The Effects of Freezing and Thawing of Prestressed Concrete

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SYNOPSIS

Freeze and thaw tests were conducted on 48 specimens representing two strength levels namely 5000 psi and 3000 psi. Some of the beams with a 5000 psi strength were post-tensioned throughout the test. Significant improvement in the durability was found to result from post-tensioning of the beams. Post-tensioned concrete specimens made of a rich mix showed better durability than unstressed concrete made of the same mix and also better than unstressed concrete made of a leaner mix.

INTRODUCTION

In the United States the use of prestressed concrete has now developed to such a stage that detailed information concerning its physical characteristics is urgently needed by engineers.

Prestressed concrete has many new and important applications in civil and structural engineering and offers many advantages. The fine cracks that develop in conventional concrete cannot be avoided. With prestressed concrete the absence of cracks as a permanent feature can be assured up to maximum loading. Prestressed concrete members of lesser depths than those required by ordinary reinforced concrete may be employed. This, of course, means a saving in the volume of concrete to be used in a given structure, in addition to the savings in the weight of steel which results from the use of high strength steel bars or wires.

The striking difference in the cost ratio of materials to labor in the United States as compared to some European countries has influenced the direction of the development of this new art. European countries have taken the lead in the use of prestressed concrete on a wide scale. Yet, there is little doubt that prestressed concrete will eventually replace many of the ordinary concrete structures.

With the birth of this new era of prestressed concrete a new field has been opened for research to study the physical characteristics of this new combination of materials. Many of the qualities of prestressed concrete have been investigated, yet it is believed that the following research work is one of the first to attempt to study the durability of prestressed concrete.

The effect of freezing and thawing on ordinary concrete has been investigated. Among the leading researchers in this field are Woods and Lewis, Barte, Pendley, Higgs, Walker and Bloem, Jackson and Hanson.

The most acceptable explanation of concrete failure under repeated cycles of freezing and thawing was the hypothesis presented by T. C. Powers. This hypothesis presents the action of frost as being the cause of producing hydraulic pressure which tends to cause the deterioration of concrete. This hydraulic pressure depends on many factors, the most important of which is the permeability of the material through which the water must flow to escape from the saturated regions on the surface of the test specimen during the cooling cycle. The degree of saturation and the absorptivity of the test specimens were emphasized as important factors in discussing freezing and thawing of concrete.

Confining our consideration to the cement paste, we know that the freezing and thawing damage is related:

1. Directly to the degree of saturation
2. Directly to the bubble spacing factor
3. Inversely to the tensile strength
4. Inversely to the permeability.

At the present time there is no universally accepted specification for the determination of deterioration characteristics of prestressed concrete. The ASTM Specification C 291-52T "Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water or Brine" was used as a guide in the execution of this research.

PURPOSE AND SCOPE

The purpose of this research was:

1. To study the durability of prestressed concrete under repeated cycles of freezing and thawing.

2. To compare the freezing and thawing effects on prestressed concrete and ordinary concrete for specimens made of the same mix giving an ultimate strength of 5000 psi or better after 28 days.

3. To compare the effect of freezing and thawing on prestressed concrete having an ultimate strength of 5000 psi and ordinary concrete

specimens made with a leaner mix giving an ultimate strength of about 3000 psi after 28 days.

The freezing and thawing machine available could accommodate a reasonable number of beams as large as 3 in. x 4 in. x 16 in. A post-tensioning arrangement was used in order to develop the desired force throughout the full length of the prestressed specimens.

Two series of tests were conducted in this study. Two different mix designs were included in each series. One mix design was used for three batches and the other for one batch. Six 3 in. x 4 in. x 16 in. beams (and three 6 in. x 12 in. compression test cylinders) were made from each batch of concrete, resulting in 24 beams for each series. The results of freezing and thawing tests on a total of 48 beams are thus reported in this study.

Series I and II were identical in all respects except the time of curing. Series I was cured for 28 days and Series II was cured for 14 days. In each series, mix designs A, B and C were the same and were intended to have a minimum ultimate compressive strength of 5000 psi. Mix design D in each series was intended to have a minimum ultimate compressive strength of 3000 psi.

MATERIALS

The coarse aggregate used in this study met the specifications of the State Highway Department of Indiana for size No. 5. The gravel was separated into four gradations: 1 in. to ¾ in., ¾ in. to ½ in., ½ in. to ⅜ in., and ⅜ in. to No. 4. All material retained on the 1-inch sieve was discarded. Four equal weights of each gradation were used in the mixes.

The fine aggregate used met the specifications of the State Highway Department of Indiana for gradation 14, No. 2. The sand was divided into two parts—with 66 per cent of the mix design weight passing a No. 16 sieve and 34 per cent by weight retained on the No. 16 sieve.

Type I portland cement was used in all mixes.

Darex was used as the air entraining agent in all mixes.

The post-tensioning steel bars were ⅝-inch round high strength steel bars furnished by Stressteel Corporation. End plates and nuts furnished by the same corporation were used on each post-tensioned beam.

EQUIPMENT

The equipment used in this study was available in the Joint Highway Research Project and the Purdue University Materials Testing and Structural Engineering Laboratories. Among those used was the concrete mixer, the vacuum saturating unit and the freezing and thawing apparatus.

Fig. 1. Sixty-ton hydraulic jacking unit and specimen in position for post-tensioning.

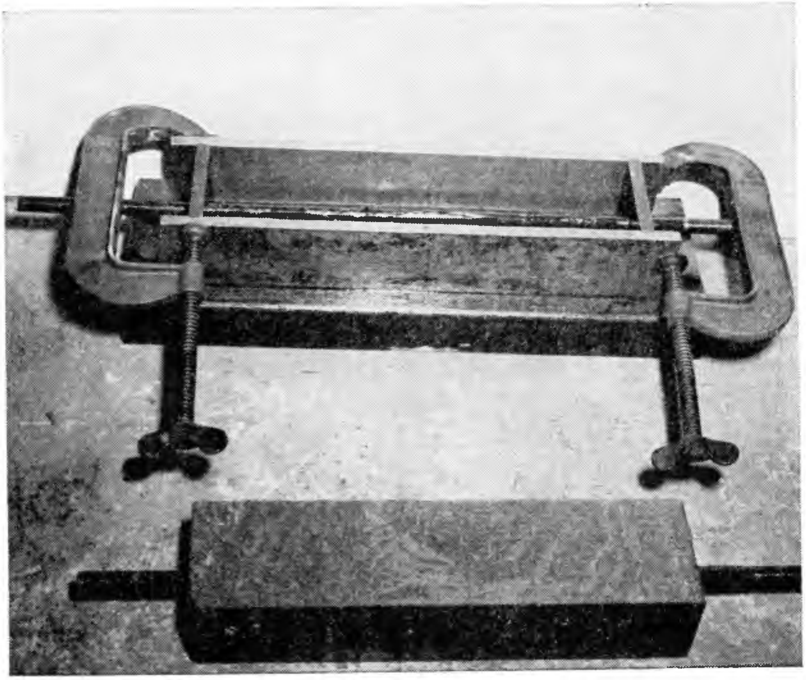


Fig. 2. A typical concrete form.

A new 60-ton capacity Simplex hydraulic jack with 3 inches of travel was used in the post-tensioning of the beams. The jack had a certified gage calibration furnished by Stressteel Corporation. The calibration of the prestressing unit was checked by use of the 120,000 pound Baldwin Universal Testing Machine in the Purdue University Structural Laboratory to assure the application of the desired magnitude of prestressing force on the beams. With this check on the calibration it was found unnecessary to use strain gages on the bars for load checks. The jacking unit in operation is shown in Fig. 1.

The steel forms, normally used for 3 in. x 4 in. x 16 in. freeze-thaw specimens, were used in this study with some minor alterations. New sliding end plates were prepared with $\frac{11}{16}$ in. holes drilled in their centers. Two "C" clamps were used on the ends of the forms

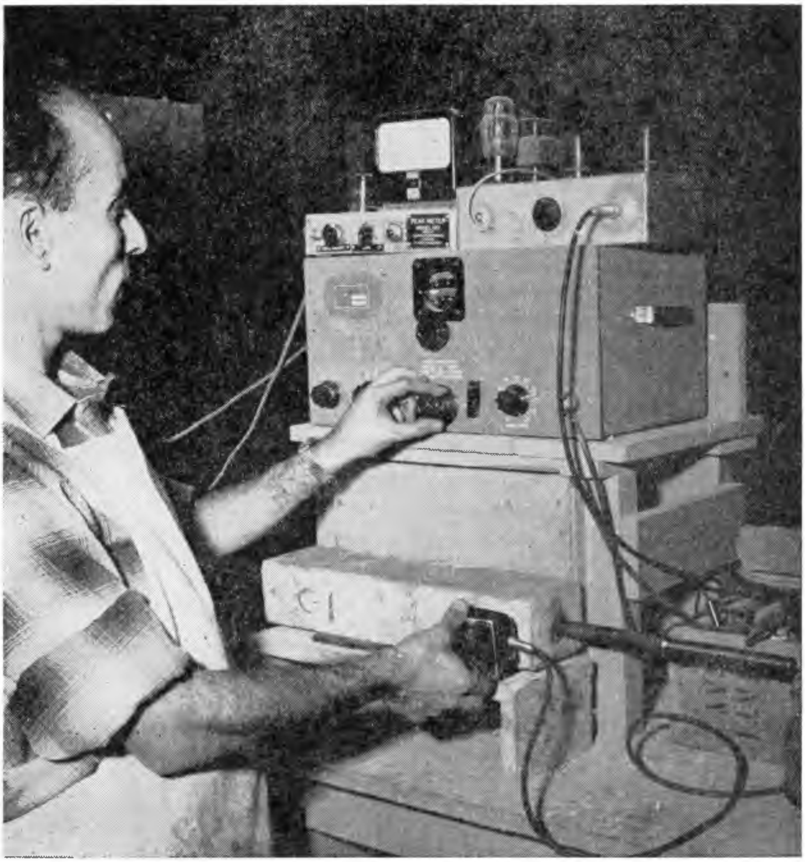


Fig. 3. The natural frequency apparatus and specimen in position for testing.

to assure proper dimensions of the beams. The molds were covered with a light film of oil before the concrete was placed. The Stressteel bars were placed through the holes in the end plates and were coated with a lubricant to prevent the development of bond between the steel and the concrete. A typical form used to mold the beams is shown in Fig. 2.

The freezing and thawing apparatus has a cycle range between 0 degrees F. and 40 degrees F. The apparatus subjected the specimens to about 7 cycles every 24 hours. The timing of each cycle was in agreement with ASTM Specification C 291-52T.

The natural frequency measuring unit used in these experiments is composed of a variable frequency oscillator, a variable frequency driving unit to induce vibrations in the specimen at controlled frequencies, and a milliammeter to measure the current flow from the pickup. When the induced vibration is the same frequency as the natural frequency of the beam, resonance occurs and is detected by a sudden increase in the milliammeter reading. Thus, the maximum current flow occurs at the fundamental frequency of vibration of the specimen. The frequency of the induced vibration can be read directly on the oscillator dial. The fundamental frequency measuring unit is shown in Fig. 3.

RESEARCH PROCEDURE

The concrete mixes were designed by the b/bo method. Mix designs A, B and C were the same and were designed for a strength of 5000 psi after 28 days. Mix D was designed for a strength of 3000 psi after 28 days. Detailed information concerning the mixes is shown in Table 1.

Each mix provided enough concrete for three 6 in. x 12 in. compression test cylinders and six 3 in. x 4 in. x 16 in. beams. The beams of Series I were cured for 28 days and Series II for 14 days in a saturated lime solution at about 70 degrees F.

At the end of the curing period the specimens were removed from the lime solution, washed, dried and weighed. They were assigned and marked with a letter-number designation as shown in Table 2.

All specimens designated by letters A, B or C followed by numbers 1 or 2 were tested for the fundamental frequency which corresponded to the zero cycle and 100 per cent relative modulus of elasticity. These specimens were meant to represent an ordinary concrete beam made of a rich mix. There was a total of six of these beams for each of the two series. The beams were tested for the fundamental frequency about every 20 freeze-thaw cycles and were weighed. Each beam had a steel bar in its center.

All specimens designated by letters A, B or C followed by numbers 3 or 4 were tested for fundamental frequency and were weighed, thus

Table 1
MIX DESIGN DATA

Mix Designation	*Compressive Strength*PSI*	*Water/ Cement*	*Sack/ Cu. Yd.*	*Air Content, Percent*	*Slump, Inches*
1A	6420	.450	6.76	2.5	2.5
1B	5540	.457	6.74	2.7	3.5
1C	5110	.514	6.61	2.3	5.5
1D	3740	.695	4.36	1.7	2.5
IIA	7000	.420	6.77	2.5	1.8
IIB	5600	.445	6.74	2.0	3.0
IIC	5800	.452	6.69	2.5	3.8
IID	3730	.622	4.24	5.2	3.0

* Standard 6 in. by 12 in. cylinders—28 days.
Note: All mixes were designed initially by the b/bo method.

Table 2
SPECIMEN MARKINGS AND TEST SUMMARY

3000 PSI CONCRETE	5000 PSI CONCRETE		
Plain Concrete Steel Bar in Center	Plain Concrete Steel Bar in Center	Prestressing Force Released During Testing	Permanently Prestressed Concrete
	A1		
	A2		
		A3	
		A4	
			A5
			A6
	B1		
	B2		
		B3	
		B4	
			B5
			B6
	C1		
	C2		
		C3	
		C4	
			C5
			C6
D1			
D2			
D3			
D4			
D5			
D6			
6	6	6	6

giving the zero cycle readings. Then these beams were post-tensioned with a net average stress of 2000 psi on the cross-sectional area. This is the recommended value of $0.4f^1c$ used in design practice. These beams were then placed in the freezing and thawing machine. The post-tensioning force was released each time before the beam was weighed and tested for its fundamental frequency. The original post-tensioning force was reapplied before the beam was put back into the freezing and thawing apparatus. The beams were tested about every 20 cycles.

Specimens designated by letters A, B or C followed by numbers 5 or 6 were post-tensioned to 2000 psi before any readings were taken. This force was left on the beams throughout the entire test period. After the initial force was applied these beams were weighed and tested for the fundamental transverse frequency. They were tested periodically about every 20 cycles.

The six beams designated by the letter D and numbers 1 through 6 represented concrete made of a leaner mix for comparison purposes. To accomplish this, the beams were cast with a steel bar in the center similar to the other specimens. They were tested periodically for weight and fundamental transverse frequency at about every 20 cycles of freezing and thawing.

RESULTS AND DISCUSSION

The number of cycles of freezing and thawing and the corresponding fundamental transverse frequency of each specimen were obtained and recorded during the experiments.

The fundamental transverse frequency is related to the modulus of elasticity by the formula

$$E = CWn^2$$

where

E = Young's modulus of elasticity in pounds per square inch

W = Weight of specimen in pounds

n = Fundamental transverse frequency in cycles per second

c = A constant for any one specimen

Basically, a change in Young's modulus as a result of cycle freezing and thawing can be assumed to represent deterioration of the concrete specimen. It has been recommended that the initial fundamental transverse frequency of the specimen be assumed to represent a Young's modulus (relative 100 per cent)to which other frequencies could be related by the formula

$$Pc = \frac{-\ ^{2}}{n_o^{2}} \text{ x } 100$$

where

Pc = Relative modulus of elasticity expressed as a percentage, after c cycles of freezing and thawing.

n_o = Fundamental transverse frequency at zero cycles of freezing and thawing.

n_c = Fundamental transverse frequency after c cycles of freezing and thawing.

Thus, the relative moduli of elasticity were calculated for each specimen after each measurement of natural frequency. The weights of the specimens were recorded throughout the experiment. Excessive pitting and pop-outs during the experiment, even at early stages, made weight analysis unmeaningful.

The durability factor was calculated by the formula

$$DF = \frac{PN}{M} \qquad \text{(ASTM C 291-52T)}$$

where

DF = Durability factor of the test specimen

P = Relative dynamic modulus of elasticity at N cycles, per cent

N = Number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less

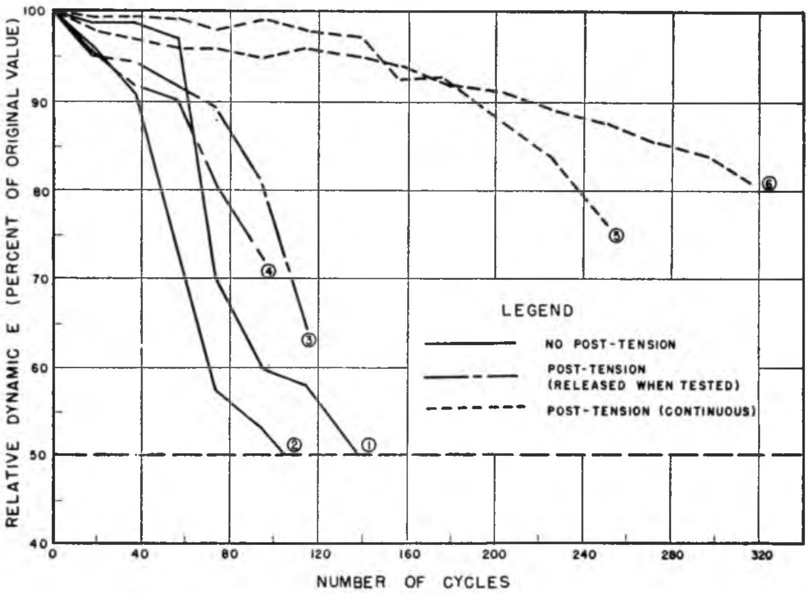
and

M = Specified number of cycles at which the exposure is to be terminated.

For the purpose of this research, the testing of any specimen was to be terminated at 300 freeze-thaw cycles or when the relative modulus of elasticity dropped to 50 per cent.

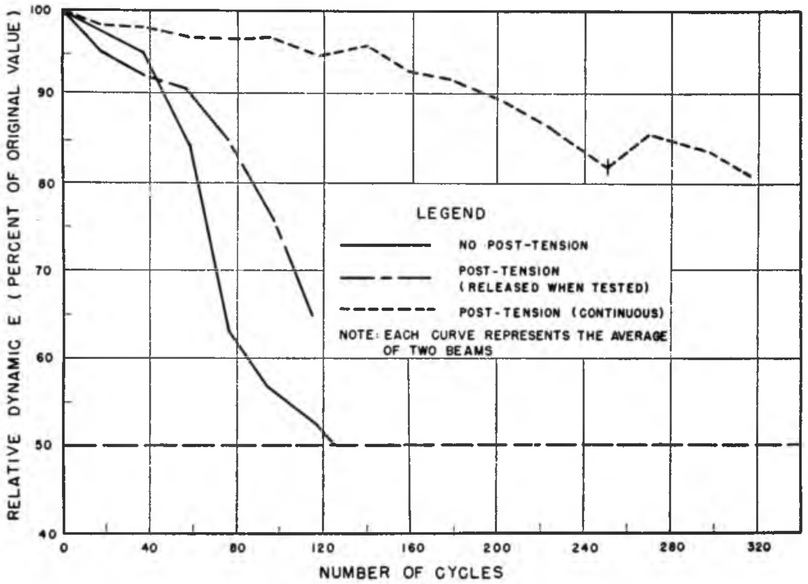
A curve showing the variation in the relative modulus of elasticity with the number of cycles of freezing and thawing was plotted for each specimen.

Fig. 4 shows the results obtained for each individual beam in mix II-A. Since these six beams were divided into three groups of similar specimens, only three legends appeared on the graph. The circled figure at the end of each line indicates the number of the specimen. Similar graphs were plotted for mixes I-A, I-B, I-C, II-B and II-C.



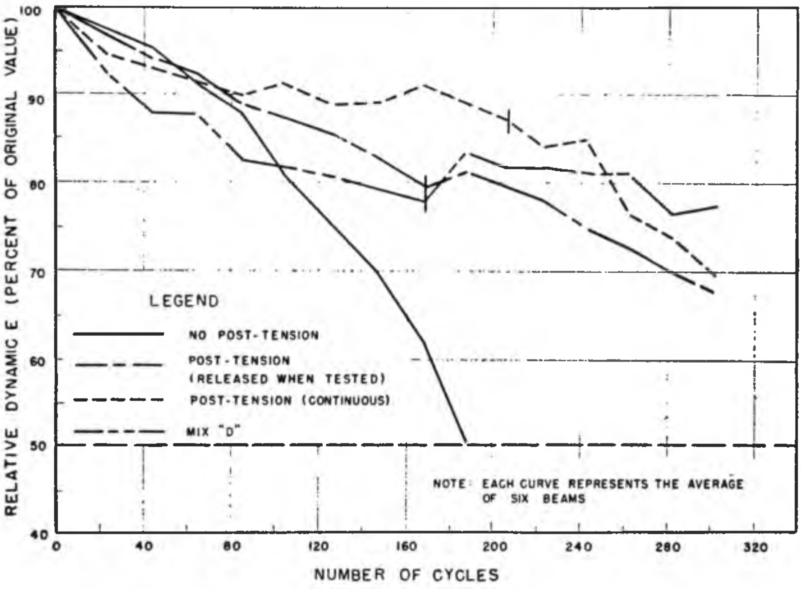
THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II A)

Fig. 4.



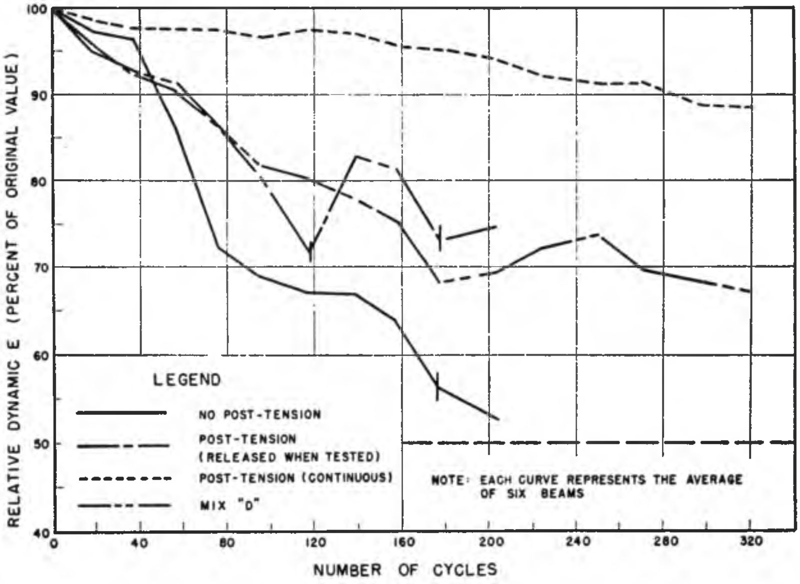
THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II A)

Fig. 5.



THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (SERIES I)

Fig. 6.



THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (SERIES II)

Fig. 7.

Fig. 5 is a plot of the average effect of freezing and thawing on the modulus of elasticity of similar specimens from mix II-A. It should be noted that each curve represents the average result from two similar specimens. Similar graphs were plotted for specimens from I-A, I-B, I-C, II-B and II-C.

Fig. 6 summarized the results of Series I. The values of the relative moduli of elasticity of each six similar specimens were averaged. Likewise, average results from the six similar specimens of mix D in Series I were computed and plotted on the same graph for purposes of comparison and evaluation. Fig. 7 shows the results of Series II in

Table 3

DURABILITY FACTORS OF SERIES I BEAMS
AT 300 CYCLES

MIX	BEAM	3000 PSI PLAIN CONCRETE	5000 PSI CONCRETE		
			Plain Concrete	Prestressing Force Released During Testing	Permanently Prestressed Concrete
A	1		27.5		
	2		28.2		
	3			67.6	
	4			54.3	
	5				84.6
	6				60.5
B	1		31.2		
	2		34.7		
	3			79.1	
	4			57.1	
	5				87.9
	6				72.4
C	1		25.7		
	2		24.3		
	3			65.8	
	4			20.1	
	5				60.5
	6				46.1
D	1	67.8			
	2	14.1			
	3	71.0			
	4	86.0			
	5	91.6			
	6	69.5			
AVERAGE		66.7	28.6	57.3	68.7

a similar manner. When a specimen was withdrawn from the experiment, its contribution to the average of the group was dropped, and the average for the remaining similar specimens only was computed. To show this on the graphs, a vertical line was drawn through the appropriate curve at the last average point taken before the withdrawal of the beam. This will explain the abrupt change in some of the curves.

Table 3 shows the values of the durability factors for the individual beams of Series I at 300 cycles of freezing and thawing. The average durability factor for each six similar beams was given.

Table 4 summarized the results of Series II in a similar manner.

Table 4
DURABILITY FACTORS OF SERIES II BEAMS
AT 300 CYCLES

MIX	BEAM	3000 PSI PLAIN CONCRETE	5000 PSI CONCRETE		
			Plain Concrete	Prestressing Force Released During Testing	Permanently Prestressed Concrete
A	1		50.0		
	2		18.0		
	3			30.1	
	4			28.0	
	5				83.2
	6				82.0
B	1		12.7		
	2		23.3		
	3			33.4	
	4			28.4	
	5				82.0
	6				91.3
C	1		77.0		
	2		63.3		
	3			35.5	
	4			37.3	
	5				95.1
	6				98.0
D	1	61.0			
	2	84.0			
	3	72.0			
	4	55.4			
	5	37.3			
	6	68.0			
AVERAGE		63.0	40.7	32.1	88.6

TYPES OF CONCRETE FAILURE

The decrease in the dynamic modulus of elasticity was measurable in all the specimens tested. In the case of beams numbered 3 and 4 of mixes A, B and C where the initial prestressing force was applied every time the beams were tested, this failure came at an early stage. In the beams numbered 5 and 6 more freeze-thaw cycles were required to produce this failure. In the latter case, the initial prestressing force was applied before the beginning of the test and was maintained permanently throughout the whole study. As the experiment proceeded, creep took place and the initial prestressing force dropped significantly. A typical failure of the prestressed concrete beams is shown in Fig. 8.

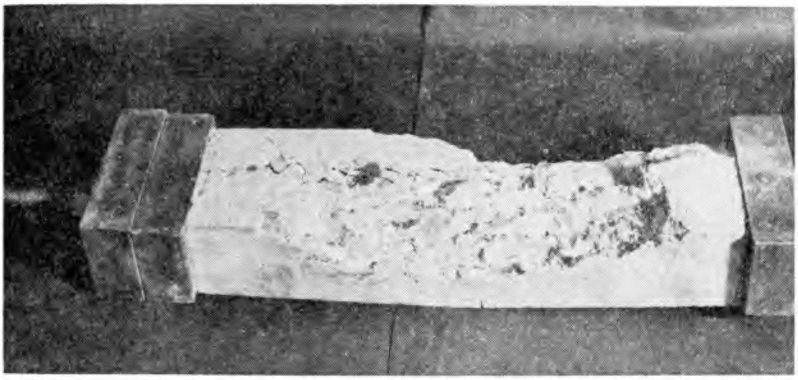


Fig. 8. A typical failure of a post-tensioned beam specimen C-3 Series I.

In addition to the decrease in the dynamic modulus of elasticity, Walker listed three major classifications of deterioration in concrete due to unsound aggregates. These are (a) pitting and pop-outs, (b) D-line deterioration, and (c) map cracking.

Pitting is the gradual disintegration of deleterious pieces of aggregates near the surface of the specimen due to frost. Pop-outs take usually a conical shape and the apex being at the aggregate particle. These are caused by rapid disruption of a saturated piece of deleterious aggregate. Pitting and pop-outs were frequent during the experiment. They were mainly caused by the limonite particles in the aggregates.

D-line cracking is a tensile failure in the matrix. D-lines first appear as fine cracks along the free edges of the specimen. These were noted on some of the specimens.

Map cracking is a form of disintegration in which random cracks develop over the entire surface. This kind of failure was not found in this study. Fig. 9 shows samples of pitting, pop-outs and D-line cracking.

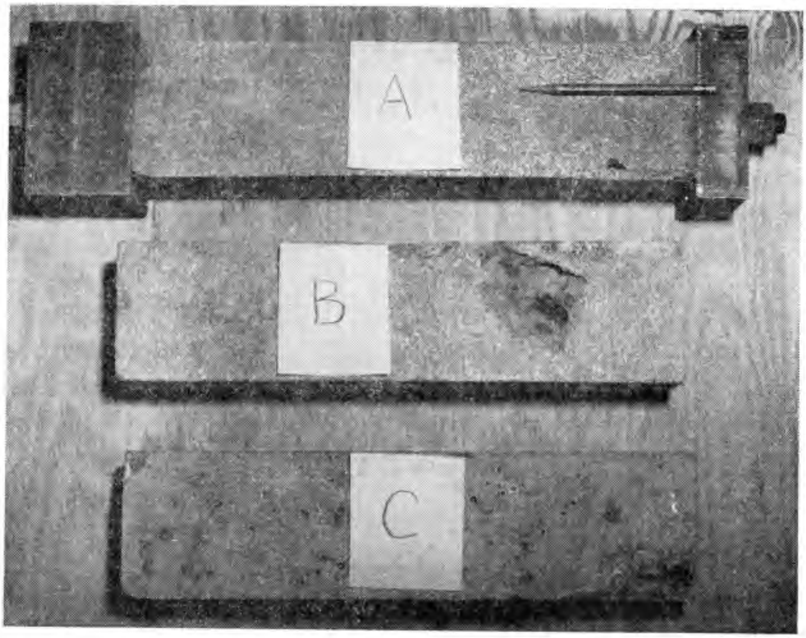


Fig. 9. Three types of failure of concrete caused by deleterious material.
A. D-line deterioration after 15 freeze-thaw cycles.
B. Pop-out after 300 freeze-thaw cycles.
C. Pitting after 300 freeze-thaw cycles.

DISCUSSION OF RESULTS

In the analysis of the results of any freezing and thawing test, certain facts should be kept in mind:

1. No generally accepted freezing and thawing test has been developed up to this time. The ASTM specifications list four tentative methods for such tests.

2. The freezing and thawing test cannot establish quantitative information to determine the length of actual performance of concrete in the field. The test is expected to give a general idea about the qualitative behavior of the concrete exposed to the natural weathering conditions.

3. At best, the results to be obtained from a freezing and thawing test are comparative data on the durability of the test specimens.

4. The accelerated freezing and thawing tests that are performed in the laboratory are generally considered to be very severe tests.

5. The vacuum saturation of the aggregate makes it particularly vulnerable to attack by freezing and thawing.

The freezing and thawing tests specified by the ASTM are meant to be performed on homogeneous beams of concrete. There is no test specified to study the effects of freezing and thawing on reinforced or prestressed concrete. The test used for plain concrete specimens was adopted in this research. The steel bars that were inserted at the center of the beam did not influence the results obtained in this study for the following reasons:

1. The steel bars were used on all beams tested. Thus the comparative results obtained are considered valid.

2. No bond was developed between the steel and the concrete. A sample beam was tested for its fundamental frequency with the bar in its center, and then the same beam was tested again with the bar completely removed. The fundamental frequencies measured in both cases were identical. This check was repeated frequently during the various stages of the experiment and the same results were obtained in every check. This means that the fundamental frequency of the concrete was not affected by the unstressed steel bar.

Beams numbered 5 and 6 of mixes A, B and C of both series were tested for the fundamental frequency in a post-tensioned condition. The loading arrangement adopted consisted of a non-bonded steel bar placed axially in the center of the beam and post-tensioned in a standard manner, distribution plates being used at the ends of the beam to transmit the load to the concrete. Steel nuts on the outer side of each end plate maintained the post-tensioning force. This arrangement provides a self-contained system which was tested dynamically in a manner similar to that used for the unstressed concrete. In this case the fundamental freuency of the stressed system, for any beam, was about half the value obtained for the same beam with end plates removed. About 5 per cent of the reduction was due to the stress, the remaining reduction was due to the mass of the end plates and nuts. This is in agreement with the detailed theoretical analysis given by Elvery and Furst. When these beams were subjected to the repeated cycles of freezing and thawing, the fundamental frequency of the system dropped. This indicated the deterioration that occurred in the post-tensioned beams. This deterioration occurred in the concrete and the post-tensioning of the concrete did influence the rate and the nature of the deterioration.

CONCLUSIONS

Based on the results obtained and within the limitations of the variables studied in this experiment, the following conclusions are drawn:

1. The post-tensioning of concrete improves its effective durability against cyclic freezing and thawing.

2. Continuously post-tensioned concrete, having a minimum ultimate strength of 5000 psi after 28 days is effectively more durable than unstressed concrete having minimum ultimate strength of 3000 psi after 28 days.

3. Continuously prestressed concrete is effectively more durable than intermittently stress-released concrete of the same mix. Furthermore, in four out of six cases, the latter is apparently more durable than unstressed concrete of the same mix.

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