PREPARATION AND DURABILITY TESTING OF PRETENSIONED PRESTRESSED CONCRETE SPECIMENS

by

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INTRODUCTION

Due to the high cost of labor, it has been only within the past decade that prestressed concrete has become a competitive construction material in the United States. The material is now being used extensively in sections of the country where the effect of freezing and thawing action is an important factor with which to reckon. Although concrete under compression was generally believed to exhibit excellent resistance to weathering action, a number of leading Illinois prestressed concrete companies initiated tests in order to more fully determine its durability.

The Durability Test Program was undertaken by the Illinois Prestressed Concrete Association in collaboration with the Prestressed Concrete Institute. In addition, the Corps of Engineers is preparing to run brine tests on prestressed beams loaded in flexure. These beams are set in the tide wash along the coast of Maine, and will probably be under test for two years.

The investigation reported herein is fundamentally concerned with the durability of prestressed concrete in regard to freezing and thawing action. Some provisions were made to study the creep in the loaded concrete specimens undergoing the tests.

Work on this particular project began during the Summer of 1958 at Midwest Prestressed Concrete Company's plant at Springfield, Illinois. A group of test specimens were programmed in an attempt to determine the effect of three primary variables on the durability of 200 prestressed concrete beams 3- by 4-in. in cross section by 32 in. in length. Programming was conducted in a manner to include the following variables: Level of stress in the concrete, method of curing (moist and steam), and type of cement (Type I and Type III). The test specimens were prepared in five series of 40 beams each. The test results obtained from any one series of 40 beams should then be very suggestive of the results to be obtained by testing the entire group of 200 beams. Consequently, it would be feasible to test only two or three series and be able to obtain an indication of the durability of the specimens. Compressive strengths of molded concrete cylinders were obtained at frequent intervals during the preparation of each series.

To facilitate molding of the beam specimens, a special prestressing bed was developed. It is discussed herein because of its uniqueness and importance in the preparation of all test specimens used in the investigation.

A lengthy discussion concerning preparation of the test specimens is included in the text, since the procedure employed is believed to be unique and may therefore be of interest to the reader.

The testing procedures conformed as nearly as practicable to ASTM specifications. All beams tested were subjected to a minimum of 400 fast cycles of freezing and thawing. The dynamic modulus of elasticity, weight, and length change over a 10-in. gauge length were periodically recorded for each beam tested as an aid in determining the effects of the variables on the durability.

Time permitted the testing of only two series of specimens; therefore, results presented, analyzed, and discussed in the investigation are concerned primarily with these two series.

PROGRAMMING OF TEST SPECIMENS

Variables

In an attempt to determine how certain factors affect durability of prestressed concrete, a group of test beams and cylinders was programmed to include three major variables consisting of:

1. Level of stress in the concrete.
2. Method of curing.
3. The type of cement.

The variables were introduced so that their effects could be studied on the basis of specimens made within the shortest possible period of time. It has been found that the variability, or so-called error of testing, is much greater for mixtures made over an extended period than for mixtures produced over a short interval, and may be so great that it tends to obscure the effect of the variables which are the subject of the study.

Level of stress in the concrete. The stresses in the concrete beam specimens were programmed to vary by 500 psi increments beginning with zero psi and ending with 2000 psi. Such a range of stresses should provide an indication of what effect different levels of stress have on the durability of the specimens. It should be understood that while undergoing tests the beams were not subjected to eccentric loads which could produce flexure and thus possible cracking of the concrete. The beams were prestressed by the pretensioning method in a manner such that the compressive stress distribution within the specimen should be symmetric with respect to the horizontal and vertical axes of the beam.

Method of curing. In actual prestressed construction practice, it is not economically practical to have a prestressing bed occupied with curing concrete for any lengthy period. Of course, the concrete need not attain its full design strength, which is assumed to require 28 days, but must be strong enough to transfer the force in the steel to the concrete through bond, and also to carry any stresses caused by handling. Since the use of steam curing is one of the means used to attain a reasonably high strength concrete in a comparatively short period of time, a comparison between moist and steam curing methods generally in use was included in the tests. One-half of the specimens programmed for the tests were moist cured, whereas the remainder received a combination of steam and moist curing.

The type of cement. High-early-strength cement may be employed along with steam and/or moist curing in developing the high strength concrete required for removal of the concrete from the prestressing bed. Type I and Type III portland cements were used in an equal number of specimens to compare their effects on the durability and creep of the loaded concrete.

Constants

The factors which were held as constant as possible throughout the investigation may be itemized as follows:

1. Dimensions of specimens.
2. Comparative specimens from each series and batch of concrete.
3. Mixture design.
4. Curing period.

Dimensions of specimens. Since the pretensioning method of prestressing was utilized, the specimens had to have a sufficient transmission or transfer length to develop the required stress through bond between concrete and tensioning strand. Conversely, the beams had to be of a size to accommodate the freeze and thaw apparatus, and light enough in weight to be readily handled by hand. The limitations of the mechanical freeze and thaw apparatus necessitated that the specimens be made no larger than 3- by 4-in. in cross section by 32-in. in length. Two 3/8-in. diameter strands were positioned relative to the beam as shown in Plate I. To insure that the beam specimens attained the proper stress over a greater part of their length, cable clamps were attached to each strand at the ends of the specimens to function as bond increasers, thus reducing the transfer length.

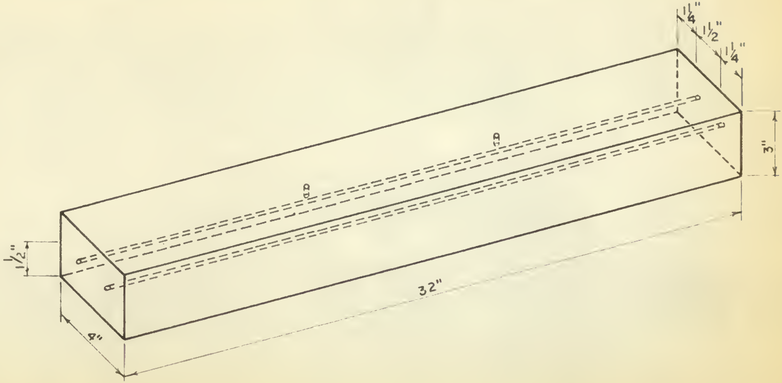
The specimens prepared for compressive strength studies were 6- by 12-in. cylinders.

Comparative specimens from each series and batch of concrete. The group of test specimens was programmed into five series, each series containing 40 beams, thus giving a total of 200 test beams. Each series possessed the same variables and was placed on days approximately at one week intervals. Theoretically, the test results obtained from any one series of 40 beams should be indicative of the results to be gained by testing the entire group of 200 beams. Accordingly, it would be

EXPLANATION OF PLATE I

Isometric view of beam specimen showing positioning of steel strand. Bond increasers attached to each strand at ends of specimen are not shown in view.

PLATE I



feasible to test only those series which time permitted, and be able to obtain an indication of the durability of the specimens.

Table 1 is a tabulation showing the programming and number of beams in one series.

Table 1. Programming of beam specimens for each series.

Stress	Type I cement		Type III cement	
psi	Moist	Steam	Moist	Steam
0	2	2	2	2
500	2	2	2	2
1000	2	2	2	2
1500	2	2	2	2
2000	2	2	2	2

It shall be noted that each series contains two beams representing each condition to be studied; after five identical pours, there would exist ten specimens for each condition to be investigated in the durability tests. For instance, upon completion of molding five series of specimens, ten beams are acquired having 1000 psi stress, Type III cement, and moist curing; also ten beams having 1000 psi concrete, Type III cement, and steam curing, etc.

Since the investigation was to extend over a prolonged period, ten zero psi concrete beams obtained for each cement and type of curing were included as standards of comparison. These particular beam specimens are strictly comparable to each set of ten beams representing any other condition.

The test beams are not of the same age; however, this should not really matter, since the tests were not started at an early age. The specimens' attainment of considerable age before the testing operation began should minimize the effect of differences in age. Actually, all specimens may be considered as being made on the same day; that is, on a day that represents the average of the five weeks of pour.

Table 2 illustrates the programming of the test cylinders used in the compressive strength investigations.

Table 2. Programming of cylinder specimens for each series showing breaking plan.

Age days	Type I cement Moist	Type I cement Steam	Type III cement Moist	Type III cement Steam
1	2	2	2	2
2	2	2	2	2
3	2	2	2	2
4	2	2	2	2
7	2	2	2	2
14	2	2	2	2
28	2	2	2	2

Eighteen cylinders were molded for each type of cement and method of curing giving 72 cylinders per series or a total of 360 for the five series poured. Cylinder breaks were made at 1, 2, 3, 4, 7, 14, and 28-day intervals for each series poured to determine the effect of type of cement and curing method on the compressive strength of the concrete.

Mixture design. The design of the mix used for all durability test specimens and other pertinent information concerning the mix may be found in the appendix.

Types I and III portland cements were obtained from the same manufacturer. Cement content was maintained at 7 bags per cubic yard. This is a figure comparable with that used in prestressed construction practice.

The coarse aggregate was a crushed limestone with 1 in. maximum size. A fineness modulus of 2.47 was recorded for the sand used as fine aggregate. Both aggregates were stockpiled and weighed to obtain the desired design proportions of 1 3/4: 3.

The only mixer readily available to mix the desired 3/4 cubic yard batch was a 4 cubic yard truck mixer. A scheme was devised whereby this mixer could be satisfactorily used throughout the test.

An attempt to maintain the entrained air content and slump of the fresh concrete at 4 per cent and 1 in., respectively, was met with limited success.

Curing period. All specimens were accorded the same curing period of 3 1/2 days. Steam was applied to the appropriate specimens for 13 hours, and then the beams and cylinders were moist cured to the completion of the curing period. The remaining specimens, of course, were subjected to moist curing throughout the curing interval.

DEVELOPMENT OF PRESTRESSING BED AND COMPONENTS

Construction of Prestressing Bed

To facilitate molding of the test specimens, a special prestressing bed was designed and constructed. The bed had to withstand the pretensioning loads, accommodate 40 beams plus 72 cylinders arranged in accordance with the programming, and provide for steam and moist curing specimens.

The bed constructed to meet these requirements is illustrated in Plate II. The reinforced concrete bed, weighing approximately eight tons, was cast upside down and later inverted to its upright position. A bulkhead divided the interior into two compartments; one side for steam and the other side for moist curing. Styrofoam, 1 1/2-in. thick, was sandwiched in the center bulkhead to provide insulation against heat transfer from the steam side to the moist compartment. Stuffing was placed in the strand portals prior to introducing the steam.

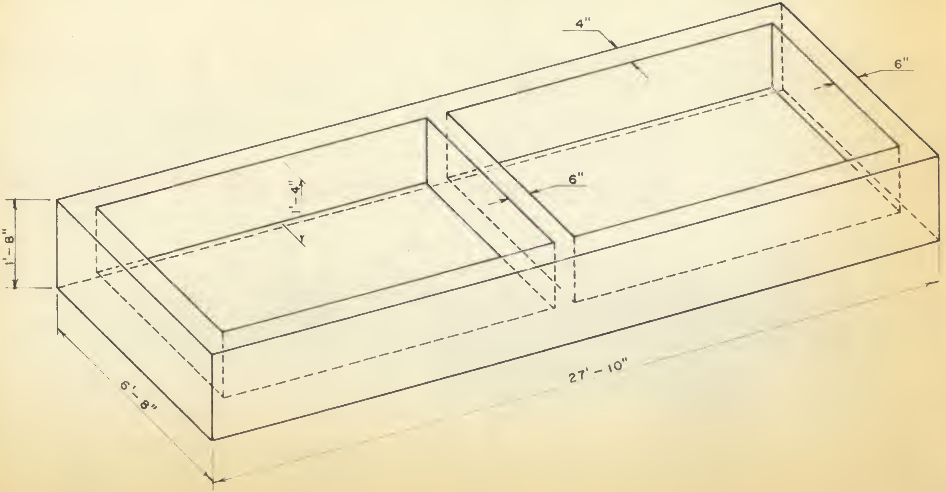
The floor of the bed and 3- by 2- by 3/16-in. angle iron with 3-in. legs spaced 4-in. back to back served as beam molds. Five lines of these molds were arranged in the longitudinal direction with room being left on the sides to store the cylinders during the curing period. The angle iron forms were fastened to the concrete bed by anchor screws with one side of the form left stationary while the other side was moveable to facilitate removal of beam specimens. The five lines of molds, one for each programmed stress level, contained eight beams each. Metal bulkheads, 1/4-in. thick, were spaced at proper intervals to provide for the 32-in. beam length. Each bulkhead was perforated to permit passage of the prestressing steel, and was held in position by a metal pin and bolt inserted behind the plate (Fig. 16, Appendix).

Steel strand was fixed at a position coincident with the horizontal axis of the beam by Strand-Vises abutting against a steel plate and a

EXPLANATION OF PLATE II

Isometric view of prestressing bed used in preparation of specimens. Details not shown.

PLATE II



strand guide system cast into an end concrete bulkhead. The other end bulkhead contained a similar plate and strand guide system; however, larger bearing plates were welded to the plate-guide system to provide a firm tensioning base for the jack.

The casting bed was located in a position subject to the warming rays of the sun. To prevent the freshly poured concrete beam specimens from setting rapidly because of being placed in warm molds, a tarpaulin canopy was erected several feet above the bed (Fig. 18, Appendix).

Method of Prestressing

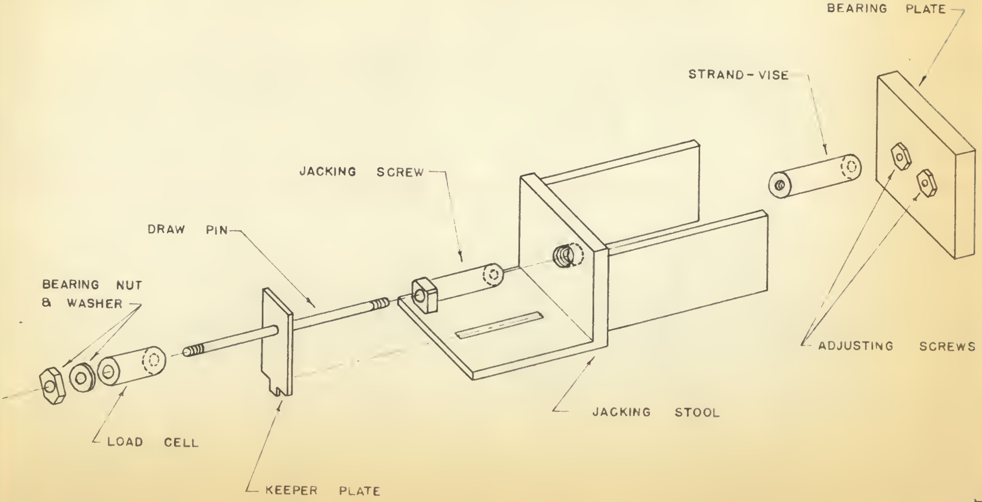
The force for tensioning the steel strand was supplied by a specially developed screw-type jack which, when incorporated with a load cell, provided an accurate method of applying the required load to the strands. Since a force of 12,000 lb. per strand was required to yield 2000 psi prestressed concrete specimens, the jack was sturdily constructed. Plate III shows an exploded view of the jack components.

Each strand at the tensioning bulkhead was grasped by the jaws of a threaded Strand-Vise. The jacking stool, containing the jacking screw, was positioned against the bearing plate and the draw pin threaded into the Strand-Vise. A load-cell, used in determining the load applied to the strand, was then placed on the opposite end of the draw pin followed by a washer and bearing nut. The keeper washer was placed between load cell and jacking screw to eliminate the torsional effect on the cell produced by the jacking screw during tensioning operations. The jacking

EXPLANATION OF PLATE III

Exploded view of pretensioning components
used in specially developed screw jack.

PLATE III


BEARING PLATE
STRAND - VISE
JACKING SCREW
DRAW PIN
BEARING NUT
& WASHER
ADJUSTING SCREWS
JACKING STOOL
LOAD CELL
KEEPER PLATE

screw was turned by a hand wrench until the proper load had been applied to the strand as evidenced by the load-cell strain readings recorded with a Baldwin SR-4 Strain Indicator (Figs. 13 and 14, Appendix). Metal shims, slotted to fit over 3/8-in. diameter strand, were placed between the Strand-Vise and adjusting screws located in the bearing plate in order to maintain the requisite elongation. Remaining slack was removed by tightening the adjusting screws. The jacking screw was then turned in the opposite direction until the strand load was transferred to the bed, whereupon the jack was removed by unscrewing the draw pin from the Strand-Vise thus leaving one strand completely tensioned. This procedure was then repeated until all strands were tensioned the desired amount.

PREPARATION OF TEST SPECIMENS

Preparation of Bed

Prior to molding the specimens, the bed floor, molds, and plate bulkheads were coated with form oil. Paper covering was temporarily placed between the two sides of the molds while 3/8-in. diameter steel strand was threaded through the strand positioner guides imbedded in the tensioning end bulkhead. Eight plate bulkheads together with the 16 cable clamps bond increasers required for one line of molds in one compartment, were threaded on the two strands used in each of the five lines contained in the prestressing bed. The strands were then pulled through the center concrete bulkhead portals, and the remaining plate bulkheads and clamps were placed on the strands before the tensioning steel was passed through the strand positioner guides and anchored to the stationary end bulkhead with Strand-Vises. The strands were positioned coincident with the horizontal axis of the beam.

Tensioning forces were applied to the strands by a screw-type jack in the manner described on page 14. Strands in the center line molds were tensioned to produce 2000 psi prestressed concrete with zero psi, 1500 psi and 1000 psi, 500 psi, lines running on opposite sides of the center line. Only tension large enough in magnitude to eliminate most of the sag in the 27 ft. length of steel was applied to the zero psi line.

Gauge plates were used to insure proper spacing of the metal forms relative to the strands after tensioning operations were completed. Plate bulkheads were positioned along the lines at 32-in. intervals with adequate space left between ends of beams to allow fastening the plate in place with a metal bolt and pin, and to allow eventual severing of the strands between beams. Preparation of the bed for molding one series of specimens was completed after bond increasers were fastened to each strand approximately 1½-in. from the beam ends. (Figs. 15 and 16, Appendix)

Molding of Specimens

Two 3/4 cu. yd. batches were required to mold each series containing 40 beams for durability testing and 72 cylinders for compressive strength studies. Type I cement was used in the first batch, and Type III in the last of the series pour.

The stockpiled aggregates were weighed to obtain the proper proportions and deposited, via wheelbarrow and ramp, into a cubic yard capacity bucket. A lift truck was utilized to deposit the contents of the bucket together with Type I cement into the 4 cu. yd. transit mixer used to mix the concrete throughout the tests. Water containing approximately 90 cu cm of Darex AEA was added uniformly to the mix, and the load mixed for 50 revolutions of the drum. The batch was slowly agitated during the molding of the specimens.

Slump tests and entrained air measurements, by the pressure method, were taken at the beginning, middle, and end of each batch pour. An attempt was made to maintain the entrained air content at 4 per cent. The addition of an amount of Darex AEA to produce this air content was not always accomplished with a high degree of accuracy as evidenced by the fact that the air content of the concrete ranged from an average reading of 3.3 to 4.8 per cent. This, however, is well within the tolerance of plus or minus 1½ per cent allowed by most specifications. The average entrained air content for the 10 batches poured was 3.8 per cent. Originally, the water content was to be maintained at 4.3 gal. per bag of cement, but this was varied somewhat to increase workability of the concrete. Slump readings ranged from a batch average of ½-in. to one high reading of 2¼-in..

The concrete was shoveled into the forms and around the strands, and then was thoroughly vibrated into all void spaces with a hand vibrator. The top surface of the beams was hand troweled to a smooth, flat surface.

Coincident with casting the 20 beams containing Type I cement, 36 cylinders were molded in a nearby room and were later transferred to the bed for curing. The 6- by 12-in. fiber cylinder molds were filled in three lifts; each lift being vibrated with a small hand vibrator. The exposed surface was hand troweled smooth and flat.

When the first batch had been poured, the mixer was cleaned, and another 3/4 cu. yd. load was prepared using high-early-strength portland cement. After the initial air and slump tests were taken the remaining 10 beam molds in each compartment of the bed were filled with concrete, vibrated, and hand troweled. Likewise, 36 cylinders containing the Type III cement were molded and then moved to the bed for curing. An average time of 40 minutes elapsed between the initial and final air and slump tests made on any one batch. An additional 60 minutes were needed to prepare the batch containing Type III cement.

The insertion of wooden blocks between the tensioning steel helped to damp out strand vibrations caused by vibration of the last 20 beams, thus preventing injury to the Type I specimens which were starting to set.

Since it was initially desired to study the shrinkage and creep in the loaded concrete, an attempt was made to place, in the beams of Series I, brass measuring plugs on a 10-in. gauge length with the intent of using a 10-in. Whittemore strain gauge to determine the changes in gauge length. Difficulty was encountered with inserting the brass plugs into the fast-setting, low slump concrete. The plugs could not be inserted deeply enough in the beam before striking large aggregate. For this, and other reasons, it was decided to install the measuring plugs prior to testing. This eliminated the opportunity for shrinkage studies between Type I and III cements, but did provide for creep investigations while the specimens were undergoing tests.

Curing and Storage

After all specimens were poured and the cylinders placed along the interior sides of the curing bed, two and three layers of moistened burlap were placed over the specimens in the steam and moist compartments, respectively (Fig. 17, Appendix). When the concrete had attained an initial set after approximately three hours, the steam was injected into the steam compartment for a period of 13 hours. The steam was transferred from the boiler to the bed by a hose and pipe system with the pipes placed between the lines of molds. A tarpaulin was draped and anchored over this compartment during the steam-curing period. In all cases, soaker hoses were placed on the burlap covering the specimens to insure keeping the burlap moist.

During the curing of Series I and Series V, an accurate 14-hour temperature record in the steam and moist compartments, and in certain beams of each compartment, was obtained by a continual recording temperature potentiometer. Under tentative plans, the temperature in the steam side would have been increased to 140° F at a rate of rise less than 40° F per hour. The actual temperature was somewhat lower than that planned. Thermocouples in the steam-cured beams revealed a temperature of approximately 100° F, while the temperature in the steam compartment was approximately 125° F in both recorded series. Moist-cured beams, in a compartment open to outside air, maintained a temperature of 75° F throughout the recorded period. The temperature in all series for the 14-hour interval should approximate those obtained in Series I and Series V, although the recording instrument was not available on the other days of pouring.

Upon termination of the steam-curing period, the cylinders were stripped of their fiber molds, and one moveable beam form in each line was loosened and parted from the beams to allow better curing. All specimens were allowed to finish the $3\frac{1}{2}$-day curing period under moist conditions.

Before the specimens were removed from the bed, they were carefully identified in accordance with the notation shown in the appendix. Each specimen was referenced by this notation throughout the tests.

At the finish of the curing period, the concrete had far surpassed the 4000 psi strength specified to safely enable the transfer of force from strand to concrete. Since a trial series of beams had been poured previously, to test the tensioning, molding, and beam removal technique, it was known that the strands could be cut with an acetylene torch without producing undesirable effects on the beams of small cross section. After removal, the strands were burned flush with the $\frac{1}{4}$-in. thick plate bulkheads, thus enabling the plate to be readily removed for re-use. Heat transferred from the steel plate to the concrete was thought to have no detrimental effect on the specimen.

Two cylinders representing each of the cement types and method of curing in each series, or a total of eight cylinders per series, were submerged in water maintained at 70° F to obtain their 28-day potential. The remainder of the specimens were prepared for shipment, and stored at room temperature and humidity.

Essentially the same preparation procedure was followed throughout the five series which were molded as rapidly as possible. Considering that it required two days to remove the specimens and prepare the bed for the next pour, plus a 3½-day curing interval, series pours were made at approximately one week intervals.

TESTING PROCEDURE

Upon completion of Series V, all beam specimens were transferred to Kansas State University, Manhattan, Kansas, to undergo rigorous durability testing.

Inasmuch as the gauge plugs inserted in Series I beams did not provide sufficient accuracy to measure the change in gauge length for creep studies during the tests, plugs fashioned 1½-in. in length from 3/8-in. diameter brass stock were installed with a neat cement in the Series II specimens.

After the preparatory work and initial test readings were recorded, Series II specimens were placed in the freeze and thaw apparatus (Plates IV and V) to undergo a minimum of 400 repetitive fast cycles. These tests were conducted as nearly as practicable in compliance with ASTM Specification C291-52T for the "Tentative Method of Tests for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water." The freeze and thaw method of testing durability was intended to

EXPLANATION OF PLATE IV

Freezing and thawing apparatus used in tests.

PLATE IV

EXPLANATION OF PLATE V

Subseries of beams shown in position
within one of the two freezing and
thawing compartments of the machine.

PLATE V

determine the effects of variation in the properties of concrete on the resistance of the concrete to the freezing and thawing cycle specified in the method.

During the freezing period of the cycle, the temperatures in the beams were reduced from 40° F ± 3° F in a 3-hour period of time. The temperature at the center of the specimens during the thawing phase of the cycle was raised from 0° F ± 3° F to 40° F ± 3° F in a time of one hour. This made possible six complete cycles every 24 hour period.

The proper cyclic period was established by use of temperature potentiometer readings taken from a thermocouple installed in the center of a beam specimen. Temperatures in the freezing compartments dropped to -3° F in 1½ hr. and were maintained at this level for another 1½ hr. which was a sufficient period to permit the specimens to attain the proper temperature. The thaw water, which was automatically pumped from the water reservoir to the freezing compartment at the end of the freeze cycle and back to the reservoir at the termination of the thaw cycle, was maintained at a temperature of between 40° F and 50° F.

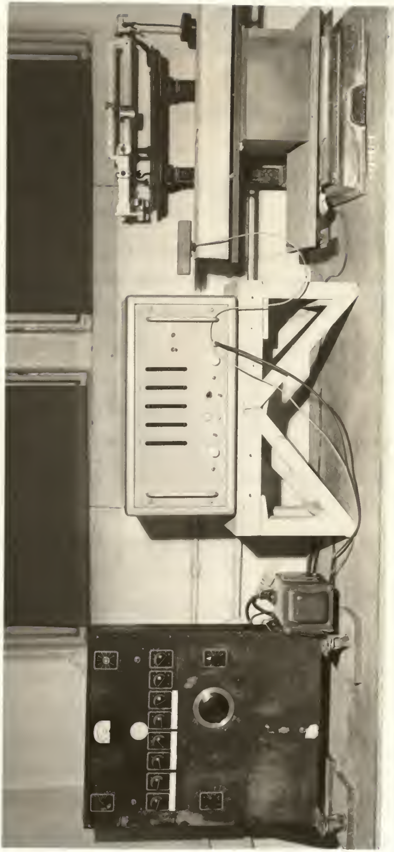
Specimens were removed from the apparatus at intervals of 50 cycles and transferred to the testing laboratory, (Plate VI). Determination of dynamic modulus of elasticity according to ASTM Specification C215-55T for "Fundamental Transverse Frequencies of Concrete Specimens," weight change, and change in gauge length measured with a 10-in. Whittemore gauge, aided analysis of the effect the freezing and thawing had on the durability of the specimens.

In order to alleviate the continual change in weight of the specimens

EXPLANATION OF PLATE VI

Apparatus used in testing for durability of specimens.
From left to right: Oscilloscope, Frequency Meter, Scales and Driver.
Beam is shown in position for testing.

PLATE VI



due to absorption of water during the thaw cycle, the beams were first read dry, and then submerged in water for approximately two weeks whereupon readings were again taken. Weight differences between dry and wet beams averaged approximately 0.5 lb. An increase in length was prevalent also. The saturated specimens were then placed in the baskets, lowered into the freeze and thaw compartments, and subjected from 2 to 10 cycles, after which the beams were removed and tested. The readings thus recorded were taken as the initial values and all succeeding readings were referenced to these. An individual durability record was kept for each beam specimen tested.

During subsequent sonic, weight, and gauge-length testing occasions, a basket containing a subseries of specimens at a temperature of 40° F was removed from the apparatus and transferred to a laboratory maintained at approximately 70° F. Since each beam was read individually, the subseries of specimens in each basket would slowly begin to warm. The specimens were, therefore, read in the same order as on the day when their initial readings were obtained. This procedure was designed to minimize any error, due to temperature differential, in gauge readings relative to preceding measurements. This error would arise if the beams were not tested in an orderly fashion as a consequence of the expansion of the specimens with increased temperature.

Series II was followed by Series III after the former specimens had been subjected to 400 cycles. Measuring plugs were installed in the beams of Series III and the tests were conducted in much the same manner as in Series II.

After Series III specimens had attained 400 cycles of exposure, a revised series composed of certain stress levels of Series II and Series III beams underwent 400 additional cycles. This gave the beams shown in Table 3 a total of 800 fast freezing and thawing cycles.

Table 3. Revised series of specimens subjected to a total of 800 cycles.

Series	Stress Level
II	0
	2000
III	0
	1000
	2000

The tests have been discontinued for the present; however, the beams are available for further investigation, if this seems desirable.

EXPERIMENTAL RESULTS

Age-Strength Relationships

Analysis of how the variables of type of cement and method of curing affected the compressive strength of the concrete is given in Figs. 1 through 12. Compressive strength of the concrete was plotted against age in days from the data available in Table 7 of the appendix. Results for Series II and Series III are presented separately, with consideration being given to the combined compressive strength tests of all five series.

Series II. Examination of Figs. 1 and 2 for the first series tested indicates the existence of a strength differential between the concretes made with Type I and III cements in favor of the latter, as would be expected from tests at early ages. Steam curing resulted in somewhat increased strength at early ages, but otherwise exhibited no great advantage over the moist-cured specimens, (Figs. 3 and 4). Both batches of concrete of Series II had an average air content of approximately 3.4 per cent, and a slump measurement of 3/4-in.

Series III.. The results for Series III shown in Figs. 5 through 8 are somewhat different from those of Series II. There seems to be no essential strength difference between concretes made with Types I and III cements. These results can be partially explained upon observation of the air contents and slump measurements recorded for Series III during the molding operations. The first batch showed an air content of four per cent, with an average slump of 1/2-in. Readings for the second batch containing Type III cement were 4.8 per cent air and 2¼-in. slump. The loss of strength due to the combination of increased air content and water-cement ratio in the second batch, accounts largely for the erroneous impression given by Figs. 5 and 6 that there is no early age strength advantages to be offered by use of Type III rather than Type I cement.

Steam curing resulted in an increased strength at early ages, as it did in Series II; although Figs. 6 and 8 indicate no advantage over the moist-cured specimens as the age increased.

Combined Series. Figures 9 through 12 show a graphical representation of the combined compressive strength data for all five series.

The resulting Figs. 9 through 10a again show the existence of an early age strength differential in favor of the concrete specimens representing Type III cement. Steam curing produced a slight strength increase during early curing stages but otherwise showed no advantage over the moist cured concrete, (Figs. 11 and 12).

Generally, 4000 psi strength concrete was obtained by the second day of curing, although the specimens which were prepared from Type I cement and moist cured, required three days to develop such a strength. In three of the five series poured, those specimens containing Type III cement which were steam cured developed sufficient strength within one day after molding to safely enable the force in the steel strand to be transferred to the concrete.

MOIST CURED

$$S = \frac{A}{a + bA}$$

$$\frac{A}{S} = a + bA$$

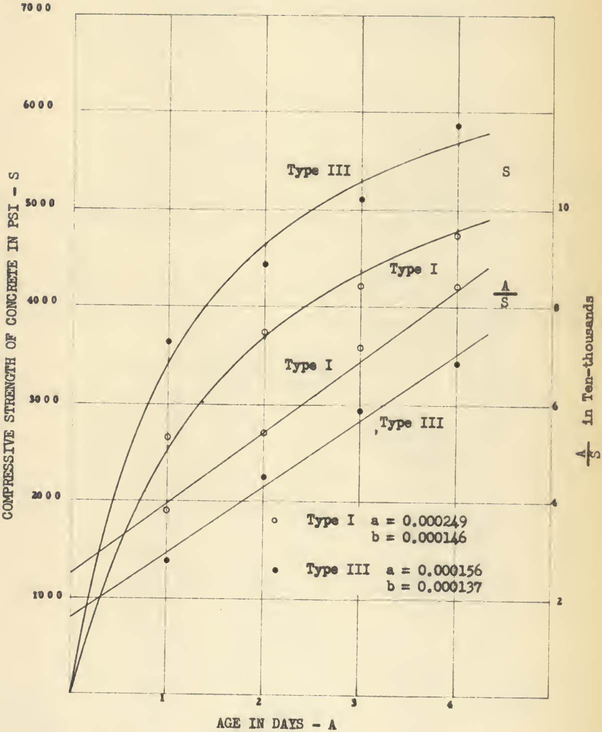


Fig. 1. Age-strength relationships for Series II specimens.

STEAM CURED

$$S = \frac{A}{a + bA}$$

$$\frac{A}{S} = a + bA$$

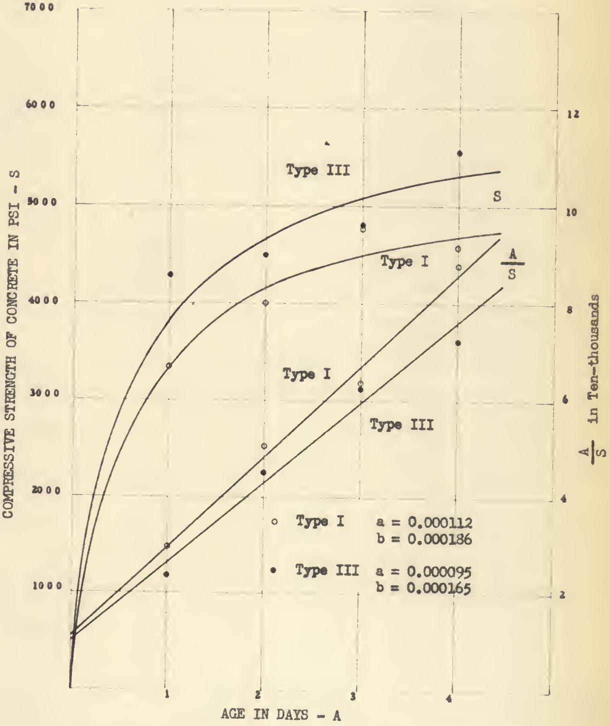


Fig. 2. Age-strength relationships for Series II specimens.

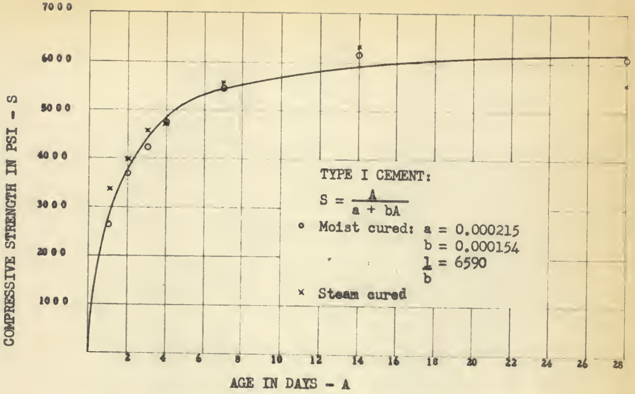


Fig. 3. Age-strength relationships for Series II specimens.

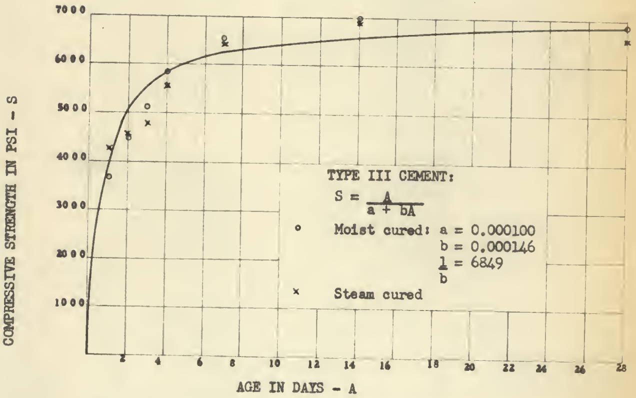


Fig. 4. Age-strength relationships for Series II specimens.

MOIST CURED

$$S = \frac{A}{a + bA}$$

$$\frac{A}{S} = a + bA$$

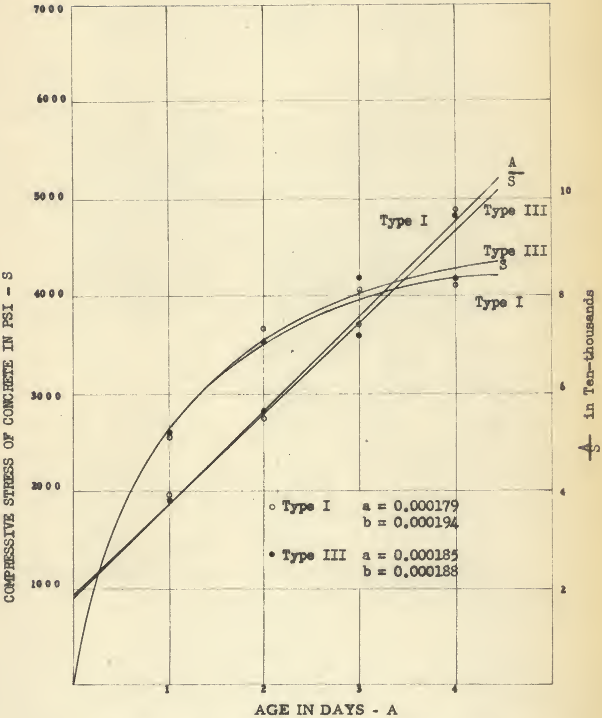


Fig. 5. Age-strength relationships for Series III specimens.

STEAM CURED

$$S = \frac{A}{a + bA}$$

$$\frac{A}{S} = a + bA$$

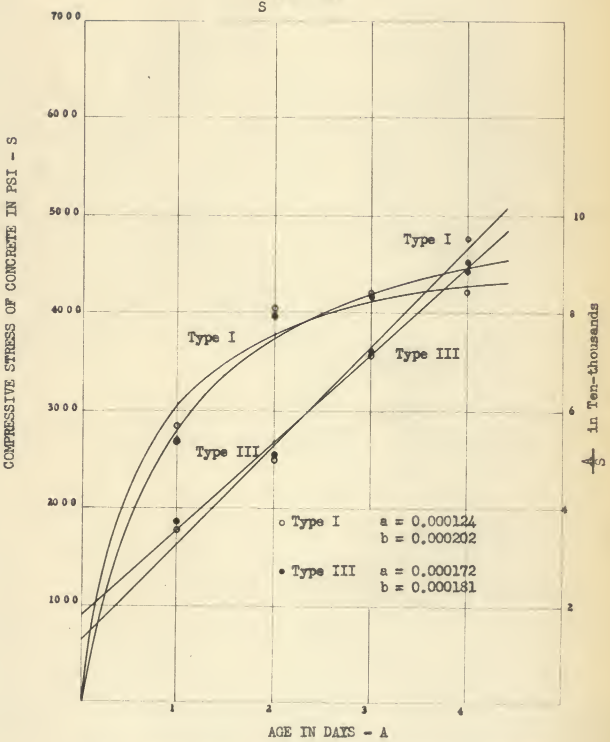


Fig. 6. Age-strength relationships for Series III specimens.

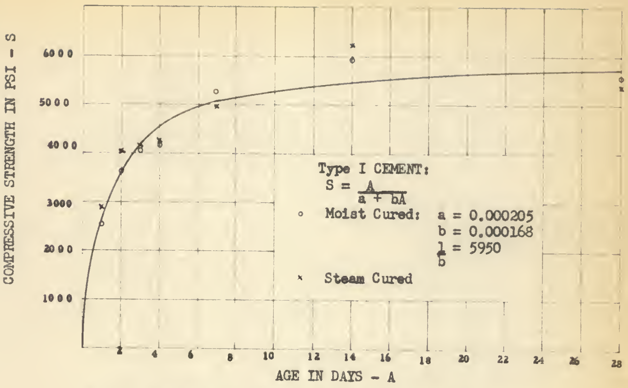


Fig. 7. Age-strength relationships for Series III specimens.

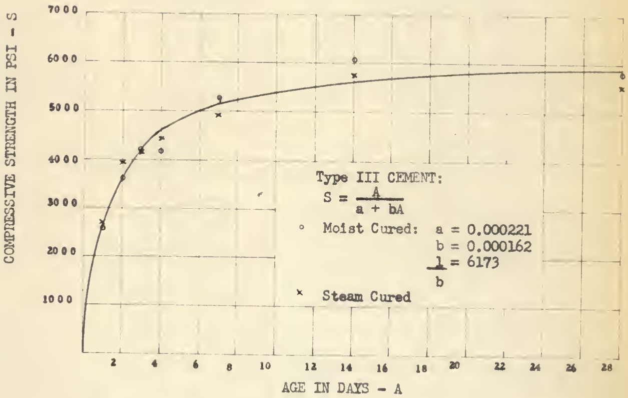
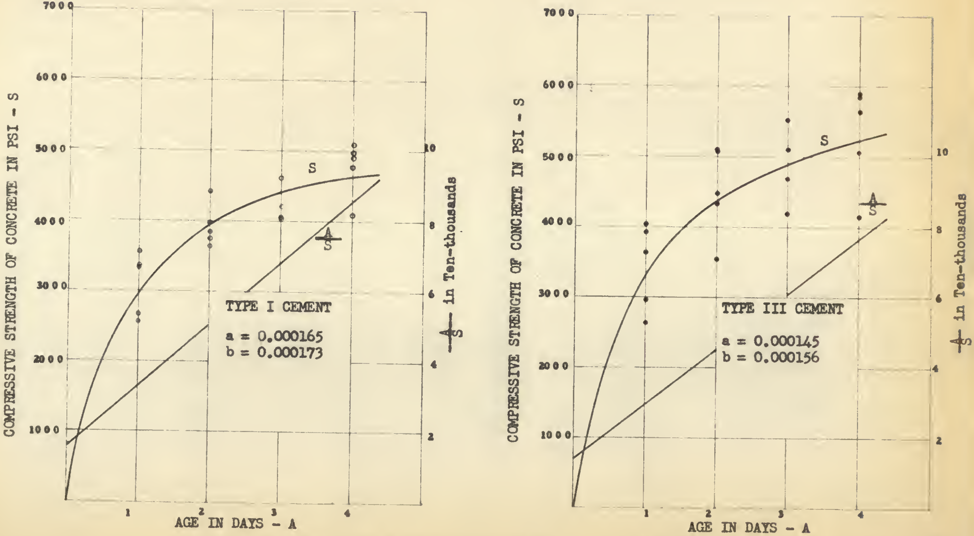


Fig. 8. Age-strength relationships for Series III specimens.

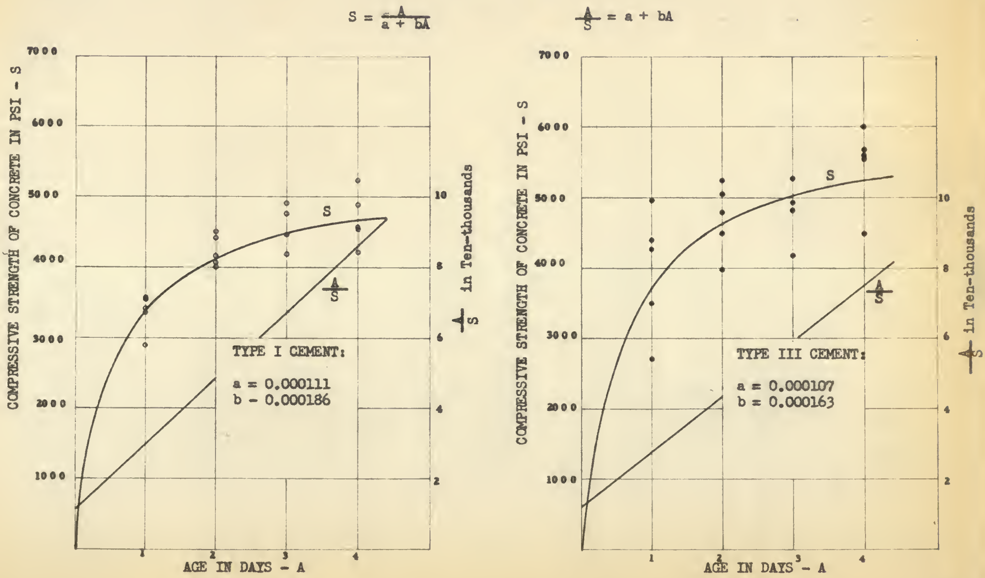
MOIST CURED

$S = \frac{A}{a + bA}$ $\frac{A}{S} = a + bA$



Figs. 9 and 9a. Age-strength relationships for all series combined.

STEAM CURED



Figs. 10 and 10a. Age-strength relationships for all series combined.

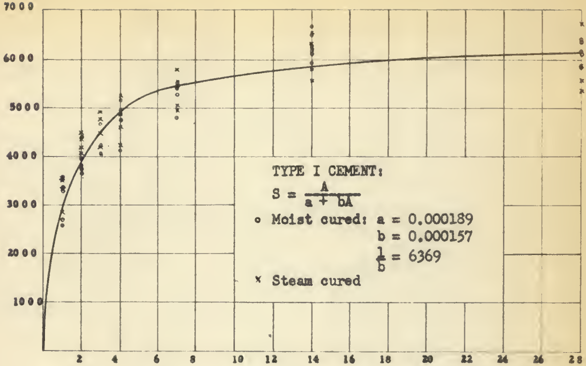


Fig. 11. Age-strength relationships for all series combined.

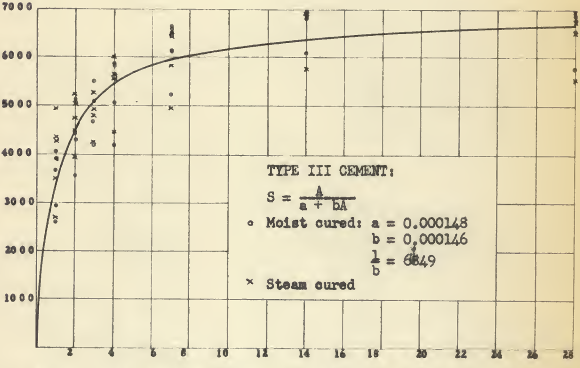


Fig. 12. Age-strength relationships for all series combined.

Durability of Prestressed Concrete in Freezing and Thawing

As mentioned previously, the specimens used in the freezing and thawing tests were prestressed concrete prisms with a 3- by 4-in. cross section, and 32-in. length. The 40 beams in each series tested were subjected to 400 repetitive fast cycles. The dynamic modulus of elasticity was determined periodically to observe the degree of reduction from the initial modulus which would give an indication of the deteriorating effect of the freezing and thawing. Time permitted only the testing of specimens from Series II and Series III. Results of these tests are recorded in Tables 8 through 10 in the appendix. Generally, readings were taken after every 50 cycles. However, since no large variation from the initial modulus or initial gauge length occurred, the observed values are reported only every 100 cycles to facilitate condensation of the tables.

The dynamic modulus of elasticity was calculated as follows: $E = CWn^2$ where E is the dynamic modulus, C is a constant for any one specimen ($C = 0.7875$), W is the weight of the specimen in pounds, and n is the fundamental transverse frequency of the beam in cycles per second.

Series II. Tables 8 through 8c pertain to the observed test readings for specimens of Series II. Examination of this data reveals that the soundness of the specimens on the basis of the dynamic modulus of elasticity determination appear very satisfactory. After 400 cycles of freezing and thawing, the durability factor of all beams was approximately

100 per cent. Needless to say, the effects of the introduced variables (level of stress in the concrete, type of cement, and method of curing) on the durability of the prestressed concrete could not be differentiated, or indeed, even noticed. There was no apparent visual deterioration of any of the beam specimens after having been subjected to 400 cycles, and only a negligible loss in weight.

Midway through the tests, difficulty was encountered with the testing apparatus used in obtaining the fundamental frequency of the beam specimens. This accounts for the numerous blanks found under the dynamic modulus heading in Tables 8a through 8c. Rather than stop the freezing and thawing tests while the trouble was being corrected, it was decided to continue with the periodic readings during which weight and gauge lengths could still be recorded.

Series III. Information concerning dynamic modulus and weight of Series III specimens is given in Tables 9 through 9c. The results generally reflect those of Series II in that the soundness of the specimens, on the basis of their dynamic modulus, appear to be very satisfactory after 400 cycles. The weights of the specimens remained essentially constant throughout the 400 cycles of exposure.

The results thus far are closely in agreement with those obtained by the State of Illinois, Bureau of Materials. The Bureau conducted tests to study the early-age-strength development of concrete made with Type III cements. For these tests, a number of 3- by 4- by 15-in. beams were made containing crushed stone coarse aggregate, and having a cement content of 5.8 bags per cubic yard of concrete. These were subjected to

400 fast freezing and thawing cycles. The concrete had an entrained air content of approximately 4.2 per cent and a slump of 2.75 in. Of the nine different brands of cement tested, only specimens made from each of four different cements experienced any apparent deterioration on basis of dynamic modulus of elasticity readings taken after periods of repetitive freezing and thawing. Of these four, specimens containing two of the cements that were tested had a final modulus which was 96 per cent of the initial, while readings of specimens made from the other two cements were 99 per cent of the initial modulus. Beams containing any one of the remaining five Type III cements encountered no reduction in dynamic modulus after 400 cycles.

Only one brand of cement was used in this investigation with the cement content being maintained at 7.0 rather than 5.8 bags per cubic yard of concrete. Slumps were generally lower; however, the amount of air-entrainment approximated that used in the tests conducted by the Illinois Bureau of Materials.

Special Series. A special series composed of beams of various stress levels from Series II and III was subjected to 400 additional cycles. Examination of dynamic modulus values in Tables 10a through 10b reveals that the soundness of all specimens is quite satisfactory. The only visual deterioration noticeable after 800 cycles was a slight surface spalling of the beams. This, however, was not excessive nor more prevalent for specimens containing Type III cement than for those representing Type I cement.

Prior to testing the special series, four 1- by 2- by 16-in. specimens were cut from two of the regular test beams of Series III. One beam contained Type I cement, and the other Type III. These smaller specimens were then subjected to the 400 additional cycles with no visible deterioration occurring.

It may be noticed that the beams of Series II, zero psi stress level, have a comparatively lower dynamic modulus for the 400 (dry) readings. Close examination of the beams revealed minute cracks perpendicular to the longitudinal axis of the specimen. The probable explanation or cause of the cracks is that the beams received a severe shock after they had undergone 100 freezing and thawing cycles. There was no apparent visual damage at the time nor did the dynamic modulus readings change abruptly. After Series II had been subjected to 400 cycles, the specimens were stored at room temperature and humidity. As the beams dried, the cracks began to open and were noticed only after the frequency readings of the dry specimens were taken. It will be noticed that the modulus returns to approximately the initial reading after the beams have been submerged in water, indicating that the cracks closed due to the expansion of the concrete. Additional freezing and thawing appears to have little effect on the modulus as recorded after the 400 (wet) reading. The cracks were not noted in the few prestressed beams which were subjected to the same shock.

Since the prestressing steel is in rather small quantities, corrosion is to be a serious consideration in the durability or permanence of prestressed concrete. Generally, the cover problem is not so critical as in reinforced concrete because even if over-loading occurs, any resulting cracks in the section will close upon removal of the load.

Upon stripping the steel from a number of beams that had undergone 800 freezing and thawing cycles, it was found that not even the slightest hint of corrosion existed.

Examination of prestressed structures in France and England also indicate that prestressed concrete can be used with every confidence, (1). In France, prestressed transmission line poles designed by Freyssinet more than 30 years ago were found completely free of corrosion troubles. Prestressed beams made in England during 1940 were also examined but indications are that with the use of good quality materials, corrosion problems are not likely to occur.

Creep Investigations

Series II. Referring again to Tables 8a through 8c, it is noticed that throughout the tests of Series II there is but little variation from the initial gauge length of the specimens. Closer examination of the data compiled in Table 4 indicates that a number of trends may exist, however.

There appears to be a general increase in length of the specimens representing Type I cement, and also those specimens representing Type III that were subjected to little or no prestressing. However, the specimens containing high-early-strength cement that were subjected to a prestressing load of 1000 psi or greater, showed a decrease in length

Table 4. Index of change in length of Series II specimens ($x\ 10^{-4}$ in.) (average of length changes observed at 50, 100, 150, 200, 250, 300, 350, and 400 cycles.)

	Moist cured		Steam cured	
Stress	Type I	Type III	Type I	Type III
0	+3.00	+4.29	+4.29	+3.29
500	+5.29	+1.14	+4.15	+2.72
1000	+0.14	-2.00	+1.71	-3.29
1500	+0.57	-1.29	-0.43	-2.29
2000	+0.86	-1.00	+2.14	-0.28

during the tests. Since the prestressing force tends to cause creep while freezing and thawing tends to cause expansion of concrete, one authority interpreted the observed decreases in length as an indication of greater creep in the concrete made with Type III cement than in the concrete made with Type I cement. While agreeing that this conclusion may have some merit, another authority pointed out that on the information available, it could be just as easily concluded that the Type III cement concrete was of a superior quality that showed very little expansion in the freezing and thawing tests, and consequently an apparently greater contraction because of creep.

Series III. The results of the creep investigations representing Series III are given in Tables 9a through 9c. No very definite trend is observable in the changes of length of the specimens during the freezing and thawing tests (Table 5).

Table 5. Index of change in length of Series III specimens ($x\ 10^{-4}$ in.) (average length changes observed at 50, 100, 150, 200, 250, 300, 350, and 400 cycles.)

Stress	Moist cured		Steam cured	
	Type I	Type III	Type I	Type III
0	+4.29	+1.67	+0.25	+1.12
500	+3.86	+0.33	+1.17	+3.62
1000	+7.00	+11.78	-0.71	+8.60
1500	-0.14	+0.20	+1.38	-3.38
2000	+1.00	+3.88	+4.17	-0.62

Deterioration of the neat cement used in fastening the gauge plugs in the specimens of Series III resulted in the loosening of a number of the plugs after approximately 150 cycles of freezing and thawing. Whenever a loose plug was discovered during measurement of the gauge length, the specimen was removed from the tests for 50 cycles at which time the plugs were reinserted. The beam was then introduced back into the tests at the time of the next periodical reading. An account was kept of the cycles each beam missed, which was generally only 50, and the tests were continued until all beams had been subjected to 400 cycles.

Since many of the gauge length readings had a tendency to be rather erratic, and evidently did not represent the true action of the concrete, they were omitted from the tabulations of changes of gauge length given in Tables 9a through 9c. For this reason, plus the increased chances for experimental error, the creep data obtained for Series III should not be regarded as having much significance in determining the effect of the two types of cement on creep action of the concrete.

It was believed that cement used in inserting the measuring plugs in Series III was partially hydrated or otherwise defective. The troubles previously described were not experienced with the specimens of Series II nor with those of Series III after the plugs had been reset.

Special Series. Table 6 is obtained from Tables 10a through 10b, which contain the experimental results for the special series comprised of beams of both Series II and III.

Table 6. Index of change in length of special series specimens ($x 10^{-4}$ in.) (average of length changes observed at 450, 500, 550, 600, 700, and 800 cycles.)

Stress	Series	Moist cured		Steam cured	
		Type I	Type III	Type I	Type III
0	II	-	+3.00	+3.00	+3.50
0	III	+2.00	+5.40	+3.34	+0.00
1000	III	+2.00	+0.17	-0.17	-1.80
2000	II	+1.50	+1.33	+1.17	+2.00
2000	III	+1.17	+2.33	+1.50	+0.17

Even after being subjected to 800 cycles there appears to be but small changes in any of the specimens 10-in. gauge length. In fact, it is quite conceivable that experimental errors made in reading the gauge length could account for most of the variances, considering that even 5.4×10^{-4} in. is not much length change over a 10-in. gauge length.

CONCLUSIONS

The foregoing presentation and discussion of test results gives an indication of the advantages to be gained by the use of high-early-strength cement and steam curing. Sufficient strength will usually be generated in one day to allow the concrete to be removed from the prestressing bed. The concrete specimens using Type I cement required two, and sometimes three days to develop a 4000 psi compressive strength. Specimens representing Type III cement generally tended to give higher compressive strengths than those specimens containing Type I cement, even after 28 days had elapsed.

The soundness of all beam specimens after being subjected to 400 and as many as 800 fast freezing and thawing cycles was very satisfactory. The effects of the introduced variables (level of stress in the concrete, type of cement, and method of curing) on the durability of the concrete could not be differentiated or, indeed, even noticed. In no instance was the final dynamic modulus less than 97 per cent of the initial modulus. Slight scaling of a number of the beams after 800 cycles was the only visible deterioration noticed due to alternate freezing and thawing of the specimens. The weight loss due to this scaling was nominal.

Creep investigations conducted on the prestressed concrete beams undergoing the freezing and thawing tests did not result in any significant or consistent information regarding the effect of Type I as compared with Type III cement on the creep of the loaded concrete.

In Series II, a slight tendency for the beams representing Type III cement that were subjected to 1000 psi stress or greater to contract during exposure to freezing and thawing, while the remaining specimens tended to expand, brought forth the speculations that perhaps, since freezing and thawing causes expansion and compressive forces tend to cause creep in the concrete, there was greater creep in the concrete made with Type III cement than in concrete made with Type I cement. However, results from neither Series III or the special series that was subjected to 800 cycles showed indications of verifying this trend.

Actually, the observed changes in gauge length with respect to the initial gauge readings were quite small for all beams tested. Much of the variation can possibly be attributed to errors in testing which will certainly be present in investigations of this nature.

The strength, mixture design, and handling of the high quality concrete used in this investigation was very similar to that used in most actual prestressed concrete construction practice. It could be concluded, on the basis of these tests, that such concrete, particularly when under compression, is a highly durable construction material from the standpoint of weathering action. The proper use of Type III cement, as a means in obtaining high strength concrete at an early age, will not be detrimental to the durability of the concrete.

ACKNOWLEDGMENTS

For their guidance and cooperation, the writer wishes to express his appreciation to Mr. J. O. Whitlock, President of the Midwest Prestressed Concrete Company of Springfield, Illinois, for his helpful reviewing of the material presented in this thesis and also to Professor C. H. Scholer and Professor M. E. Raville, both of the Department of Applied Mechanics, Kansas State University, for their helpful comments and review of the thesis. The author takes this opportunity to thank also the State of Illinois, Division of Highways, Bureau of Materials, Springfield, Illinois, particularly Mr. O. Larson who analyzed much of the test results, and Mr. F. Blandin who was of great assistance throughout the tests. Thanks also to Mr. J. Butler, employee of Midwest Prestressed Concrete Company, who greatly aided in the preparation of the specimens, and to all who, in some manner, participated in the investigation.

LITERATURE CITED

1. *Permanence of Prestressed Concrete*, Prestressing News, Prestressed Concrete Development Group of Groovenor Gardens, London, England, 1958.
2. *Tests of High-Early Strength Cements Available for Highway Construction in Illinois*, State of Illinois, Department of Public Works and Buildings, Division of Highways, Bureau of Materials, 1951. 17 p, Table 8(b).

APPENDIX

Fig. 13. Screw-type jack used to pretension steel strand.

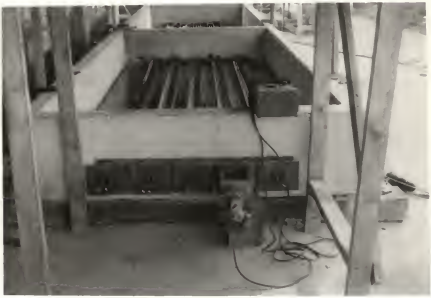


Fig. 14. View of tensioning bulkhead along with jack and Baldwin SR-4 strain indicator.

Fig. 15. View of bed just prior to molding test specimens. Bed has a capacity of 40 beams and 72 cylinders.

Fig. 16. Detail of beam mold ends. Note bond increasers and method of securing plate bulkheads.

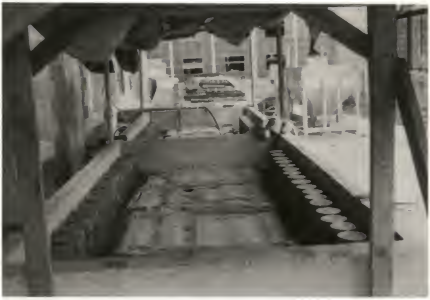


Fig. 17. View of bed after completion of molding one series of specimens. Moist burlap covered the beams and cylinders during the curing period.

Fig. 18. The cured specimens were carefully identified before removal from the bed. Tarpaulin canopy kept bed and molds from becoming excessively warm during molding operations and early curing stages.

CONCRETE DESIGN USED IN TEST SPECIMENS

Crushed stone - Size B - Specific Gravity 2.69 Voids.

Sand - Specific Gravity, 2.63

Portland cement - Types I and III

7 bags per cu yd
3.86 cu ft per bag
4.0 per cent air
4.3 gal water per bag
0.79 mortar factor

		Quantities per bag	Per 3/4 cu yd
Cement	(lb)	94	494
Sand	(lb)	167	877
Stone	(lb)	275	1442
Water	(gal)	4.3	22.6

Abs. vol. cement	0.48 cu ft
Abs. vol. sand	1.02 " "
Abs. vol. stone	1.64 " "
Vol. water	0.57 cu. ft
Vol. air	0.15 " "
Yield	3.86 cu ft

Note: Water given is for aggregate in saturated, surface dry condition. Sand, stone, and water to be corrected for actual field conditions.

Strand: Three-eighths inch diameter steel strand (7 wires) manufactured by the American Steel & Wire Co. of Waukegan, Illinois.

Spool No. C-302
Average breaking load of 5 samples composed of 2 strands each taken from the above spool - 21,123 lb.

Aggregates: Crushed stone - Size B

Producer - Lehigh Stone Co., Joliet, Illinois.
Laboratory No. 58-6251
Sampled from stockpile

Test Results

Specific gravity - dry ———— 2.62
" " - surface dry ———— 2.69
Absorption (per cent) ———— 2.9
Abrasion loss (per cent) ———— 33.3
Weight per cu ft (lb) ———— 98.2
Voids (per cent) ———— 41.5

Soundness - Na_2SO_4, 5 cycles

wt'd. av. per cent loss - 12.98

Sieve Analysis

Sieve Size	Total Passing, %
1"	100
3/4"	95
1/2"	75
3/8"	56
No. 4	10
8	4.1

Sand

Producers - Buckhart Sand & Gravel Co., Buckhart, Ill.
Laboratory No. 58-7595
Sampled from stockpile

Test Results

Specific gravity - dry ———— 2.63
" " - surface dry ———— 2.64

Soundness - Na_2SO_4, 5 cycles

wt'd. av. per cent loss - 4.23

Sieve Analysis

Sieve Size	Total Passing, %
No. 4	100
8	97
16	72
30	48
50	27
100	9
200	1

Cement: Standard Portland Cement (Type I) and High-early-strength Portland Cement (Type III)
Manufactured by Medusa Portland Cement Co. of Dixon, Ill.
Laboratory No. 58-6250

Test Results

		Type I	Type III
Autoclave expansion (%)		0.22	0.13
Time of set	Initial	3 hr 15 min	3 hr 15 min
	Final	5 hr 0 min	5 hr 0 min
Water for normal consistency (%)		24.0	27.0
Compressive strength (psi) (Standard mortar)			
	24 hours		2442
	3 days	2558	3917
	7 days	3167	
Insoluble residue (%)		0.16	0.30
Ignition loss (%)		1.30	1.83
Sulphuric anhydride (SO_3) (%)		2.37	2.42
Magnesia, Mg O (%)		3.18	3.08

Note: All tests were made by the State of Illinois, Division of Highways, Bureau of Materials, Springfield, Illinois.

			Quantities per bag of cement				Air
	Series	Type Cement	Sand lb	Stone lb	Water gal	Slump in.	Content %
Data on Concrete Mixtures	I	I	167	275	4.38	0.50	4.1
		III	167	275	4.75	0.75	3.7
	II	I	167	275	4.38	0.75	3.4
		III	167	275	4.57	1.00	3.3
	III	I	167	275	4.75	0.50	4.0
		III	167	275	4.80 ?	2.25	4.8
	IV	I	167	275	4.57	0.50	3.4
		III	167	275	4.40	0.50	4.4
	V	I	167	275	4.57	0.75	3.5
		III	167	275	4.68	1.00	3.6
						0.85	3.8

Table 7. Compressive strength of concrete determined from 6" by 12" cylinders (psi).

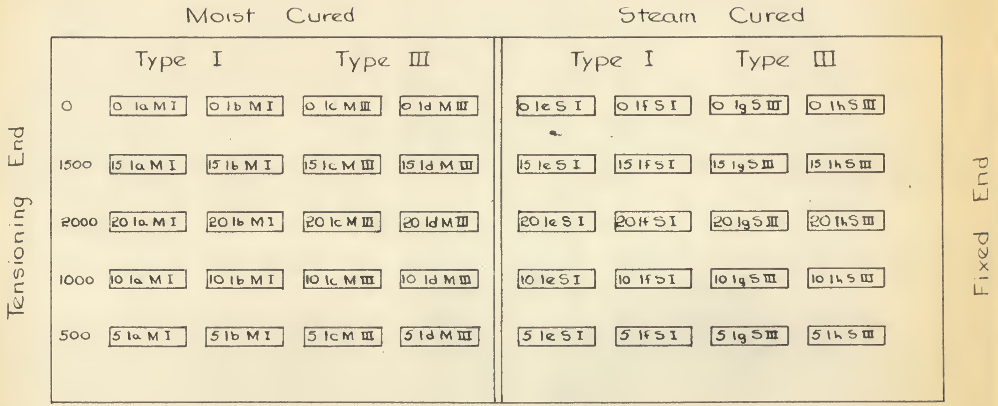
Age		Moist		Steam	
(days)	Series	Type I	Type III	Type I	Type III
1	I	3310	2920	3520	3500
	II	2650	3645	3345	4265
	III	2550	2600	2850	2690
	IV	3330	3910	3380	4370
	V	3555	4020	3540	4955
	Av.	3079	3419	3327	3964
2	I	3965	4300	4370	4775
	II	3715	4440	4000	4490
	III	3645	3560	4035	3965
	IV	3805	5115	4160	5010
	V	4390	5080	4480	5220
	Av.	3904	4499	4209	4692
3	I	4640	4690	4905	4920
	II	4210	5100	4745	4795
	III	4055	4190	4195	4180
	IV	4050	5505	4460	5225
	V	-	-	-	-
	Av.	4238	4871	4576	4780
4	I	4885	5060	5205	5650
	II	4760	5840	4570	5540
	III	4105	4160	4210	4425
	IV	4960	5645	4530	5560
	V	5150	5805	4865	6000
	Av.	4766	5302	4676	5435

Table 7. (concl.)

Age (days)	Series	Moist		Steam	
		Type I	Type III	Type I	Type III
7	I	5490	6160	5785	6460
	II	5450	6600	5525	6460
	III	5260	5235	4970	4905
	IV	4795	6145	5030	5860
	V	5415	6655	5490	6480
	Av.	5282	6159	5360	6033
14	I	6480	6885	6530	7135
	II	6160	7120	6300	6955
	III	5930	6070	6215	5730
	IV	6110	6815	5560	7080
	V	6670	6960	5735	7240
	Av.	6270	6770	6068	6828
28	I	6390	6850	6710	6920
	II	6110	6530	5560	6535
	III	5595	5790	5310	5525
	IV	6160	6765	5855	7425
	V	5855	6850	5840	6750
	Av.	6022	6557	5855	6631

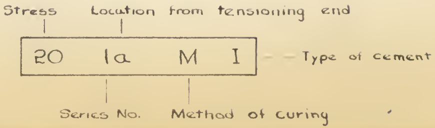
Note: All values of compressive strengths for each series are the average of two cylinder breaks.

PLAN OF BED SHOWING ARRANGEMENT OF SPECIMENS



	Moist Cured				Steam Cured			
	Type I		Type III		Type I		Type III	
0	0 1a M I	0 1b M I	0 1c M III	0 1d M III	0 1e S I	0 1f S I	0 1g S III	0 1h S III
1500	15 1a M I	15 1b M I	15 1c M III	15 1d M III	15 1e S I	15 1f S I	15 1g S III	15 1h S III
2000	20 1a M I	20 1b M I	20 1c M III	20 1d M III	20 1e S I	20 1f S I	20 1g S III	20 1h S III
1000	10 1a M I	10 1b M I	10 1c M III	10 1d M III	10 1e S I	10 1f S I	10 1g S III	10 1h S III
500	5 1a M I	5 1b M I	5 1c M III	5 1d M III	5 1e S I	5 1f S I	5 1g S III	5 1h S III

Notation



Information Concerning the Forthcoming Tables

Series II

Date of molding - July 31, 1958.
Date that series was first subjected to freezing and thawing test - October 28, 1958.
Date that series was removed from test - December 30, 1958.

Series III

Date of molding - August 6, 1958.
Date that series was first subjected to freezing and thawing test - December 31, 1958.
Date that series was removed from test - March 12, 1959

Special Series

This series was composed of beams from Series II and Series III.
Date of molding - given above.
Date that series was first subjected to freezing and thawing test - March 31, 1959.
Date that series was removed from test - June 10, 1959.

Table 8a. Dynamic modulus of elasticity, weight, and change in gauge length of 3" by 4" by 32" prestressed concrete beams after various periods of repetitive freezing and thawing (fast cycle) - Series II.

The first line in each tabulation under dynamic modulus shows initial modulus in millions of psi. All other values are in per cent of the initial modulus.

A (+) sign and (-) sign denote an increase and decrease, respectively, from the initial gauge length.

Zero psi Stress

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
			TYPE I				
2	5.9 x 10^6	34.72	0.0	2	5.8 x 10^6	34.76	0.0
2	100	34.72	0.0	2	5.8	34.76	0.0
50	100	34.68	-3	50	100	34.72	-2
100	98	34.64	+2	100	100	34.70	+4
150	100	34.64	+2	150	100	36.68	+2
200		34.59	+7	200	100	34.66	+4
250	100	34.55	+7	250		34.56	+6
300				300		34.57	+10
350				400	102	34.58	+6
400							
			TYPE III				
2	6.1 x 10^6	35.25	0.0	2	6.2 x 10^6	35.65	0.0
2	100	35.27	0.0	2	100	35.65	0.0
50	100	35.24	-2	50	100	35.60	-2
100	98	35.20	+4	100	97	35.57	+2
150	100	35.20	+4	150	97	35.57	+2
200		35.17	4	200		35.55	+4
250		35.12	5	250		35.48	+6
300		35.10	9	300		35.48	+9
350				350			
400		35.15	6	400	97	35.51	+2

Table 8b. (contd.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length, (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
			TYPE I (500 psi stress)				
2	6.1×10^6	35.40	0.0	2	6.1×10^6	35.60	0.0
100	100	35.31	+6	100	100	35.55	+5
200		35.30	+4	200		35.56	+5
300		35.29	+1	300		35.56	+6
400	102	35.29	+17	400	103	35.54	+6
			TYPE III				
2	6.0×10^6	35.55	0.0	2	6.1×10^6	35.68	0.0
100	97	35.46	+2	100	100	35.61	+4
200		35.46	+1	200		35.61	+3
300		35.46	+2	300		35.60	+4
400	102	35.45	+4	400		35.57	+6
			TYPE I (1000 psi stress)				
2	6.0×10^6	35.83	0.0	2	6.2×10^6	35.68	0.0
100	98	35.78	+1	100	98	35.60	+4
200		35.78	+1	200		35.61	+2
300		35.78	+2	300		35.61	+2
400	105	35.78	-3	400	105	35.59	+4
			TYPE III				
2	6.2×10^6	35.69	0.0	2	6.1×10^6	35.60	0.0
100	100	35.66	+1	100	98	35.51	-1
200		35.62	-1	200		35.52	-4
300		35.62	-2	300		35.48	-2
400	103	35.62	-3	400	102	35.42	-4

Table 8c. (concl.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
TYPE I (1500 psi stress)							
2	6.1×10^6	35.49	0.0	2	6.1×10^6	35.42	0.0
100	98	35.40	+1	100	98	35.35	-1
200		35.40	+2	200		35.34	-1
300		35.39	+3	300		35.26	+4
400	103	35.41	0.0	400	103	35.26	-2
TYPE III							
2	6.2×10^6	35.79	0.0	2	6.2×10^6	35.74	0.0
100	100	35.70	-2	100	97	35.68	-3
200		35.70	-2	200		35.65	-4
300		35.57	0.0	300		35.59	+1
400	103	35.64	+2	400	103	35.59	-5
TYPE I (2000 psi stress)							
2	6.1×10^6	35.26	0.0	2	6.5×10^6	35.60	0.0
100	95	35.15	0.0	100	95	35.52	+4
200		35.16	+1	200		35.50	+1
300		35.11	+6	300		35.48	+6
400	102	35.10	0.0	400	100	35.47	+5
TYPE III							
2	6.3×10^6	35.71	0.0	2	6.3×10^6	36.00	0.0
100	100	35.65	+2	100	98	35.94	0.0
200		35.67	0.0	200		35.92	-1
300		35.67	-3	300		35.87	+4
400	103	35.61	-3	400	103	35.89	0.0

Table 9a. Dynamic modulus of elasticity, weight, and change in gauge length of 3" by 4" by 32" prestressed concrete beams after various periods of repetitive freezing and thawing (fast cycle) - Series III.

The first line in each tabulation under dynamic modulus shows initial modulus in millions of psi. All other values are in per cent of the initial modulus.

A (+) sign and (-) sign denote an increase and decrease, respectively, from the initial gauge length.

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
			TYPE I (zero psi stress)				
10	6.2×10^6	34.84	+0.0	10	6.4×10^6	34.82	+0.0
10	100	34.84	+0.0	10	100	34.82	+0.0
50	100	34.88	+1.0	50	100	34.87	+0.0
100	100	34.89	+4.0	100	100	34.87	+0.0
150	102	34.91	+9.0	150	100	34.90	+1.0
200	102	34.94	+5.0	200	100	34.91	+2.0
250	102	34.95		250	100	34.94	+1.0
300	102	34.97	+1.0	300	100	34.93	+0.0
350	100	34.94	+4.0	350	98	34.93	-2.0
400	100	34.98	+6.0	400	100	34.93	+0.0
			TYPE III				
10	5.8×10^6	34.12	+0.0	10	6.3×10^6	34.30	+0.0
10	100	34.12	+0.0	10	100	34.30	+0.0
50	100	34.18	+0.0	50	100	34.33	+0.0
100	100	34.20	+0.0	100	100	34.33	+0.0
150	100	34.23	+0.0	150	100	34.34	+1.0
200	100	34.23		200	100	34.39	+4.0
250	102	34.27		250	98	34.39	+1.0
300	100	34.25	+3.0	300	98	34.39	+0.0
350	98	34.23	+3.0	350	98	34.39	+0.0
400	99	34.23	+4.0	400	97	34.41	+3.0

Table 9b. (cont.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
TYPE I (500 psi stress)							
10	6.1×10^6	35.08	+0.0	10	6.2×10^6	35.44	+0.0
100	100	35.08	+0.0	100	101	35.48	+0.0
200	102	35.15		200	102	35.52	
300	100	35.12	+3.0	300	101	35.51	+1.0
400	98	35.12	+13.0	400	97	35.53	+1.0
TYPE III							
10	5.9×10^6	34.40	+0.0	10	5.7×10^6	34.51	+0.0
100	101	34.42	+0.0	100	102	34.53	+0.0
200	101	34.45		200	101	34.56	+8.0
300	100	34.47	+1.0	300	101	34.57	+4.0
400	100	34.48	-1.0	400	100	34.57	+0.0
TYPE I (1000 psi stress)							
10	6.3×10^6	35.53	+0.0	10	6.4×10^6	35.53	+0.0
100	100	35.57	-2.0	100	101	35.53	+0.0
200	100	35.69	+12.0	200	101	35.56	
300	99	35.65	+4.0	300	100	35.57	-2.0
400	99	35.72	+6.0	400	99	35.95	-5.0
TYPE III							
10	5.9×10^6	34.50	+0.0	10	5.6×10^6	33.96	+0.0
100	101	34.51	+6.0	100	101	33.97	+3.0
200	102	34.55	+15.0	200	101	34.00	+10.0
300	101	34.58	+16.0	300	101	34.05	
400	100	34.58	+16.0	400	99	33.96	

Table 9 c. (concl.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
TYPE I (1500 psi stress)							
10	6.1×10^6	35.23	+0.0	10	6.3×10^6	35.19	+0.0
100	103	35.22	+0.0	100	102	35.20	+0.0
200	103	35.33		200	102	35.30	+6.0
300	102	35.30	-1.0	300	102	35.27	-5.0
400	101	35.32	-3.0	400	101	35.29	+3.0
TYPE III							
10	5.8×10^6	35.07	+0.0	10	5.6×10^6	34.13	+0.0
100	102	35.10	+0.0	100	101	34.16	+1.0
200	102	35.17		200	101	34.12	-1.0
300	102	35.11		300	101	34.14	-10.0
400	100	35.20	+0.0	400	101	34.14	+5.0
TYPE I (2000 psi stress)							
10	6.2×10^6	35.38	+0.0	10	6.4×10^6	35.31	+0.0
100	100	35.42	+2.0	100	100	35.32	-2.0
200	100	35.44		200	100	35.39	
300	100	35.46	-1.0	300	100	35.35	+0.0
400	100	35.46	+0.0	400	99	35.43	+9.0
TYPE III							
10	6.0×10^6	34.81	+0.0	10	5.6×10^6	33.98	+0.0
100	101	34.87	+6.0	100	100	34.00	+2.0
200	101	34.90	+4.0	200	100	34.00	+0.0
300	101	34.91	+2.0	300	100	34.00	-3.0
400	100	34.93	+4.0	400	98	34.00	+0.0

Table 10a. Dynamic modulus of elasticity, weight, and change in gauge length of 3" by 4" by 32" prestressed concrete beams after various periods of repetitive freezing and thawing (fast cycle) - Special Series.

The fourth line in each tabulation under dynamic modulus shows initial modulus in millions of psi. All other values are in per cent of the initial modulus.

A (+) sign and (-) sign denote an increase and decrease, respectively, from the initial gauge length.

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
SERIES II							
			TYPE I (zero psi stress)				
400				400	99	34.58	+6.0
400(dry)				400(dry)	87	34.32	+0.0
400(wet)				400(wet)	102	34.78	+10.0
405				405	6.0 x 10^6	34.77	+0.0
450				450	100	34.71	+3.0
500				500	100	34.77	+1.0
550				550	100	34.72	+2.0
600				600	100	34.72	+2.0
700				700	100	34.70	+4.0
800				800	100	34.70	+6.0
			TYPE III				
400	95	35.15	+6.0	400	100	35.51	+2.0
400(dry)	61	34.84	-2.0	400(dry)	75	35.17	-8.0
400(wet)	107	35.30	+10.0	400(wet)	105	35.68	+11.0
405	5.7 x 10^6	35.28	+0.0	405	6.0 x 10^6	35.66	+0.0
450	98	35.25	+4	450	101	35.61	+0.0
500	98	35.25	+0	500	101	35.66	+2.0
550	96	35.25	+2	550	101	35.65	+2.0
600	96	35.24	+2	600	101	35.63	+4.0
700	96	35.25	+4	700	103	35.60	+0.0
800	100	35.26	+6	800	105	35.58	+7.0

Table 10a. (cont.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
SERIES II			TYPE I (2000 psi stress)				
400	100	35.10	+0.0	400	100	35.47	+5.0
400(dry)	100	34.89	-4.0	400(dry)	100	35.21	-11.0
400(wet	100	35.28	+11.0	400(wet)	100	35.60	+12.0
405	6.2 x 10^6	35.28	+0.0	405	6.5 x 10^6	35.60	+0.0
500	100	35.25	+0.0	500	100	35.57	+0.0
600	100	35.20	+1.0	600	100	35.57	+1.0
700	100	35.20	+2.0	700	100	35.54	+1.0
800	100	35.17	+3.0	800	100	35.51	+2.0
			TYPE III				
400	100	35.61	—3.0	400	100	35.89	+0.0
400(dry)	100	35.32	-18.0	400(dry)	100	35.69	+2.0
400(wet)	99	35.77	+18.0	400(wet)	100	36.02	+12.0
405	6.5 x 10^6	35.77	+0.0	405	6.5 x 10^6	36.03	+0.0
500	100	35.75	+0.0	500	100	36.00	+0.0
600	100	35.72	+0.0	600	100	35.97	+2.0
700	100	35.72	+2.0	700	100	35.97	+3.0
800	100	35.70	+4.0	800	100	35.96	+5.0

Table 10b. SERIES III

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
TYPE I (zero psi stress)							
400	98	34.98	+6.0	400	100	34.93	+0.0
400(dry)	100	34.79	-2.0	400(dry)	99	34.79	-1.0
400(wet)	100	35.07	+8.0	400(wet)	100	35.04	+8.0
405	6.4 x 10^6	35.06	+0.0	405	6.4 x 10^6	35.04	+0.0
500	100	35.09	+0.0	500	100	35.06	+1.0
600	100	35.03	+0.0	600	100	35.03	+2.0
700	100	35.04	+8.0	700	100	35.07	+8.0
800	100	35.00	+4.0	800	100	35.02	+7.0
TYPE III							
400	100	34.23	+4.0	400	100	34.41	+3.0
400(dry)	97	34.01	-12.0	400(dry)	100	34.25	-7.0
400(wet)	98	34.31	+8.0	400(wet)	100	34.46	+5.0
405	5.8 x 10^6	34.32	0.0	405	6.1 x 10^6	34.49	+0.0
500	100	34.33	+3.0	500	102	34.46	+0.0
600	100	34.29	+6.0	600	102	34.44	-1.0
700	100	34.29		700	100	34.45	+4.0
800	100	34.27	+9.0	800	102	34.40	+1.0

Table 10-b. (cont.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)
TYPE I (1000 psi stress)							
400	100	35.72	+6.0	400	99	35.95	-5.0
400(dry)	100	35.52	+4.0	400(dry)	99	35.40	-2.0
400(wet)	100	35.80	+10.0	400(wet)	99	35.70	+9.0
405	6.3×10^6	35.78	+0.0	405	6.4×10^6	35.69	+0.0
500	100	35.80	+0.0	500	100	35.71	-1.0
600	100	35.75	+2.0	600	100	35.68	-1.0
700	100	35.77		700	100	35.68	+3.0
800	100	35.74	+3.0	800	100	35.60	-1.0
TYPE III							
400	100	34.58	+16.0	400	100	33.96	
400(dry)	100	34.43	+0.0	400(dry)	100	33.86	0.0
400(wet)	100	34.74	+8.0	400(wet)	100	34.16	+8.0
405	5.9×10^6	34.74	+0.0	405	5.5×10^6	34.16	+0.0
500	102	34.75	-1.0	500	100	34.15	-2.0
600	102	34.70	-1.0	600	100	34.10	-3.0
700	102	34.71	+4.0	700	100	34.12	
800	100	34.70	+0.0	800	100	34.08	-2.0

Table 10-b. (concl.)

MOIST CURED				STEAM CURED			
No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length (10^{-4} in.)	No. of cycles of test	Dynamic modulus	Weight (lb)	Change in 10" gauge length
TYPE I (2000 psi stress)							
400	98	35.46	+0.0	400	98	35.43	+9.0
400(dry)	98	35.33	+4.0	400(dry)	100	35.25	+2.0
400(wet)	98	35.60	+12.0	400(wet)	98	35.51	+11.0
405	6.3×10^6	35.59	+0.0	405	6.4×10^6	35.53	+0.0
500	100	35.58	+0.0	500	100	35.53	+0.0
600	100	35.55	+1.0	600	100	35.49	+1.0
700	100	35.57	+1.0	700	100	35.52	+3.0
800	100	35.54	+2.0	800	100	35.51	+3.0
TYPE III							
400	100	34.93	+4.0	400	100	34.00	+0.0
400(dry)	100	34.69	+3.0	400(dry)	100	33.85	-4.0
400(wet)	98	35.08	+11.0	400(wet)	98	34.22	+9.0
405	6.0×10^6	35.08	+0.0	405	5.5×10^6	34.20	+0.0
500	100	35.08	+0.0	500	100	34.18	+0.0
600	100	35.03	+2.0	600	100	34.16	-1.0
700	100	35.03	+4.0	700	100	34.20	+3.0
800	100	35.03	+4.0	800	100	34.17	-1.0

PREPARATION AND DURABILITY TESTING OF PRETENSIONED PRESTRESSED CONCRETE SPECIMENS

by

STANLEY LEE RIEB

B. S., Kansas State University, 1958

AN ABSTRACT OF A THESIS

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The investigation was fundamentally concerned with the soundness of prestressed concrete as indicated by its resistance to freezing and thawing action, although some provisions were made to study the creep in the loaded concrete specimens undergoing tests. It is a part of the Durability Test Program, undertaken by the Illinois Prestressed Concrete Association and additionally supported by the prestressed Concrete Institute, to more fully determine the durability and permanence of prestressed concrete.

A group of test specimens were programmed in an attempt to determine the effect of three primary variables on the durability of 200 pretensioned, prestressed concrete prisms 3- by 4-in. in cross section by 32 in. in length. Programming was conducted in a manner to include the following variables: amount of stress in the concrete, type of cement (Types I and III), and method of curing (moist and steam).

The test specimens were prepared in series of 40 beams, and 72 concrete cylinders; the cylinders being used to determine age-strength relationships of the concrete. To facilitate molding of the five series of beam specimens, a special prestressing bed was developed. The steel prestressing strand was pretensioned by a screw-type jack designed especially for the project.

Time permitted the testing of only two series of beams. The dynamic modulus of elasticity, weight, and length change over a 10-in. gauge length were observed periodically as an aid in determining the effects of the repetitive freezing and thawing on the specimens.

Results of the age-strength relationships show that 4000 psi strength concrete can generally be obtained in one day by the use of high-early-strength cement, and steam curing the low slump, air-entrained concrete used in many prestressed structures. The concrete specimens representing Type I cement required two, and sometimes three days to develop sufficient strength to allow removal of the concrete from the prestressing bed.

The soundness of all beam specimens after being exposed to 400, and as many as 800, fast freezing and thawing cycles was very satisfactory. In no instance was the final dynamic modulus less than 97 per cent of the initial modulus. Slight surface scaling of a number of the beams which were subjected to 800 cycles was the only visible deterioration due to alternate freezing and thawing of the specimens.

Creep investigations conducted on the prestressed concrete beams undergoing the freezing and thawing tests did not result in any significant or consistent information regarding the effect of Types I and III cements on the creep of the loaded concrete. The observed changes in gauge length with respect to the initial gauge readings were quite small for all beams tested.

Since the high quality concrete used in this investigation is very similar to that used in most prestressed concrete construction practice, it could justifiably be concluded, on the basis of these tests, that such concrete, particularly when under compression, is a highly durable construction material from the standpoint of weathering action.

The use of Type III cement as a means of obtaining high strength concrete at an early age should not be detrimental to the durability of the concrete.