had the following objectives:

- To determine the current mixes being used in the fabrication of prestressed I-beams, and their typical 28 day compressive strengths.

- To determine the effect of accelerated curing methods during the winter months on the concrete compressive strength.

- To determine, without changing the transfer strength requirement of 4000 psi, the 28 day compressive concrete strength that could be specified without causing any major changes in current production procedures and concrete mix proportioning.

3.2 Results of the Survey

Precasters in Indiana typically use between 6.5 and 8 bags of Type III cement per-cubic yard of concrete, 3/4 inch crushed limestone as the coarse aggregate, and a variety of admixtures to obtain the desired transfer design strengths. A precast plant typically has more than one standard mix. The mix proportioning is determined from factors such as the ambient air temperature (curing conditions), time schedule and plant economics.

The 28 day compressive strength of concretes being used by the surveyed precast plants is not well known or documented. Standard practice is to load the test cylinders up to the strength specified by the design engineer. Once the specified strength is exceeded, the cylinder is unloaded without necessarily carrying the test to failure. Hence, the actual compressive strength of the elements is, in many instances, unknown. There are two reasons for this method. First, is to reduce the impact and sudden energy release to the testing machine. This reduces the wear, possible expensive repair costs and down time of the testing machine. Second, is to eliminate the brittle failure of concrete for obvious safety reasons. Also, keeping the cylinder intact allows the precasters to obtain a direct measurement of the concrete strength of a structural member at later date, and at the same time reduce the number of samples needed.

Winter time casting was also investigated in this survey. Some fabricators have indoor facilities and the cold weather has no effect on the transfer strength, but may effect the 28 day strength as the member is placed outdoors to continue curing after the transfer of the prestress force. The precast plants that were contacted use either low pressure steam or radiant heat accelerated curing as specified in IDOH Specification 707.07.[1] Precast fabricators indicated no detrimental effects due to accelerated curing methods.

All of the fabricators indicated that the 28 day strength requirement could easily be increased. It was indicated that with proper curing conditions, the 5000 psi strength is sometimes exceeded prior to transfer of the prestress force. The question, "What could be a reasonable value of the 28 day strength?" presented somewhat of a dilemma to the manufacturers. The fabricators all said that 6500 psi would be no problem with their standard concrete mix, whether in the winter or summer months. At 7000 psi, the general consensus seemed to be that the use of a high-range water reducers or additional cement would be needed. The strength of 8000 psi and above would require special admixtures such as the use of micro-silica, fly ash or some other type of mix modification to reach the required strength at 28 days.

3.3 Summary

Precast plants proportion their mixes to reach early transfer strengths. Curing conditions, time and plant economics dictate the quantity of Type III cement and the use of admixtures.

The transfer strength of 4000 psi is usually reached in less than 24 hours. This allows the producer to utilize the casting beds on a daily cycle. The 28-day requirement of 5000 psi is easily obtained in a few days due to the fact that the transfer strength is reached at a very early age.

The 28 day requirement of 5000 psi could be increased without increasing the cost of the product. All plants surveyed agreed that a 6500 psi requirement would present no major changes to their current mix proportioning. However, the compressive strength evaluation techniques currently used by the producers do not allow for a definite 28 day requirement to be specified.

Information on the winter curing procedures indicated that there was no problem in reaching the 28 day compressive strength requirement of 5000 psi.

In the following chapter the conclusions of this survey are evaluated with actual test data obtained from a study conducted at a local precast plant. Test data is from concrete mixes used in precast prestressed I-beams manufactured for the state of Indiana. Further discussion based on the results of such evaluation will add to the conclusions of this chapter.

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 General

The evaluation conducted at a local precast plant of concrete mixes used in prestressed structural members for the IDOH began in June of 1985. Many combinations of mix proportioning were evaluated. These included 6.5 or 6.9 bags of Type III cement per cubic yard of concrete, and crushed limestone or round river gravel as the coarse aggregate. The mixes evaluated also included retarding, air entraining, and superplasticizing admixtures.

Samples were taken year around. The evaluation first included compressive strength vs. time, and later expanded to the static modulus of elasticity, modulus of rupture and split cylinder tests.

Nine individual batches were evaluated. In Batches B1, B2, and B3 the concrete compressive strength versus time was evaluated. In Batches C1 through C6 the concrete compressive strength and modulus of elasticity versus time were evaluated. Appendix A contains stress-strain curves for a few individual compression tests. Appendices B and C contain the information and test results for batches B1, B2, and B3 and C1 through C6, respectively. The tensile strength of the concrete was evaluated for all the batches using flexure beams and split cylinder tests.

4.2 Fabrication of Test Specimen

A typical batch consisted of 6 flexure beams and 24 cylinders. The flexure beams were 6" x 6" x 18" and the cylinders 6" x 12". The flexure beams and the cylinders were cast in accordance with ASTM C31-84.[4] Steel flexure beams and plastic cylinders with lids were used as specimen molds.

The local precast plant has a mixer with a capacity for 4 cubic yards of concrete. The test specimens were made after the slump and air content readings were taken. All the specimens were cast from the same batch with the exception of batch B1. Batch B1 had a variety of samples of the same mix proportioning, but from different batches. The test specimens of all the the batches were placed on the casting bed to simulate the curing environment of the precast beams. Batches B3 and C3 were steam cured up to the time of transfer. Curing conditions in the remaining batches consisted of wet burlap and tarpaulin up to the time of transfer of the prestress force.

Just prior to the prestress force transfer, the test specimens were removed from the casting bed and transported to the Purdue University Structural Laboratory located a few miles from the precast plant. The test specimens were then stripped and field cured outside the laboratory until the time of testing.

4.3 Testing Procedures

Two Baldwin testing machines were used, a 600 kip capacity and a 120 kip capacity machine. The 120 kip Baldwin was used to in the tests to determine the static modulus of elasticity and the 600 kip Baldwin for the compressive strength tests.

The compressive strength versus time was recorded for batches B1 - B3.

Each test consisted of testing the compressive strength of at least 3 cylinders capped with "Forney HI-CAP Capping Compound."

The static modulus of elasticity and compressive strength were evaluated for batches C1 - C6. Each test consisted of three cylinders. The three cylinders were weighed and then capped. The compressive strength of one cylinder was evaluated and recorded. The remaining two cylinders were then tested to determine the static modulus of elasticity. They were loaded up to 40 percent of the compressive strength of the cylinder tested to failure to determine the static modulus of elasticity as specified in ASTM C469-83.[4] The test set-up used to determine the modulus of elasticity is shown in Figures 3 and 4. Two gage rings were diametrically attached to the cylinders with a gage length of 6 inches. Each gage ring rests on pivoting lever arms which are attached to a linear variable differential transducer (LVDT). The load and displacement values of each test were recorded using an automated data acquisition system and stored in a personal computer. The two cylinders were then tested to failure in the 600 kip Baldwin to determine the compressive strength. In addition to the LVDT set-up, two 2 inch electrical resistance strain gages were placed diametrically on a few cylinders from chosen batches. The modulus of elasticity determined from the two methods was within 5% indicating excellent agreement. The strain gages were also used to obtain the stress-strain curve for the compressive strength tests.

Flexure beams and specimens for split cylinder tests were also cast from all the batches. The flexure beams were tested using a third point loading system as specified in ASTM C78-84.[4] The test set-up is shown in Figure 5. Three flexure beams were tested at the time of transfer and the remaining three were tested at 28 days. After 28 days of curing, split cylinders were

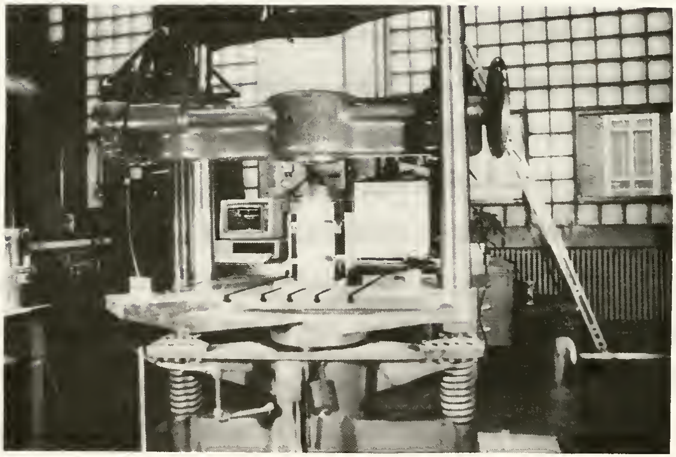

Figure 3 - Static Modulus of Elasticity Test Set-up.

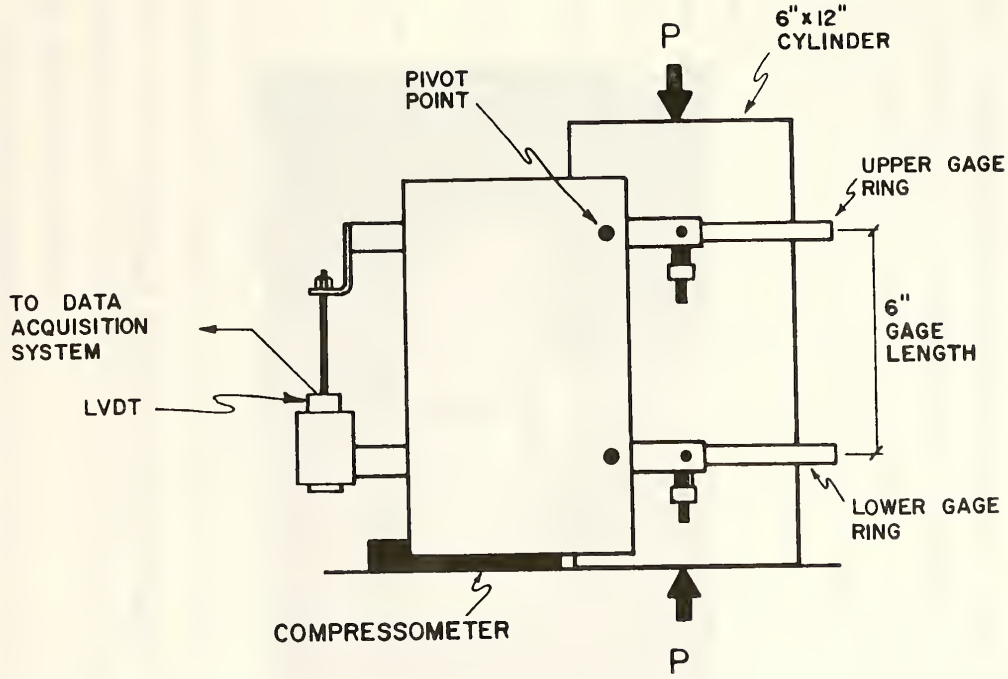

Figure 4 - Experimental Set-up to Measure the Modulus of Elasticity.

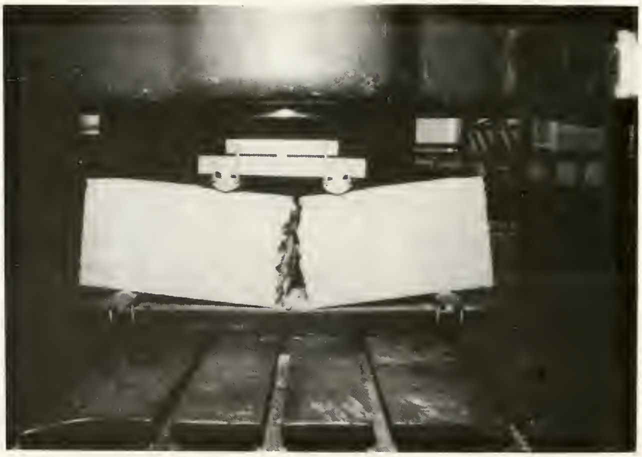

Figure 5 - Modulus of Rupture Test Set-up.

tested as shown in Figure 6 in accordance to ASTM C496-85[4].

4.4 Test Results

Appendix A contains stress-strain curves for several of the compression tests. Also, the modulus of elasticity, compression strength and corresponding strain are given. Appendix B contains information on the compressive strength versus time for Batches B1, B2, and B3. The curing time of the test along with the compressive strengths are listed. Appendix C contains information on the compressive strength and modulus of elasticity versus time for batches C1 - C6. The curing time, unit weight, compressive strength, measured modulus of elasticity, predicted modulus of elasticity from Equation (1) and the ratio of the measured to the predicted modulus of elasticity for each test are included.

4.4.1 Stress-Strain Curve

The stress (f_c) versus strain (ϵ) curves in Appendix A show typical behavior of concrete loaded in uniaxial compression. The maximum stress (f_c') and corresponding strain (ϵ_o) are also given. The initial part of the ascending curve is quite linear. As the load is increased past 0.6 f_c', the curve becomes non-linear. The corresponding strain at f_c' is 0.0020 in/in for cylinders cast with limestone coarse aggregate. Cylinders cast with gravel gave a lower modulus of elasticity and the strain at f_c' is 0.0022 in/in. Though the tests are limited in number, this behavior is in agreement with the results of other studies.[7]

In this study the descending part of the curve was not determined; however, the post-peak behavior of the higher strength concrete was quite brittle and explosive.

Figure 6 - Split Cylinder Test Set-up.

4.4.2 Compressive Strength

The transfer strength requirements for the 9 batches was either 3500 or 4000 psi. The 28 day requirement was 5000 psi. Table 1 summarizes the results from the 9 batches. Indiana specifications[1] require a slump between 3 and 5 inches. When plasticizing admixtures are used, the slump must be between 4 and 6 inches. The air content must be between 5 and 8 percent. All batches evaluated met these requirements as shown in Table 1. The average compressive strength at the time of transfer of prestress force, and 28 days are listed in Table 2. The results of the last set of cylinders and corresponding age are also included.

Batches C1 with limestone coarse aggregate and C2 with gravel aggregate were cast the same day. The slump, air content, and curing conditions were kept the same in these two batches to evaluate the differences between mixes with limestone and gravel aggregate. No significant difference in the compressive strengths was observed as shown in Table 2.

Batches C1 and C3 contained limestone as the coarse aggregate. Batch C3 had 6.9 bags of cement per cubic yard and Batch C1 had 6.5 bags of cement per cubic yard. Batch C3 was steam cured until the time of transfer and Batch C1 received no form of accelerated curing. The transfer strength of Batch C3, 4420 psi, exceeded that of Batch C1, 3970 psi. However at 28 days, Batch C1, 6600 psi, had a higher compressive strength than Batch C3, 5900 psi. A similar comparison can be made between Batches B3 and C2. Batch B3 differed from Batch C2 in that it contained a superplasticizing admixture and was steam cured prior to transfer. The transfer strength of Batch B3, 4830 psi, was higher than C2, 4080 psi; however, the 28 day strength of Batch C2, 6440 psi, exceeded that of Batch B3, 5970 psi.

Table 1 - Mix Data for all Batches.

		Mix Data		
Batch	Casting Date	Contents*	Slump (inches)	Air Content (%)
B1	6/27/85	6.9/LS/Ret/Sup	3.5-4.25	5.0-6.2
B2	7/19/85	6.9/LS/Ret/Sup	5	7.0
B3#	11/5/85	6.5/G/Ret/Sup	5.5	5.8
C1	5/28/86	6.5/LS/Ret	3	5.8
C2	5/28/86	6.5/G/Ret	3.25	5.5
C3#	3/4/87	6.9/LS/Ret	3.5	7.0
C4	6/11/86	6.9/LS/Ret/Sup	3.5	5.3
C5	10/2/86	6.9/LS/Ret/Sup	3	5.8
C6	4/1/87	6.9/LS/Ret/Sup	3.5	6.5

*

LS = coarse aggregate, limestone.
G = coarse aggregate, gravel.
Ret = Retarding admixture.
Sup = Superplasticizing admixture.

All Batches contain an air entrainment admixture.
6.5 and 6.9 represents the number of bags of Type III cement per cubic yard.

\#
Batch steam cured prior to the transfer of prestress, all other batches field cured.

Table 2 - Compressive Strength for all Batches

Batch	Compressive Strength Transfer† (psi)	28-Day (psi)	f'_c/age (psi/days)
B1	5700	7870	7970/56
B2	5860	7670	8710/91
B3#	4830	5970	----
C1	3970	6600	7050/101
C2	4080	6440	7130/101
C3#	4420	5900	6530/ 84
C4	5540	7700	8330/ 76
C5	6030	8340	8650/195
C6	5260	7530	8030/ 56

†
Transfer times are given in Appendices B and C.

#
Batch steam cured prior to the transfer of prestress, all other batches field cured.

The reduction on the 28 day compressive strength could be attributed to the steam curing; however, other variables which effect the compressive strength such as air content and slump also need to be addressed. As these two increase, a reduction of the compressive strength occurs. Even though batch C3 had a greater amount of cement than Batch C1, the values of slump and air content were also greater. Curing conditions in the field after transfer are also important to the strength gain of the concrete. Batches B3 and C3 were cast in early November and early March, respectively. Batches C1 and C2 were cast in late May. Hence, field curing conditions for Batches C1 and C2 were much more favorable than those of Batches B3 and C3.

Batches B1, B2, C4, C5 and C6 had similar mix characteristics. These batches received no form of accelerated curing to reach the desired transfer strength. The compressive strength at the time of transfer exceeded both the 4000 psi requirement, and the 28 day compressive strength requirement of 5000 psi. The benefits from using the plasticizing admixture are shown in the compressive strengths which exceeded 7000 psi at 28 days and continued to increase to over 8000 psi. The superplasticizing admixture reduces the amount of mixing water producing a lower water/cement ratio while maintaining a workable concrete.

4.4.3 Static Modulus of Elasticity

The variation of the static modulus of elasticity with different concrete compressive strengths for Batches C1 through C6 is shown in Figures 7 through 10. Each data point represents the average of two modulus of elasticity measurements at a given curing time. The result is normalized for a concrete with a unit weight of 145 pcf. This is done to facilitate the com-

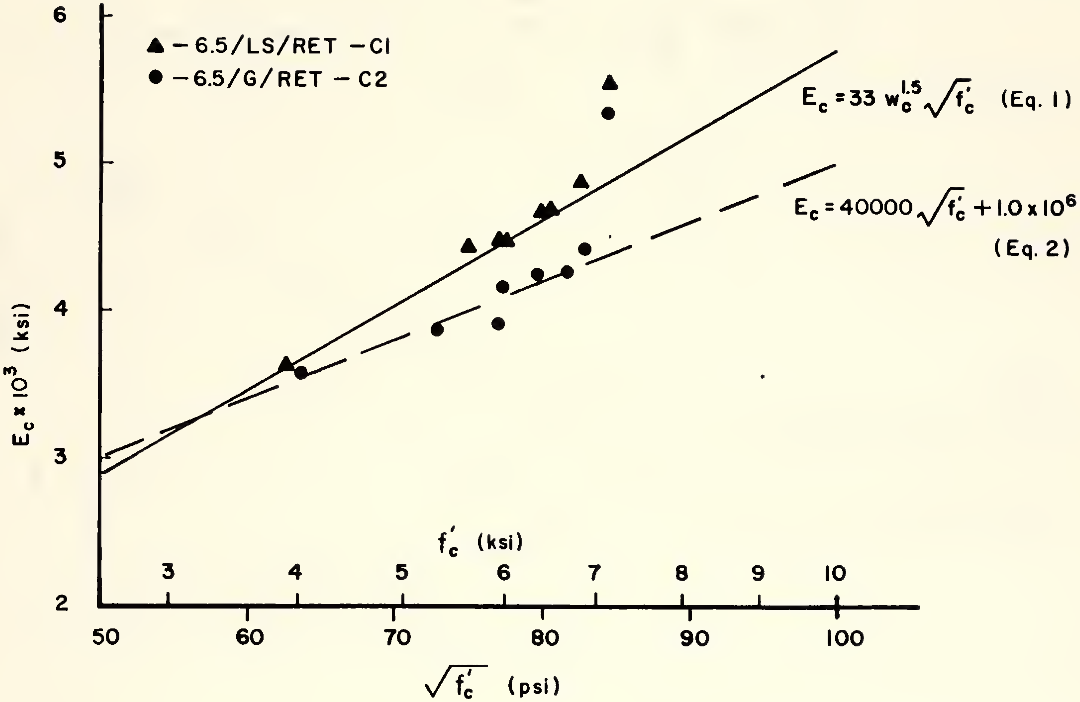

Figure 7 - Modulus of Elasticity vs. Compressive Strength, Batches C1 and C2.

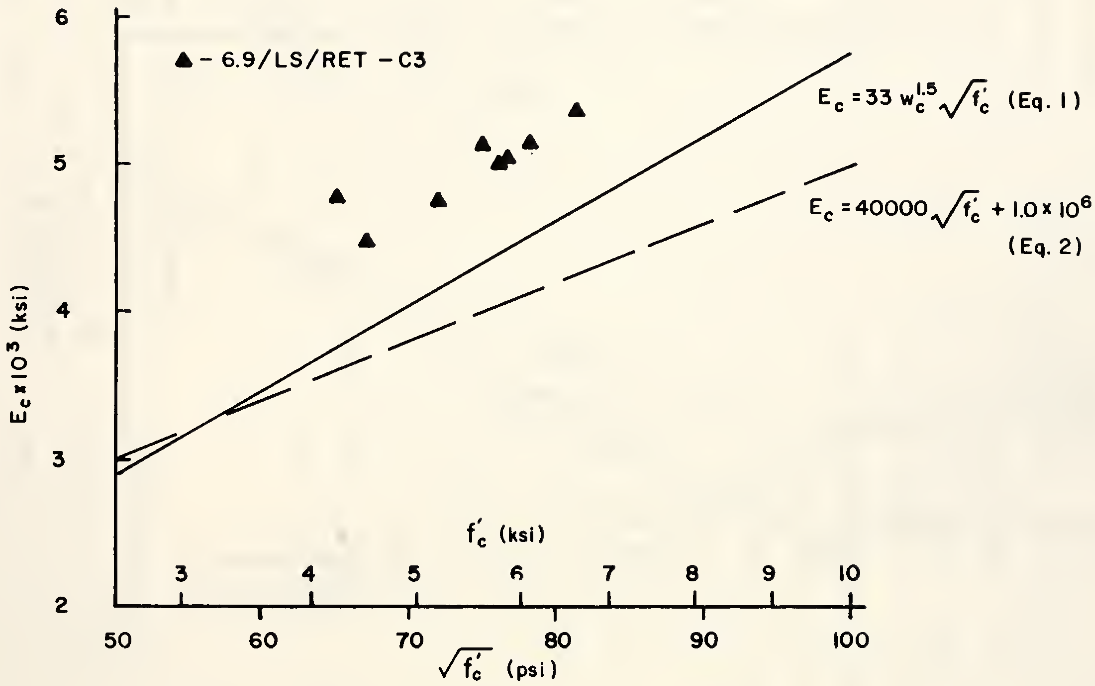

Figure 8 - Modulus of Elasticity vs. Compressive Strength, Batch C3.

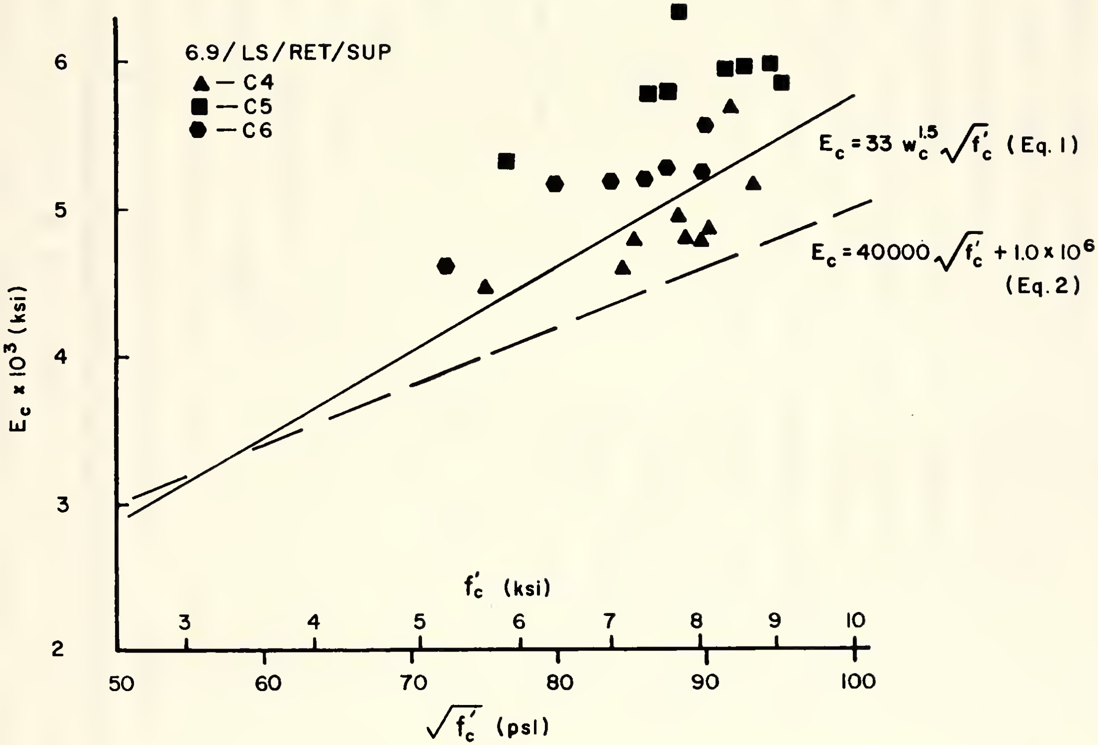

Figure 9 - Modulus of Elasticity vs. Compressive Strength, Batches C4, C5, and C6.

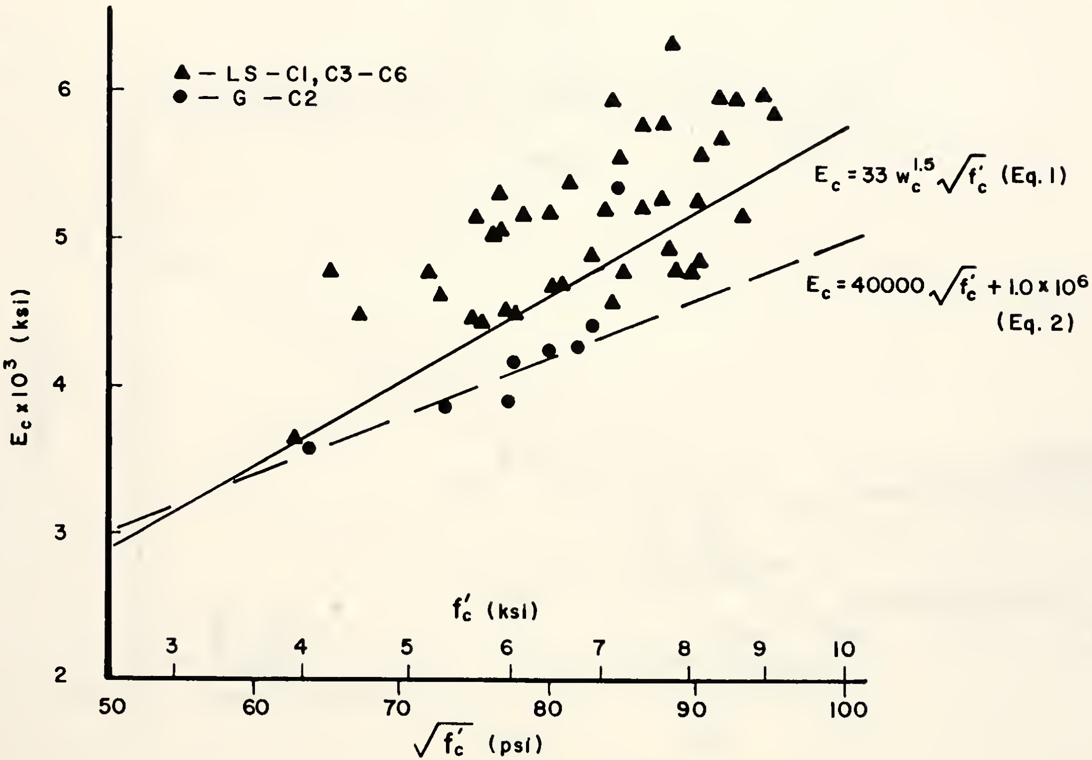

Figure 10 - Modulus of Elasticity vs. Compressive Strength, Batches C1 - C6.

parison of these results with those obtained using Equation (1) and the Committee 363 proposed high strength Equation (2) with w_c = 145 pcf.

Figure 7 shows a graph of the modulus of elasticity versus the compressive strength for Batches C1 and C2. A noticeable difference in the modulus of elasticity values is observed when comparing the limestone and gravel mixes. The limestone aggregate results in a stiffer concrete mix due to the better bond between the mortar and the aggregate. The gravel was round and had a smooth surface, while the crushed limestone had an angular shape and a rough surface. The limestone aggregate test data agrees very well with the Equation (1). The gravel batch test data lies slightly below Equation (1) and agrees with the proposed high strength concrete Equation (2).

Figure 8 shows the modulus of elasticity versus compressive strength values for Batch C4. Batch C4 had a 6.9 bag mix with limestone used as the coarse aggregate. The mix was steam cured up to the time of transfer of prestress force. Figure 8 shows that the Equation (1) under-estimated the measured values by an average of 15%. This difference can possibly be attributed to steam curing effects. The cast took place late in the afternoon and the local precast plant has a manually operated accelerated steam curing system. The steam was applied to the casting bed somewhere around 1 to 2 hours after completion of the cast. Batch C4 had a retarding admixture in the mix, hence steam was most likely applied prior to initial setting of the concrete. This can be quite detrimental to the compressive strength of the concrete at 28 days as was reported in Reference 13. If the compressive strength was reduced while not affecting the modulus of elasticity, this would explain the shift of the data shown in Figure 8. In other words, adding say 1000 psi to the compressive strengths would shift the data closer to the Equation (1) predicted values.

The data from batches C4, C5, and C6 are shown in Figure 9. Each batch had the same mix proportioning. The casts took place in June, October, and April, respectively. Hence, each batch was exposed to different seasonal temperatures and humidity. The compressive strengths were very similar for the batches. Equation (1) approximates the data reasonably well.

Figure 10 combines the modulus of elasticity versus compressive strength for Batches 1 through 6. Equation (1) was determined as a best fit curve to the data shown in Figure 1. Equation (1) approaches the lower bound of the data containing limestone as the coarse aggregate and the upper bound for the mixes using gravel for the coarse aggregate. All variables considered, Equation (1) is shown to be a good empirical model for the data collected.

4.4.4 Modulus of Rupture

Shown in Figure 11 are the test data of all the flexure beam tests. Flexure beams were generally tested at transfer and at 28 days. The mix with limestone aggregate is superior to the mix with gravel aggregate. Common expressions used to predict the modulus of rupture in design applications are also shown. These values are used in stress calculations for precast prestressed members. Current AASHTO[7] design recommendations specify $6\sqrt{f_c'}$ as the allowable stresses after prestress losses for members with bonded reinforcement and $3\sqrt{f_c'}$ for severe corrosive exposure conditions. Figure 11 shows that these concrete stress limits are in general below the data collected. However, Equation (4) from Chapter 2 proposed by ACI Committee 363 is shown to be an upper bound of the test data.

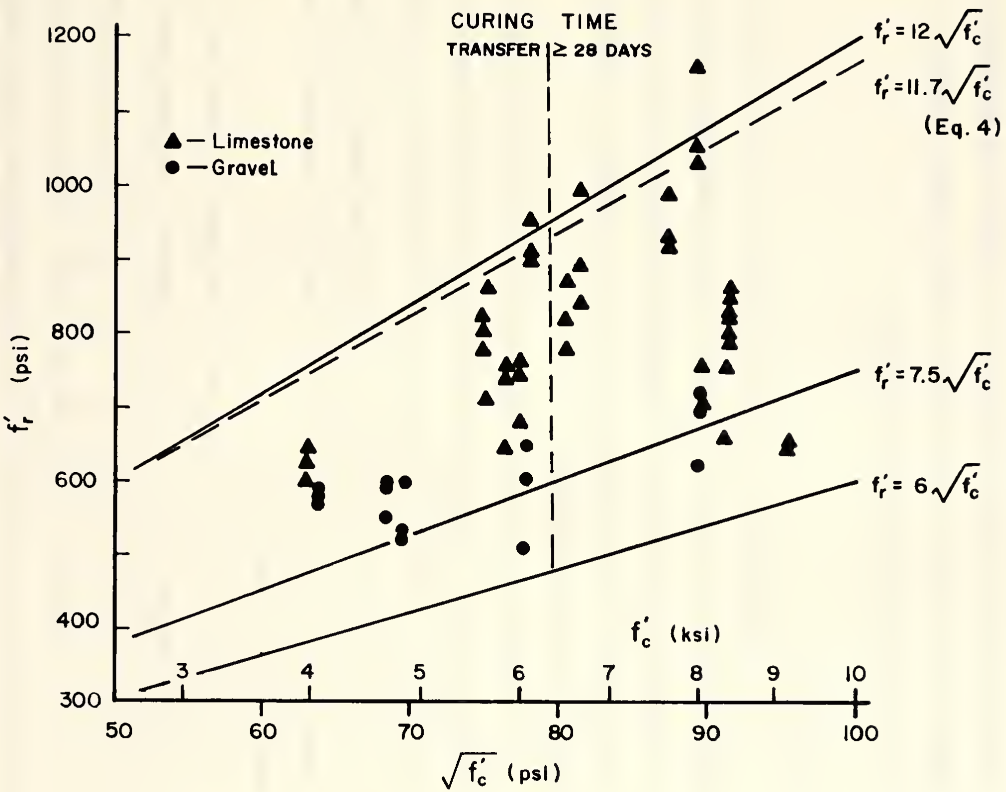

Figure 11 - Modulus of Rupture vs. Compressive Strength.

4.4.5 Split Cylinder Tests

Figure 12 shows that the limit 3.5 $\sqrt{f'_c}$, is a lower bound to the data from split cylinder tests. The proposed Equation (5) overestimates the split cylinder test data as shown in Figure 12. Concrete with limestone coarse aggregate once again shows a superior tensile strength. However, more tests are needed to confirm such observation.

4.5 Summary

In the evaluation of the concrete produced at the local precast plant sample. Batches were taken year around. The test samples were field cured and various combinations of mix proportioning were surveyed. Data was collected from one local precast plant which manufactures prestressed I-beams for the State of Indiana.

The information on the concrete compressive strength collected from other precast plants in Indiana and Kentucky agreed with the results of this in-depth study. In addition, plants use crushed limestone in some instances from the same quarry. Therefore, it is expected that material properties of comparable mixes throughout the state are similar to those found in the data collected in the in-depth study.

The current mix proportioning used in the state of Indiana for precast prestressed I-beams could reach 28 day compressive strengths greater than 8000 psi under favorable curing conditions. However, detrimental effects to the 28 day compressive strength can occur due to the improper application of accelerated curing methods, and the unfavorable field curing conditions during the winter months.

The value predicted by the current design Equation (1) for the modulus

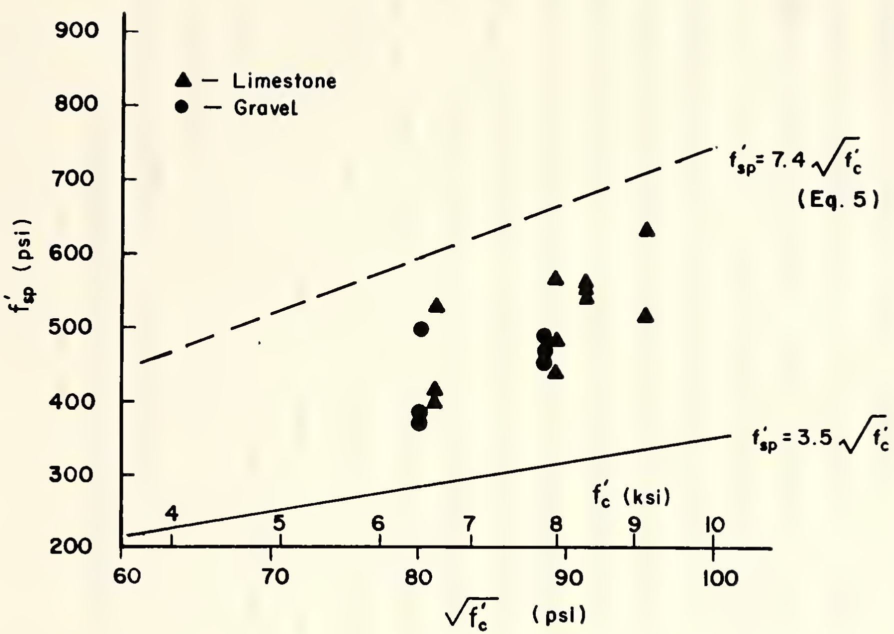

Figure 12 - Split Cylinder Strength versus Compressive Strength.

of elasticity yields a conservative estimate for the batches evaluated containing limestone as the coarse aggregate. Equation (2) seems to give a better estimate of the static modulus of elasticity for concrete mixes containing gravel. In general Equation (1) provides a better fit for the test data of all the mixes evaluated.

Crushed limestone is superior to gravel when comparing splitting tensile strength, modulus of rupture, and modulus of elasticity for concrete with equal compressive strength. Differences in the compressive strengths due to the type of aggregate are negligible.

Test results for the modulus of rupture and tensile splitting strength exceeded the predictions from current design equations. However, the data is below the proposed equations suggested by ACI Committee 363 for higher strength concretes. The Equations (4) and (5) which are proposed by ACI Committee 363 to predict the modulus of rupture and tensile splitting strength, respectively, were developed using reduced size specimens. No account for the size affects were applied to those test results. Also, the test specimens were moist cured until the time of testing. Drying effects have been observed to reduce the strength of the concrete.[2] The effects are more pronounced on the tensile strength than in the compressive strength of the concrete. All the specimens in this study were field cured. The size and drying effects could possibly explain the differences in the actual test data and the proposed equations by ACI Committee 363.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Proper quality control and the use of admixtures have facilitated the production of concrete with compressive strength exceeding 7000 psi in Indiana precast plants. The 28 day requirement of 5000 psi is easily exceeded with current mix proportioning. Precast plants have indicated that a 28 day compressive strength requirement of 6500 psi could be specified with no major changes or additional costs to the product. Special attention should be given to the mix quality control and curing method during the winter months. The improper application of accelerated curing methods and unfavorable field curing conditions during the winter months could lead to a reduction in the 28 day concrete strength.

Test data collected from an in-depth study at a local precast plant shows that compressive strengths in excess of 7000 psi are being produced in Indiana. In these mixes the use of limestone aggregate results in higher values of modulus of elasticity, modulus of rupture, and tensile splitting strength than those of mixes with gravel aggregate for equivalent compressive strengths. Limestone and gravel aggregates, show similar compressive strengths for equivalent mix proportioning.

5.2 Conclusions

The survey conducted in 5 different precast plants indicated that the 28-day compressive strength could be increased to 6500 psi. All the plants indicated that accelerated curing during the winter months does not present problems in obtaining the current 28 day compressive strength requirements. However, it was observed from data collected at a local plant, that there is a reduction in the 28 day compressive strength during the winter months. However, the 28 day strength requirement of 5000 psi was always satisfied.

Current empirically derived equations used to estimate engineering properties of concrete with compressive strength of less than 6000 psi can be used in concretes with compressive strengths reaching 9000 psi. The specific concrete properties evaluated were the modulus of elasticity, modulus of rupture, and tensile splitting strength.

In a following report, deflections and cracking loads obtained from nine full scale tests on AASHTO Type I and II girders will be used to further evaluate the observations of this study.

5.3 Recommendations

The following recommendations are based on the results of the in-depth study conducted at a local precast plant, and information collected from four other precast plants from Indiana and Kentucky which produce prestressed structural members for the State of Indiana.

1 - Allow the use of 28 day concrete compressive strengths up to 6500 psi in the design of prestressed I-Beams. During the winter months the current mixes may need to be modified to achieve this higher strength. These modifications would be needed to

compensate for the unfavorable field curing conditions, and the use of accelerated curing methods to achieve the required transfer strengths. It is also suggested to continue the evaluation of concrete compressive strengths up to 28 days. The data collected will aid in the evaluation of further modifications to the 28 day compressive strength requirement.

2 - Continue the use of the current design equations for tensile strength and modulus of elasticity of concrete for compressive strengths up to 9000 psi.

Modulus of Elasticity:

$$E_c = 33\, w_c^{1.5} \sqrt{f_c'} \quad \text{(psi)} \tag{1}$$

Modulus of Rupture:

$$f_r' = 7.5 \sqrt{f_c'} \quad \text{(psi)} \tag{3}$$

3 - The use of crushed limestone as coarse aggregate is suggested when deflections and crack control are critical.

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LIST OF REFERENCES

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APPENDICES

APPENDIX A

Stress-Strain Curves for Compression Tests

MIX CONTENTS — 6.9/LS/RET/SUPER

CURING METHOD — T/F

DATE OF CAST — 6/11/86

CURING AGE — 76 DAYS

MODULUS OF ELASTICITY — 5440 ksi

f'_c — 8240 psi

ϵ_0 — 0.0020 in/in

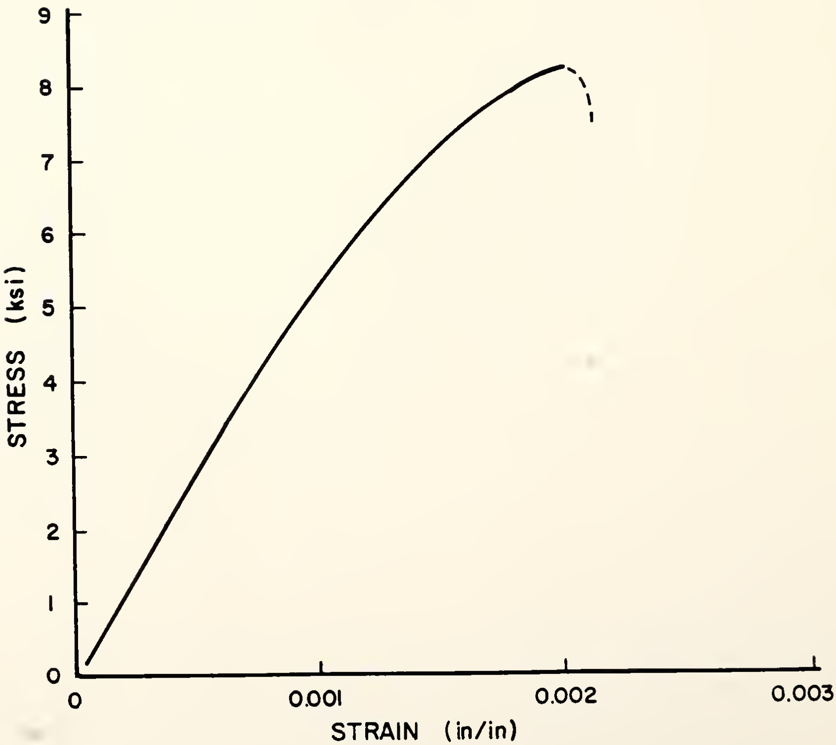

Figure A1 - Stress-Strain Curve, 76 days, Batch C4.

MIX CONTENTS — 6.9/LS/RET/SUPER

CURING METHOD — T/F

DATE OF CAST — 6/11/86

CURING AGE — 76 DAYS

MODULUS OF ELASTICITY — 5620 ksi

f'_c — 8340 psi

ϵ_o — 0.0021 in/in

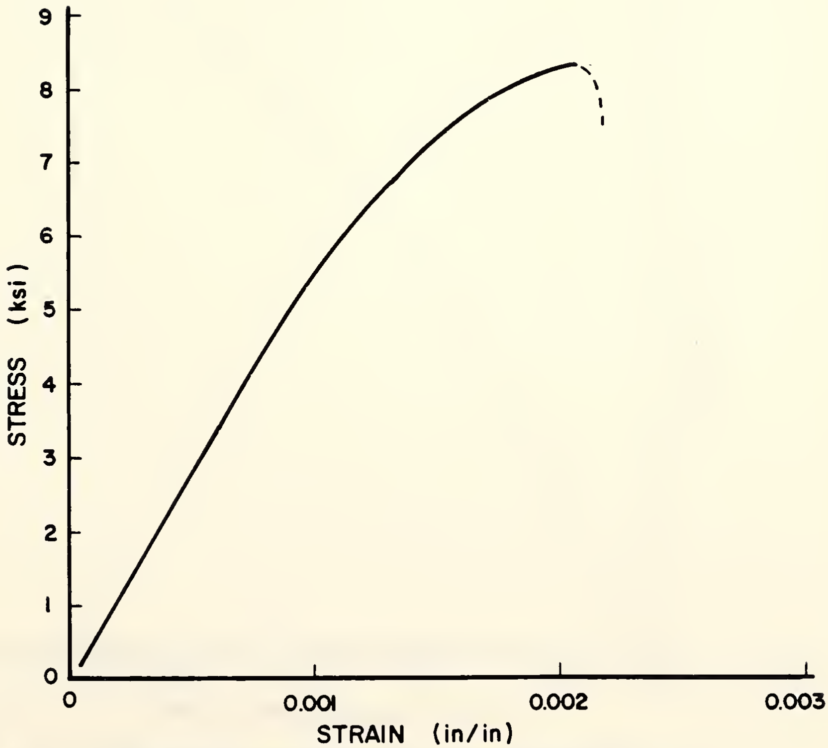

Figure A2 - Stress-Strain Curve, 76 days, Batch C4.

MIX CONTENTS — 6.9/LS/RET/SUPER

CURING METHOD — T/F

DATE OF CAST — 10/2/86

CURING AGE — 30 DAYS

MODULUS OF ELASTICITY — 5920 ksi

f'_c — 8370 psi

ϵ_0 — 0.0020 in/in

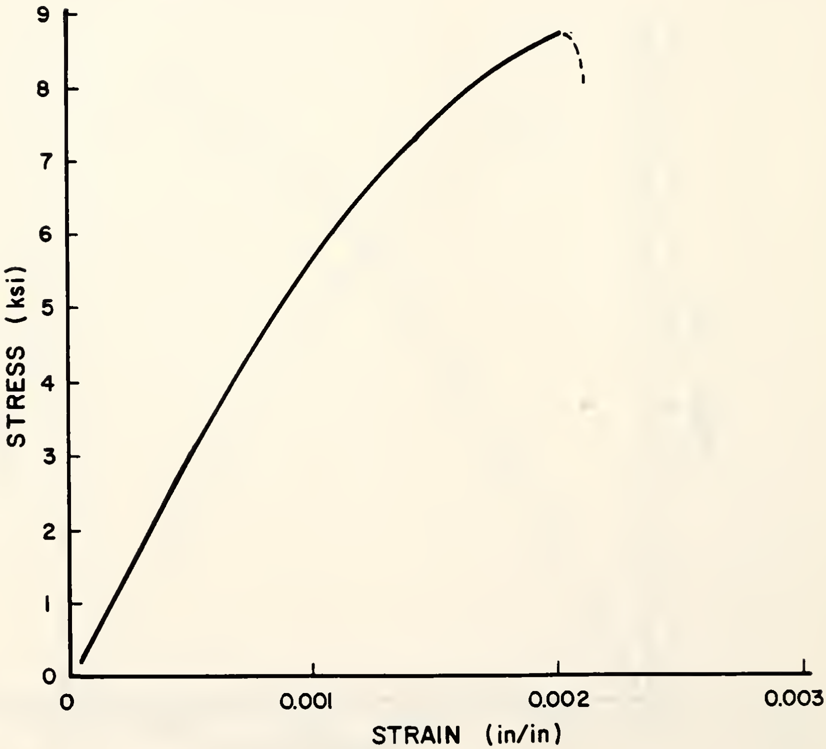

Figure A3 - Stress-Strain Curve, 30 days, Batch C5.

MIX CONTENTS – 6.9/LS/RET/SUPER

CURING METHOD–T/F

DATE OF CAST – 10/2/86

CURING AGE – 30 DAYS

MODULUS OF ELASTICITY – 5910 ksi

f'_c — 8510 psi

ϵ_0 — 0.0020 in/in

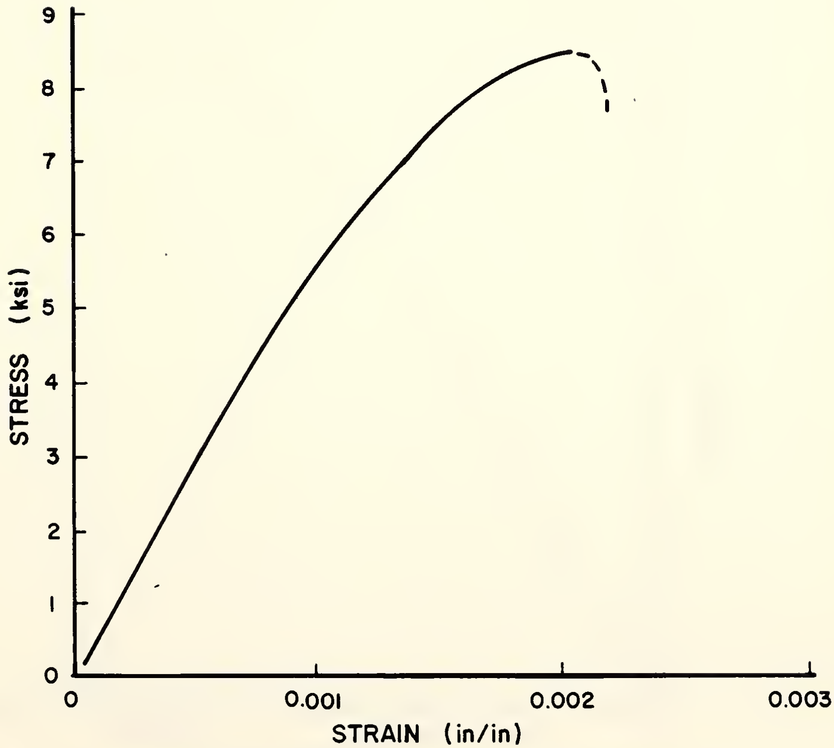

Figure A4 - Stress-Strain Curve, 30 days, Batch C5.

MIX CONTENTS – 6.9/LS/RET/SUPER

CURING METHOD – T/F

DATE OF CAST – 10/2/86

CURING AGE – 51 DAYS

MODULUS OF ELASTICITY – 6010 ksi

f'_c – 8980 psi

ϵ_0 – 0.0020 in/in

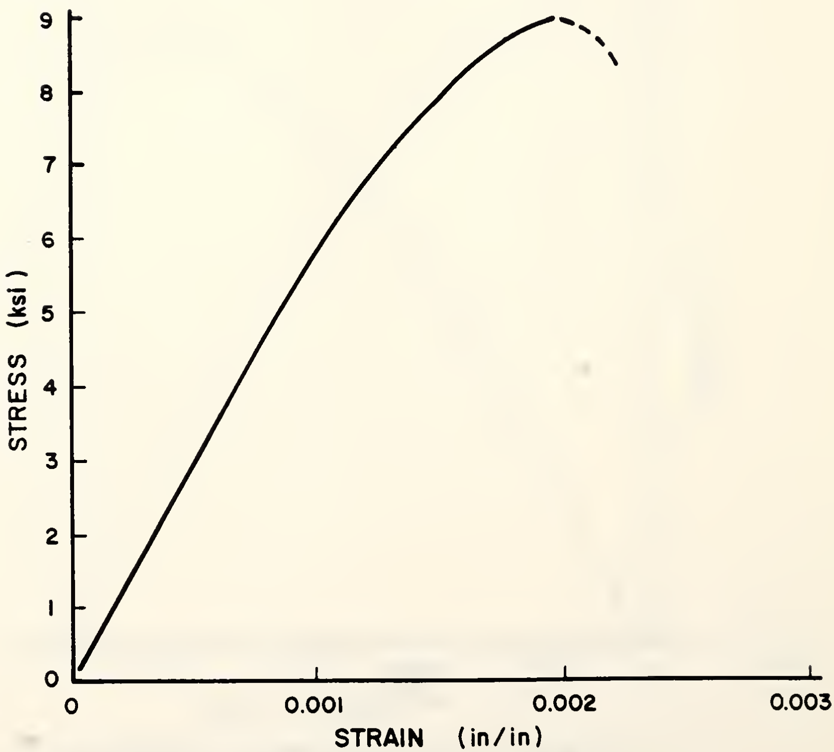

Figure A5 - Stress-Strain Curve, 51 days, Batch C5.

MIX CONTENTS – 6.9/LS/RET/SUPER
CURING METHOD – T/F
DATE OF CAST – 10/2/86

CURING AGE – 51 DAYS
MODULUS OF ELASTICITY – 6000 ksi
f'_c – 9090 psi
ϵ_o – 0.0024 in/in

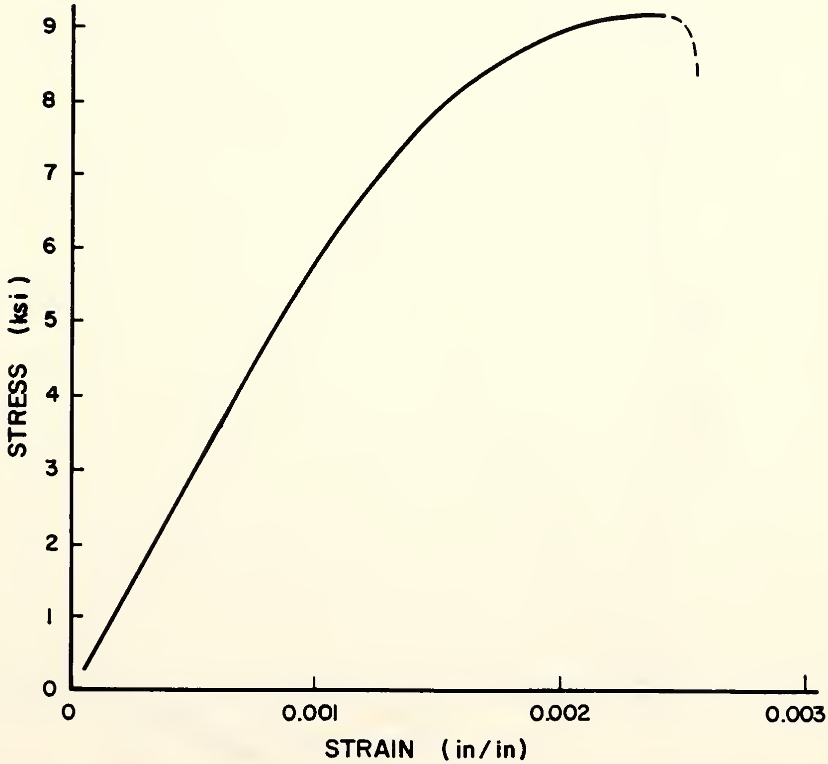

Figure A6 - Stress-Strain Curve, 51 days, Batch C5.

MIX CONTENTS — 6.9/LS/RET/SUPER
CURING METHOD — T/F
DATE OF CAST — 10/2/86

CURING AGE — 195 DAYS
MODULUS OF ELASTICITY — 5800 ksi
f'_c — 8320 psi
ϵ_0 — 0.0019 in/in

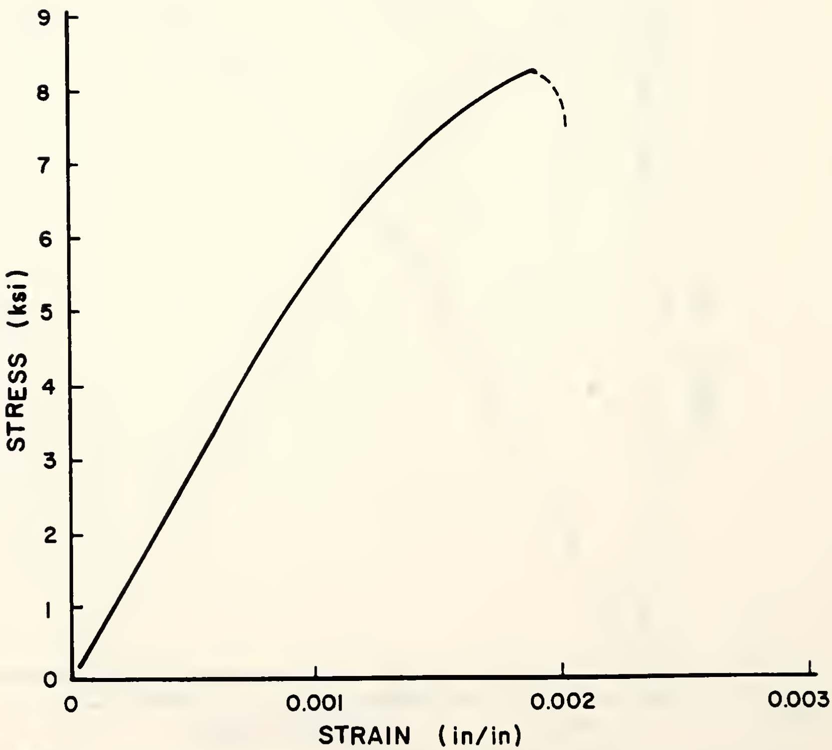

Figure A7 - Stress-Strain Curve, 195 days, Batch C5.

MIX CONTENTS — 6.5/G/RET/SUPER

CURING METHOD — T/F

DATE OF CAST — 3/26/86

CURING AGE — 28 DAYS

MODULUS OF ELASTICITY — 4820 ksi

f'_c — 8040 psi

ϵ_o — 0.0022 in/in

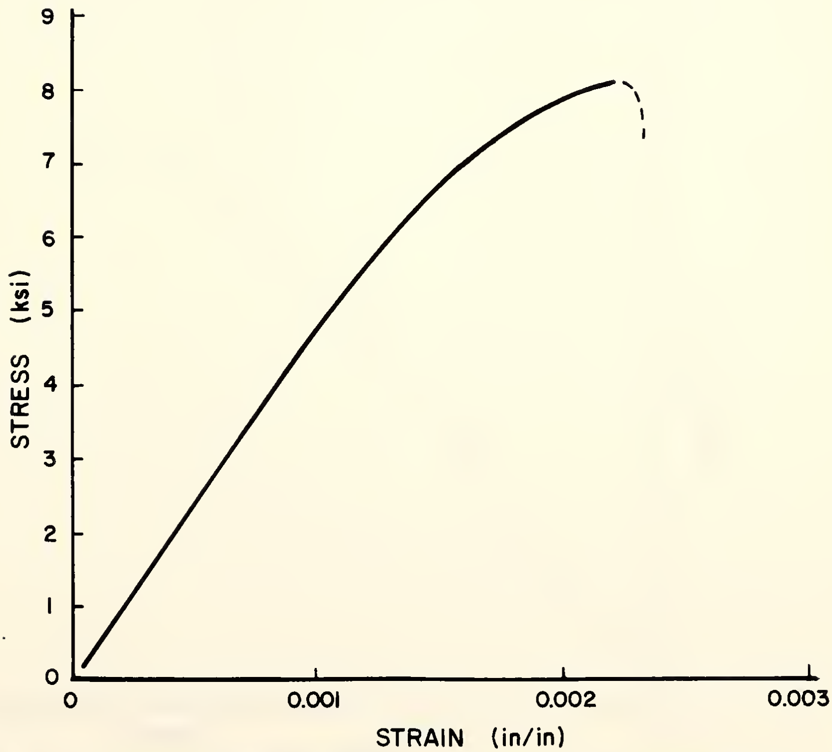

Figure A8 - Stress-Strain Curve, 28 days, 6.5/G/Ret/Super, Cast 3/26/87, Tarpaulin/Field Cured.

MIX CONTENTS — 6.5/G/RET/SUPER

CURING METHOD — T/F

DATE OF CAST — 3/26/86

CURING AGE — 28 DAYS

MODULUS OF ELASTICITY — 4510 ksi

f'_c — 7740 psi

ϵ_0 — 0.0022 in/in

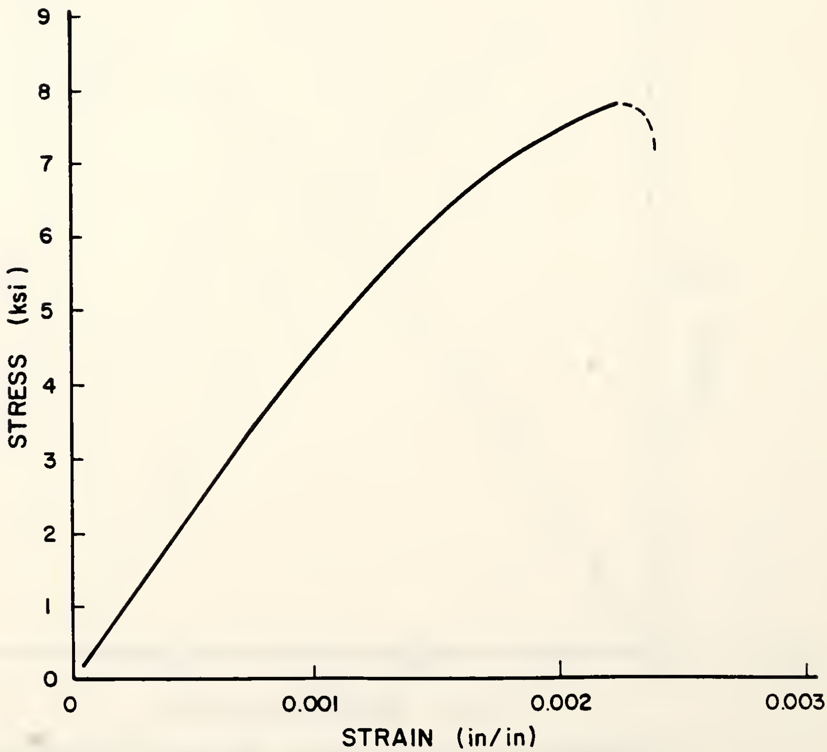

Figure A9 - Stress-Strain Curve, 28 days, 6.5/G/Ret/Super, Cast 3/26/87, Tarpaulin/Field Cured.

APPENDIX B

Material Properties for Batchs B1-B3

Table B.1 - Material Properities for Batch B1.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	June 27, 1985
Curing Method:	Tarp/Field
Slump:	3.5-4.25 in.
Air-content:	5.0-6.2 %

Cylinder Tests

Curing Time	f_c' (psi)
18 Hours	5980
	5130
	5160
	5980
	6230
26 Hours	5660
	5660
	6010
	5340
3 Days	6860
	6760
	7110
7 Days	6860
	6970
	7360
	7720
	7400
14 Days	5230
	6830
	8060
21 Days	7920
	8490
	8130
28 Days	8280
	7430
	7890
56 Days	8030
	8060
	7820

Table B.2 - Material Properties for Batch B2.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	July 19, 1985
Curing Method:	Tarp/Field
Slump:	5 in.
Air-content:	7 %

Cylinder Tests

Curing Time	f_c' (psi)
18 Hours	5730
	5990
	5870
3 Days	6440
	6190
	6650
7 Days	7320
	7320
	7360
14 Days	6860
	7040
	7500
21 Days	7710
	7430
	7670
28 Days	7640
	7600
	7780
35 Days	7680
	7530
	7000
57 Days	8210
	8170
	8670
91 Days	8740
	8840
	8560

Table B.3 - Material Properties for Batch B3.

Mix Contents:	6.5 bag/Gravel/Retarder/Superplasticizer
Cast:	November 5, 1985
Curing Method:	Steam/Field
Slump:	5.5 in.
Air-content:	5.8 %

Cylinder Tests

Curing Time	f_c' (psi)
18 Hours	4630
	4850
	5020
3 Days	5060
	5130
	5730
7 Days	5980
	5840
	5800
14 Days	5450
	5800
	5730
21 Days	5710
	5940
	5890
29 Days	6470
	5410
	6030

APPENDIX C

Material Properties for Batches C1-C6

Table C.1 - Material Properties for Batch C1.

Mix Contents:	6.5 bag/Limestone/Retarder
Cast:	May 28, 1986
Curing Method:	Tarp/Field
Slump:	3.0 in.
Air-content:	5.8 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
20 Hours	145	4030	-	-	-
	146	4000	3660	3680	0.99
	145	3890	3690	3590	1.03
3 Days	145	4880	-	-	-
	144	4850	-	-	-
	144	4780	-	-	-
7 Days	143	5590	-	-	-
	144	5380	4220	4180	1.01
	145	5900	4630	4430	1.05
16 Days	146	6080	-	-	-
	145	5940	4490	4440	1.01
	145	5940	4470	4440	1.01
21 Days	143	5940	-	-	-
	145	6080	4480	4490	1.00
	143	5870	4440	4320	1.03
31 Days	143	6470	-	-	-
	144	6650	4650	4650	1.00
	144	6690	4730	4660	1.02
42 Days	143	6400	-	-	-
	144	6400	4690	4560	1.03
	143	6650	4680	4600	1.02
56 Days	145	6930	-	-	-
	144	6900	4780	4740	1.01
	145	6790	5010	4750	1.05
101 Days	144	6910	-	-	
	144	7060	5490	4790	1.15
	144	7170	5620	4830	1.16

Table C.2 - Material Properties of Batch C2.

Mix Contents: 6.5 bag/Gravel/Retarder
Cast: May 28, 1986
Curing Method: Tarp/Field
Slump: 3.25 in.
Air-content: 5.5 %

Cylinder Tests

Curing Time	ω (pcf)	f_c' (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
21 Hours	145	4100	-	-	-
	145	4030	3540	3660	0.97
	145	4100	3430	3690	0.93
3 Days	145	5060	-	-	-
	146	4950	-	-	-
	145	4490	-	-	-
7 Days	144	5520	-	-	-
	142	5410	3710	4110	0.90
	143	5270	3790	4100	0.92
16 Days	143	5800	-	-	-
	143	5910	3890	4340	0.90
	143	5980	3720	4360	0.85
21 Days	144	6230	-	-	-
	144	6190	4150	4490	0.92
	143	5770	3980	4290	0.93
31 Days	144	6580	-	-	-
	144	6440	4250	4580	0.93
	143	6300	4060	4480	0.91
42 Days	141	6330	-	-	-
	143	6930	4270	4700	0.91
	143	6790	4330	4650	0.93
56 Days	144	6500	-	-	-
	144	6470	4190	4590	0.91
	142	7000	4140	4720	0.88
101 Days	143	7060	-	-	-
	143	7320	5100	4830	1.06
	143	7020	5320	4730	1.12

Table C.3 - Material Properties of Batch C3.

Mix Contents:	6.9 bag/Limestone/Retarder
Cast:	March 4, 1987
Curing Method:	Steam/Field
Slump:	3.5 in.
Air-content:	7.0 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
20 Hours	146	4240	-	-	-
	145	4490	4640	3860	1.20
	144	4530	4210	3840	1.10
3 Days	144	5060	-	-	-
	142	3430	4540	3760	1.21
	143	5060	4800	3910	1.23
7 Days	142	4990	-	-	-
	143	5090	4560	4030	1.13
	143	5270	4750	4100	1.16
14 Days	141	5310	-	-	-
	141	5620	4790	4140	1.16
	142	5620	5110	4190	1.22
21 Days	145	5620	-	-	-
	143	5870	5020	4320	1.16
	142	5940	4790	4300	1.11
28 Days	143	5980	-	-	-
	144	5800	4920	4340	1.13
	144	5910	4980	4380	1.14
42 Days	145	6050	-	-	-
	144	6150	5030	4470	1.13
	144	6150	5100	4470	1.14
84 Days	143	6440	-	-	-
	145	6540	5470	4660	1.17
	145	6610	5250	4680	1.12

Table C.4 - Material Properties of Batch C4.

Mix Contents: 6.9 bag/Limestone/Retarder/Superplasticizer
Cast: June 11, 1986
Curing Method: Tarp/Field
Slump: 3.5 in.
Air-content: 5.3 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
22 Hours	149	5340	-	-	-
	150	5450	4520	4480	1.01
	150	5840	4860	4630	1.05
3 Days	150	7220	-	-	-
	150	7180	5040	5140	0.98
	150	7220	4980	5151	0.97
7 Days	151	7780	-	-	-
	148	7100	4730	5010	0.94
	149	7220	4760	5100	0.93
14 Days	148	7680	-	-	-
	149	7780	5040	5300	0.95
	147	7850	4810	5210	0.92
21 Days	150	8350	-	-	-
	150	8100	4950	5460	0.91
	150	7890	5090	5490	0.93
28 Days	146	7570	-	-	-
	146	7820	5010	5150	0.97
	146	7710	4960	5110	0.97
42 Days	148	8840	-	-	-
	147	8310	4700	5360	0.88
	147	7920	5170	5230	0.99
56 Days	149	9020	-	-	-
	149	8630	5370	5580	0.96
	149	8700	5380	5600	0.96
76 Days	148	8380	-	-	-
	149	8770	6130	5620	1.09
	148	8340	5620	5430	1.03
	148	8240	5440	5390	1.01

Table C.5 - Material Properties of Batch C5.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	October 2, 1986
Curing Method:	Tarp/Field
Slump:	3 in.
Air-content:	5.8 %

Cylinder Tests

Curing Time	ω (pcf)	f_c' (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
18 Hours	151	6260	-	-	-
	151	5980	5580	4740	1.18
	150	5840	5620	4630	1.21
3 Days	150	7110	-	-	-
	150	6760	6060	4980	1.22
	151	7390	6490	5260	1.23
7 Days	150	7390	-	-	-
	151	7670	6700	5360	1.25
	151	7850	6760	5430	1.24
14 Days	151	7570	-	-	-
	150	7180	6170	5140	1.20
	150	7710	5970	5320	1.21
21 Days	150	7850	-	-	-
	150	7960	6600	5410	1.22
	150	7390	5520	5210	1.06
30 Days	149	8140	-	-	-
	150	8370	5920	5520	1.07
	149	8500	5900	5530	1.07
42 Days	150	9230	-	-	-
	151	9020	6260	5820	1.08
	151	8910	6450	5780	1.12
51 Days	149	9340	-	-	-
	149	9100	6000	5730	1.05
	150	8980	6010	5750	1.05
195 Days	149	8810	-	-	-
	150	8320	5800	5530	1.05
	149	8810	6240	5630	1.11

Table C.6 - Material Properties of Batch C6.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	April 1, 1987
Curing Method:	Tarp/Field
Slump:	3.5 in.
Air-content:	6.5 %

Cylinder Tests

Curing Time	ω (pcf)	f_c' (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
2 Days	146	5200	-	-	-
	147	5270	4740	4270	1.11
	146	5300	4600	4240	1.08
7 Days	146	6610	-	-	-
	146	6370	5040	4130	1.22
	146	6510	5380	4700	1.14
14 Days	146	6970	-	-	-
	146	7140	5480	4920	1.11
	146	6970	5010	4860	1.03
21 Days	146	7710	-	-	-
	145	7360	5090	4940	1.03
	145	7530	5320	5000	1.06
29 Days	145	7890	-	-	-
	146	7530	5200	5050	1.03
	146	7890	5400	5170	1.04
45 Days	146	7750	-	-	-
	146	8240	5510	5280	1.04
	146	7990	5080	5200	0.98
56 Days	145	7780	-	-	-
	146	8100	5450	5240	1.04
	147	8200	5800	5330	1.09

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