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DURABILITY AND BEHAVIOR OF PRETENSIONED-PRESTRESSED CONCRETE BEAMS

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Vicksburg, Mississippi

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CORPS OF ENGINEERS
Vicksburg, Mississippi

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PREFACE

This paper, by Mr. Edwin C. Roshore of the Concrete Division, U. S. Army Engineer Waterways Experiment Station (WES), was prepared for consideration for publication in the Proceedings, American Concrete Institute. The manuscript was approved for publication by the Office, Chief of Engineers, by first indorsement dated 29 April 1963 to a letter dated 28 March 1963. It was also reviewed and approved for publication by Task Committee No. 6 of the Reinforced Concrete Research Council; and contains revisions based on the results of these reviews.

The manuscript is based on WES Technical Report No. 6-570, Report No. 1.

Col. Edmund H. Lang, CE, and Col. Alex G. Sutton, Jr., CE, were Directors of the WES during the conduct of the work discussed and the preparation of the manuscript; Mr. J. B. Tiffany was Technical Director.

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DURABILITY AND BEHAVIOR OF PRETENSIONED-

PRESTRESSED CONCRETE BEAMS*

by

Edwin C. Roshore**

Synopsis

To develop data on the factors affecting the durability of prestressed (pretensioned) concrete beams, 28 large beams containing pretensioning strands and 412 small companion specimens without pretensioning strands were fabricated. The concrete in 22 of the beams was air-entrained; that in the other 6 was not. Appendix A presents computations used in designing the beams.

Some of the beams were subjected to laboratory tests, which indicated that the air-entrained beams showed less average camber, about the same average sink-in of pretensioning strands, less midspan deflection, and an ability to withstand greater flexural loads than the nonair-entrained beams. Creep tests are still in progress. A number of the auxiliary specimens were also tested in the laboratory to determine the strength, elastic, and plastic properties of the concrete.

The rest of the beams and auxiliary specimens were exposed to natural weathering at stations on the Maine and Florida coasts. In Maine they are

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* Based on U. S. Army Engineer Waterways Experiment Station, CE, Durability and Behavior of Prestressed Concrete Beams; Pretensioned Concrete Investigation, Progress to July 1960, Technical Report No. 6-570, Report 1 (Vicksburg, Miss., June 1961).

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being subjected to cyclic freezing in air and thawing in seawater, and in Florida to sulfate attack in warm seawater. At the Maine station the nonair-entrained beams failed during the first winter of exposure, whereas the air-entrained beams remain in good condition after four winters. No significant results of the Florida exposure have been observed to date.

Purpose and Scope of Investigation

Factors affecting the durability of conventionally reinforced concrete beams representing a variety of concrete conditions, steel types, and degrees of stress were previously studied.[4*] The study described herein, begun in 1957, was conducted to obtain information on the factors affecting the durability of pretensioned-prestressed concrete beams; these factors include creep in the steel, creep in the concrete, resulting relaxation of the prestressing force, and corrosion resistance of the prestressing elements.

A group of pretensioned-prestressed concrete beams were made. Most of these were made with air-entrained concrete, but a few were made using concrete without air-entraining admixture. Because nonair-entrained concrete could be expected to deteriorate more rapidly than air-entrained concrete, the nonair-entrained beams were included in the program to determine whether any information could be obtained in a relatively short time on the effects of severe weathering on pretensioned-prestressed concrete beams regardless of the type of concrete used. A few beams were made in which the prestressing strands were not pretensioned. Most of the beams were subjected to sustained flexural (third-point) load; others were not loaded.

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* Raised numerals refer to similarly numbered items in the list of references at end of text.

Laboratory tests were conducted on the beams to determine sink-in of steel strands, camber, midspan deflection during flexural loading, length and midspan-deflection change with time, and ultimate strength in flexure. Field exposure tests are being made to determine resistance to natural weathering as judged both visually and by measurement of length change and pulse velocity.

Auxiliary specimens (cylinders and small beams) were molded from the same concrete batches used for the test beams, and were tested in the laboratory to determine compressive strength, flexural strength, creep, modulus of elasticity in compression, dynamic modulus of elasticity, Poisson's ratio, and resistance to laboratory freezing-and-thawing. Auxiliary specimens are also being subjected to natural weathering.

In addition to the tests of the beams and auxiliary specimens, tests were conducted to determine the tensile strength and modulus of elasticity of the steel pretensioning strands.

Materials

Crushed limestone fine and coarse aggregates, graded to 3/4-in. maximum size, were used. Physical properties and gradings of the aggregates are shown in table 1. Type III portland cement was used. The air-entraining admixture was neutralized vinsol resin. The properties of the high-strength steel strands used for pretensioning are given in table 2.

Mixtures and Specimens

Mixtures

Data on the two concrete mixtures, each of which was proportioned to have a nominal 1-3/4-in. slump and a nominal 28-day compressive strength of 6000 psi, are given in table 3.

Specimens

Twenty-eight batches of concrete were mixed in a 10-S rocking-tilting mixer, and the following specimens were molded from these batches:

Specimen Size, in.	Type	No. per Batch	Total
4-1/2 by 9 by 81	Beams	1	28
6 by 12	Cylinders	5	140
3-1/2 by 4-1/2 by 16	Small beams	11*	264
6 by 16	Cylinders	4**	8
			440

* All batches except batches A, B, C, and D.
** Batches 2 and 16 only.

The 28 beams were molded in wooden forms on an outdoor reinforced-concrete casting bed. Nine nominal 1/4-in. (1 by 7) steel strands were positioned in each beam as shown in fig. 1. In 24 of the beams, the strands were tensioned to approximately 70% of their ultimate strength (approximately 3 tons per strand); the strands in the remaining four beams were not tensioned appreciably. Twenty-four of the beams (not A, B, C, and D) also contained eight stainless steel gage points† located at midspan for the measurement of the length change of the concrete. The position of the gage points is also shown in fig. 1.

The cylinders (both types) and small beams were fabricated indoors in metal molds. Each 6- by 16-in. cylinder contained one strain meter embedded axially.

† These gage points were of the type developed by Messrs. H. K. Stephenson and T. R. Jones, Jr., Texas A. & M. College, College Station, Tex.

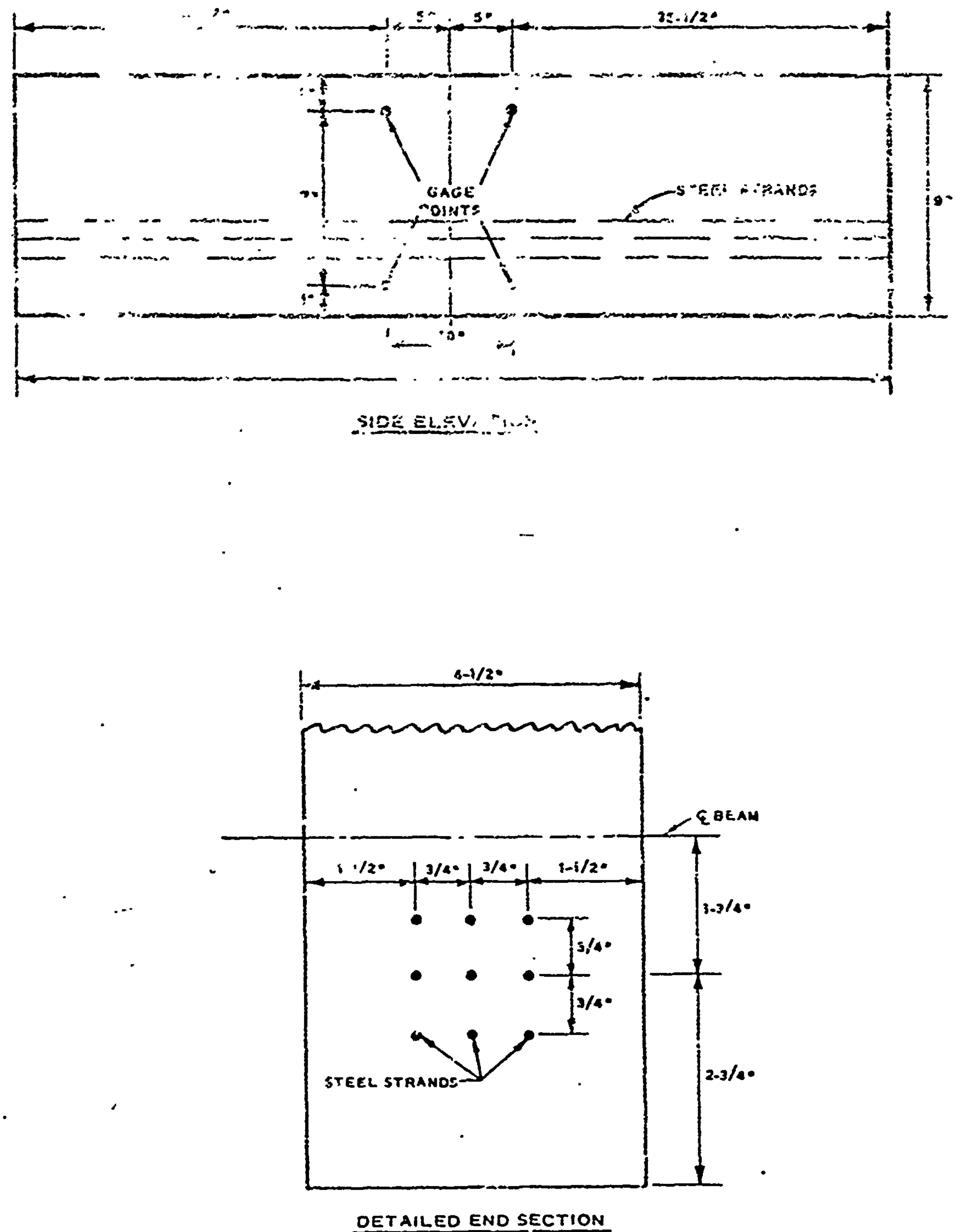

Fig. 1. Two views of beam, showing position of steel strands and gage points

Prestressing

The 5- by 54-ft casting bed used for tensioning the strands and casting the beams is shown in fig. 2. The bed had two loading posts with steel header plates at each end which served as buttresses for the pretensioning (see fig. 3), and was long enough so that as many as six of the beams could be fabricated simultaneously. The reaction capacity of the bed was 100 tons.

The steel strands were stretched between the buttresses of the casting bed and tensioned with a 50-ton hydraulic jack prior to placing of the concrete (see fig. 4). The strands were fastened to both ends of the casting bed with quick-release end anchorages. The tensioning load was measured by the jack gage (see fig. 4) and by calibrated load cells which consisted of aluminum cylinders on which were mounted two resistance-wire strain gages (see figs. 3 and 5). One load cell was positioned on each strand between the casting bed buttress and the end anchorage. Average tensioning loads for all of the beams tested are given in table 4.

Placement of concrete

After the strands were tensioned as desired, the concrete was placed and consolidated using electric vibrators. The top surface of each beam was coated with a white pigmented membrane curing compound; the other surfaces of the beams were protected during curing by the wooden forms, which were not stripped until the day the pretensioning load was released.

Transfer of load

The beams remained on the casting bed for 10 days (only 3 days for beams A, B, C, and D*) with the tension remaining on the steel strands for

* Beams A, B, C, and D were cast primarily to develop the techniques and procedures to be used.

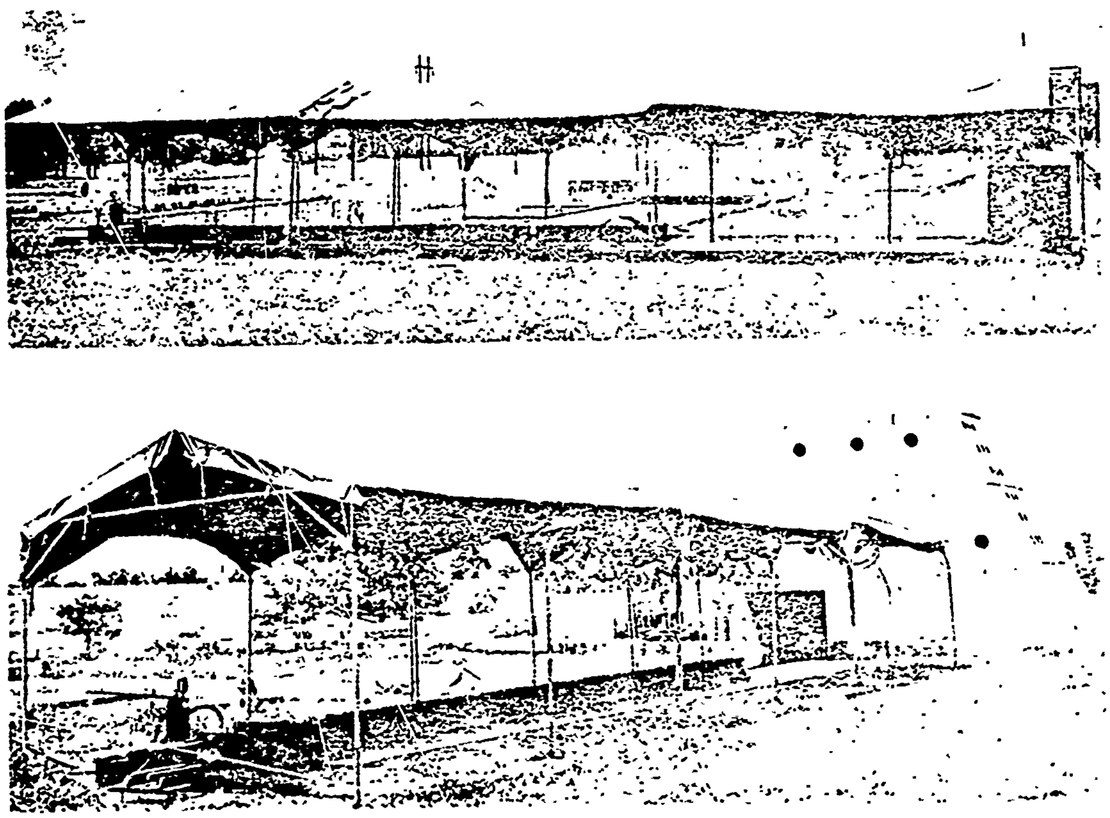

Fig. 2. Two views of casting bed

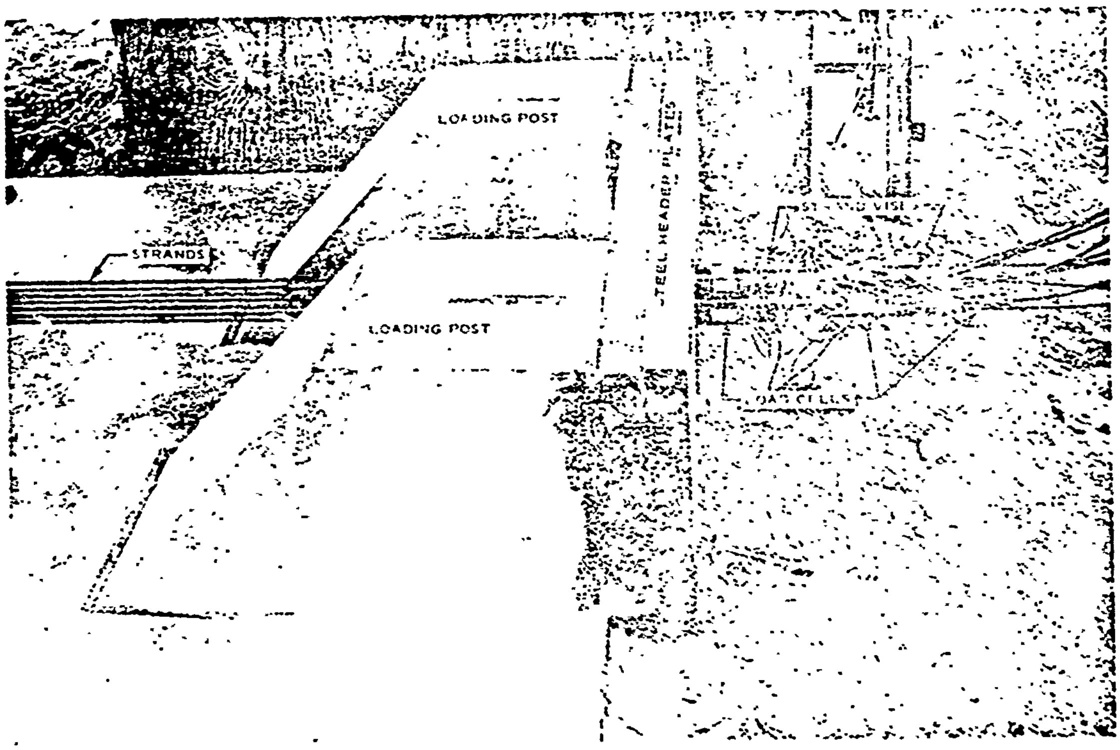

Fig. 3. Close-up of north end of casting bed

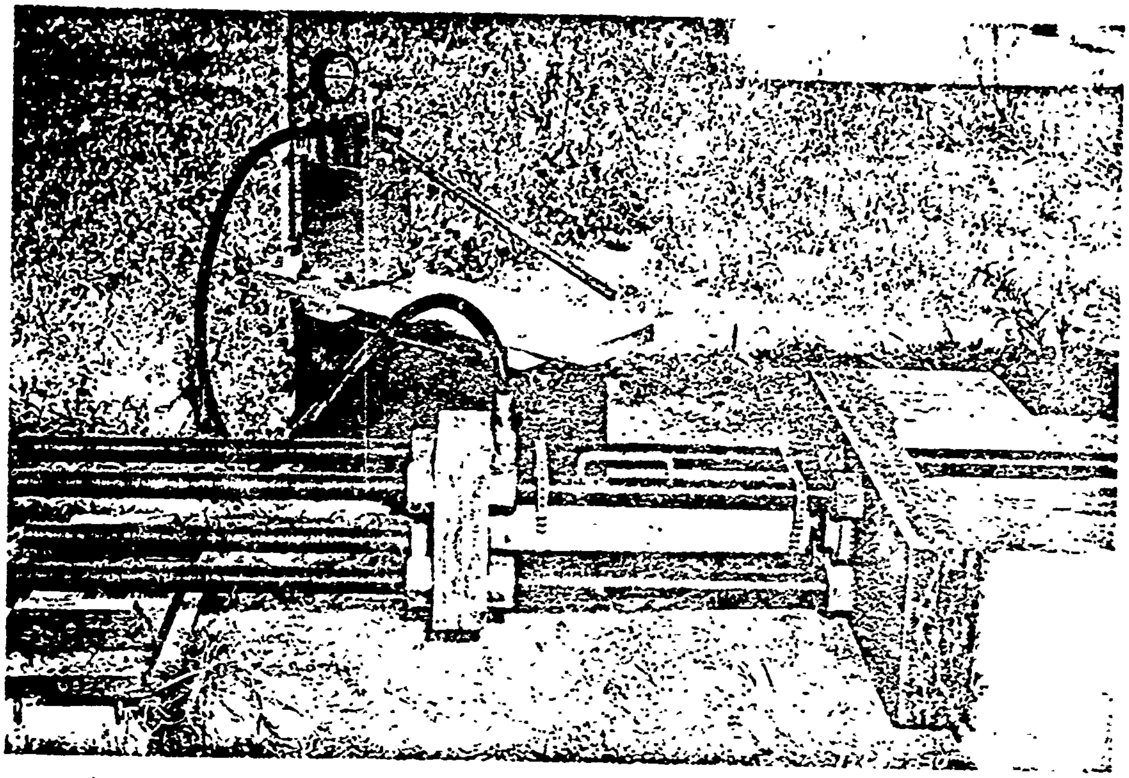

Fig. 4. Hydraulic jack and ram in position on south end of casting bed

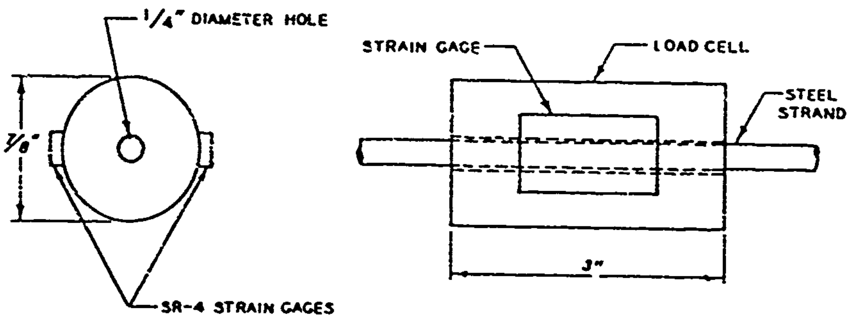

Fig. 5. Strain gages mounted on load cell

this period. Then the load on the steel strands was released, causing the lower half of the concrete beam to be in compression (approximately 2800 psi on the outer fiber), and the upper half to be in tension (approximately 200 psi on the outer fiber).* After this transfer of load, the strands were cut and the beams were removed from the casting bed and water-cured to an age of 28 days. The exposed ends of the pretensioning strands were covered with pads of epoxy resin compound to protect the strands from corrosion. The disposition made of the 28 beams after curing is listed in table 5.

Laboratory Tests and Results

Twenty-two batches of air-entrained concrete were made in this investigation; two had a water:cement ratio of 5.64 gal per bag, and the remainder a water:cement ratio of 5.85 gal per bag. Six batches of nonair-entrained concrete were made, all of which had a water:cement ratio of 6.22 gal per bag. The behavior of the air-entrained and nonair-entrained concretes is compared in the following discussion of the results of the various tests.

Camber and sink-in.

Determinations of camber were made on 20 beams after transfer of load. These measurements were made at the midspan of each beam using dial gages that measured the camber to the nearest ten-thousandth of an inch. Measurements (to the nearest five-thousandth of an inch) were also made of the sink-in of three steel strands in each beam after transfer of load,

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* Appendix A gives the computations used in design of the beams. These computations were made according to the methods outlined in reference 2.

using a fiducial mark on the strand and a measuring magnifier. These measurements were corrected to allow for the elastic shortening of that portion of the strand between the beam end and the fiducial mark. Results of both types of measurements are given in table 4 and summarized in the following tabulation.

Pretensioning Force (Load per Strand), lb	Air-Entrained Beams (w:c = 5.85 gal per bag) No. Tested	Camber in.	Sink-in in.	Nonair-Entrained Beams (w:c = 6.22 gal per bag) No. Tested	Camber in.	Sink-in in.
5744	2	Max 0.0126	0.026	2	0.0250	0.032
		Min 0.0034	0.022		0.0200	0.021
		Avg 0.0080	0.024		0.0225	0.026
5662	4	Max 0.0322	0.026	2	0.0304	0.019
		Min 0.0031	0.017		0.0138	0.019
		Avg 0.0176	0.022		0.0221	0.019

As can be seen above, the average camber of the nonair-entrained beams was greater than that of the air-entrained beams for the same pretensioning force. The average sink-in of the pretensioning strands in the nonair-entrained beams was not significantly different from that in the air-entrained beams for the same pretensioning force.

Flexural loading

Eighteen of the beams were yoked (in pairs) and loaded flexurally (third-point loading method), using spring and yoke loading frames. The loading of the beams was accomplished by use of two hydraulic rams, positioned near the ends of the beam, to jack the beams against other channel sections attached to the loading frames by extension rods (see fig. 6). Two intensities of loading were used: in one, the compression due to prestressing was just balanced (100%), and in the other, the compression due to prestressing was exceeded so that approximately 200-psi tension existed

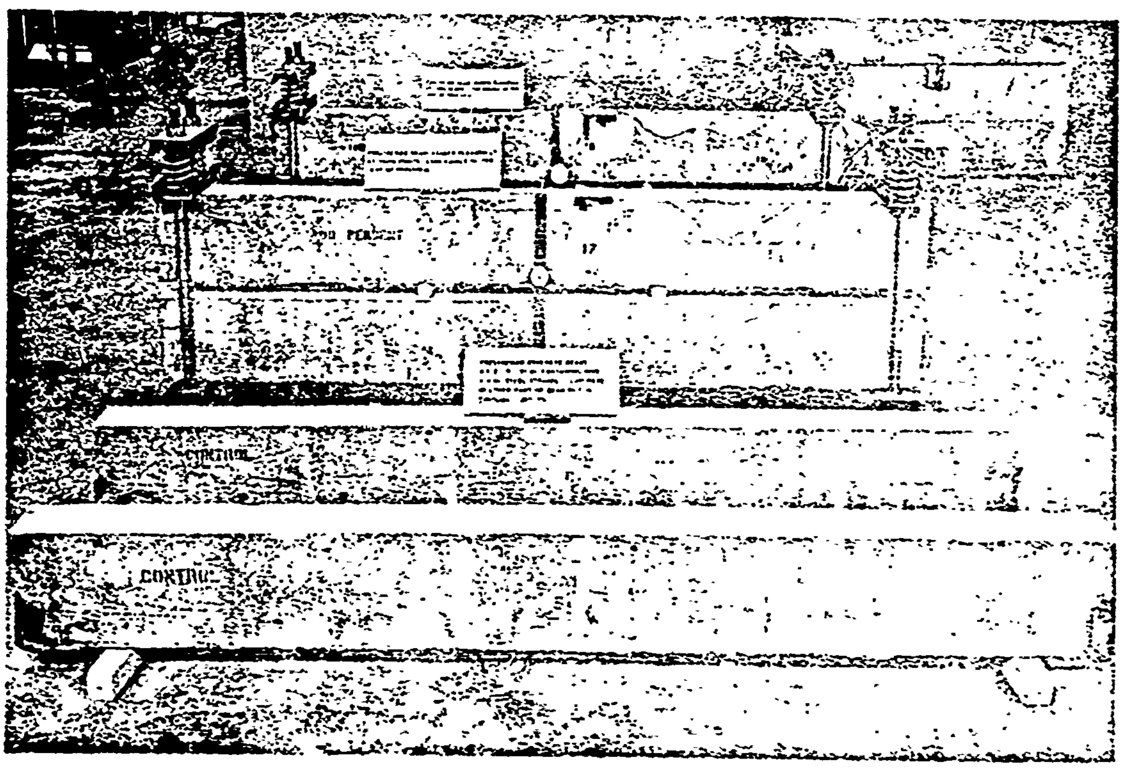


Fig. 6. Loaded and unloaded control beams during storage in the laboratory showing flexural loading yokes, dial gages, and strain gage wiring

in the outer fibers of the beams (108%). The midspan deflection of each beam was measured to the nearest ten-thousandth of an inch by means of dial gages, two gages per beam. Resistence-wire strain gages were attached to several of the beams, and strain was measured to the nearest millionth of an inch per inch. Readings were also taken on embedded gage points (see fig. 7) with an external strain gage before and after flexural loading.

Table 6 summarizes the data obtained in these flexural loading tests. As illustrated by the following typical data, greater average midspan deflections were experienced by the nonair-entrained beams than by the air-entrained beams with the same pretensioning force and flexural load.

Pretensioning Force (Load per Strand), lb	Flexural Loading % of Prestress	Type Beam	No. Tested	Water: Cement Ratio gal per bag	Midspan Deflection in.
5662	100	Air-entrained	4	5.85	Max 0.0555 Min 0.0361 Avg 0.0477
		Nonair-entrained	2	6.22	Max 0.0640 Min 0.0578 Avg 0.0609

In addition to the tests just discussed, eight beams of various ages were loaded flexurally (third-point method) to destruction. For these tests, the test beam was paired with a steel beam and loaded by means of two hydraulic rams Was note until failure of the concrete in the outer fiber of the beam (compression side). No steel bond slip, Midspan deflection of the concrete beams was measured by means of dial gages; gage-point readings were also taken to determine fiber strain

Results of the flexural load tests to destruction are also given in table 6. The following tabulation shows that for the same pretensioning force and approximately the same age of concrete, the average flexural load

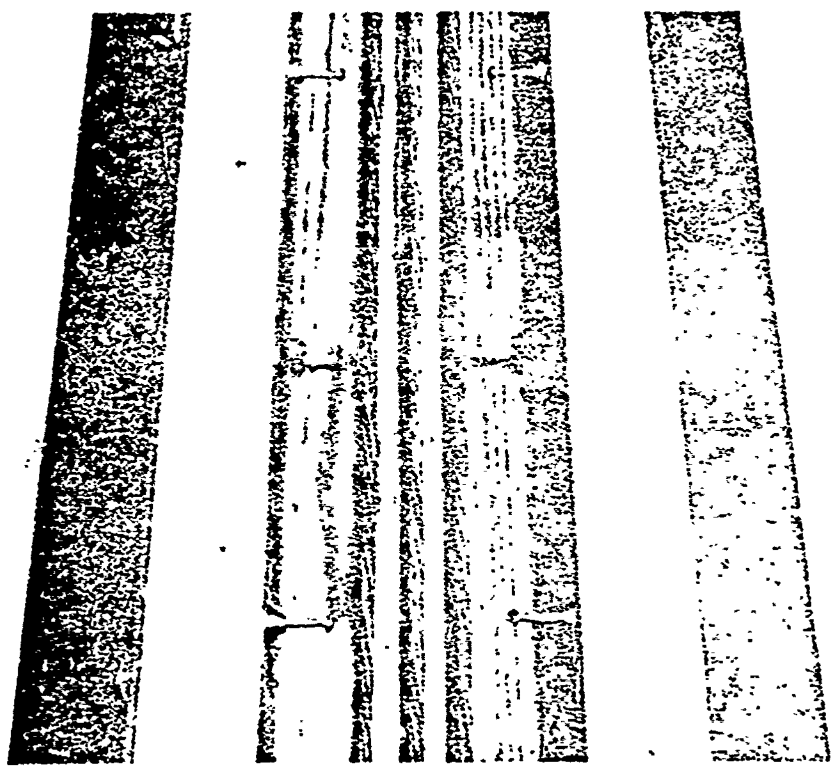


Fig. 7. Close-up of wooden beam mold showing strands and Whittemore gage points

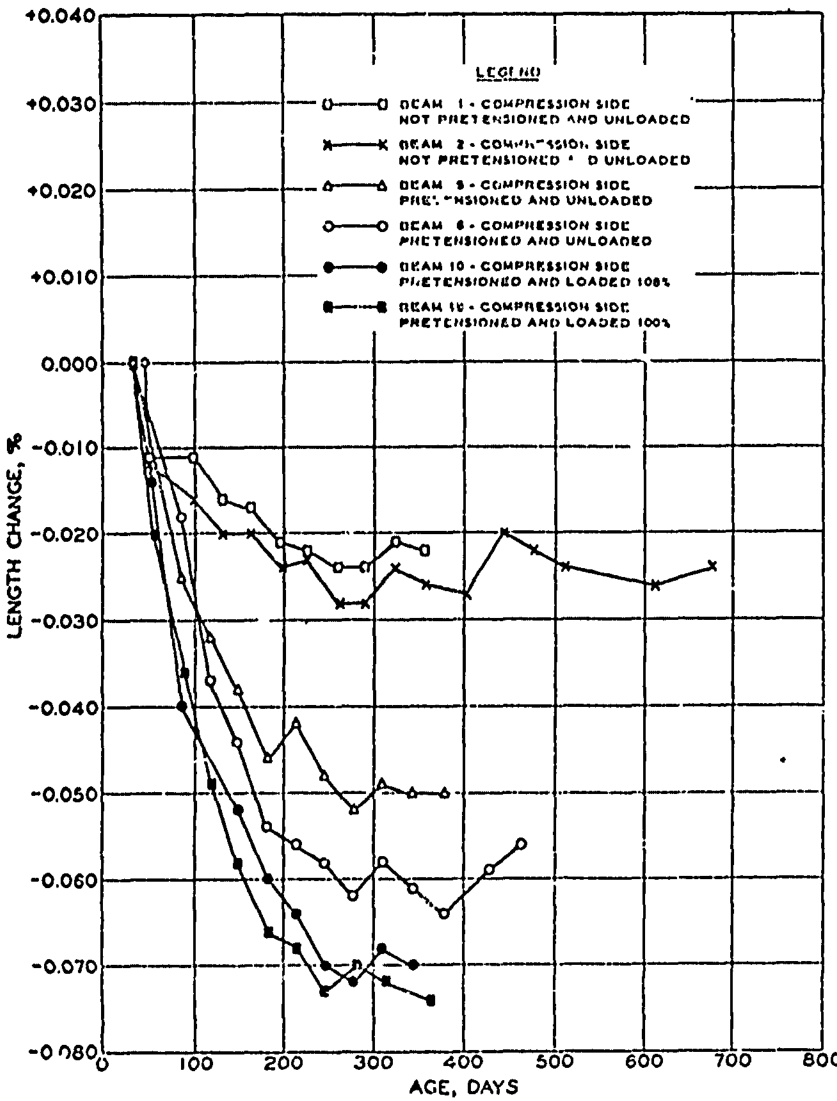
required to destroy nonair-entrained beams was greater than that required to destroy air-entrained beams.

No. Tested	Pretensioning Force (Load per Strand), lb	Water:Cement Ratio gal per bag	Age of Concrete at Destruction, Days	Ultimate Load (Each End), lb
		Air-Entrained Beams		
2	5928	5.64	115 and 120	Max 14,935 Min 14,355 Avg 14,645
		Nonair-Entrained Beams		
2	5928	6.22	106 and 113	Max 16,240 Min 13,775 Avg 15,010

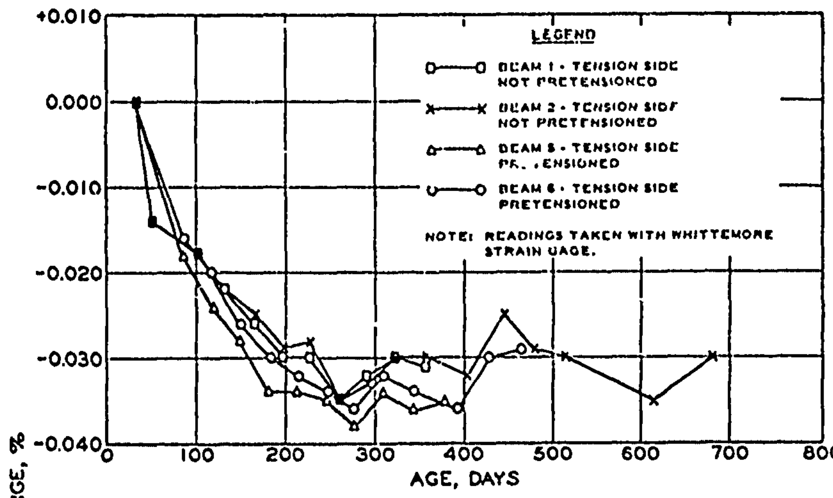
The flexural strength of 120 of the small beams was also determined. One small beam from each of 24 concrete batches was tested at each of five ages: 3, 7, 28, 91, and "N" days ("N" being a selected age which may differ for each batch). Results are given in table 7. The average flexural strength of the 5.85-gal-per-bag water:cement ratio air-entrained concrete was higher than that of the nonair-entrained concrete at four of the six ages tested, i.e. at 7, 28, 45, and 91 days age (table 7). The nonair-entrained concrete showed higher flexural strengths at 3 and 35 days age.

Length and midspan-
deflection change with time

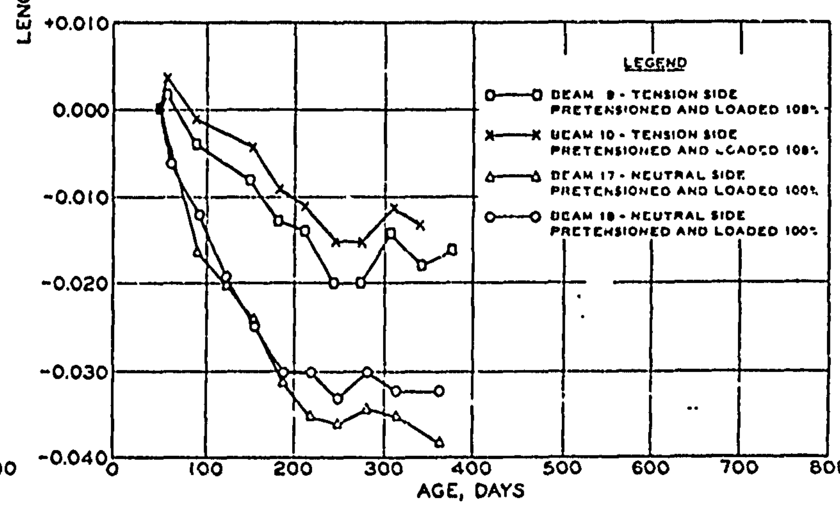
Length-change tests, based on readings taken on the embedded gage points, were conducted on eight of the beams stored in the laboratory. Four were tested in a loaded condition and four in an unloaded condition. Two of the unloaded beams were pretensioned; two were not. These length-change test results are shown in fig. 8. Length-change readings were also



a. Loaded and unloaded beams, compression side



b. Unloaded beams, tension side



c. Loaded beams, tension and neutral sides

Fig. 8. Results of laboratory length-change tests

taken using SR-4 strain gages mounted on the outer fiber of four loaded beams; these results are given in table 8. The length changes of the four unloaded beams were also expressed as volume changes, as shown in fig. 9. The volume change was greater for the pretensioned than for the nonpretensioned, unloaded beams. Changes in midspan beam deflection with time were measured by means of dial gages, and are given in table 9.

Compressive strength and static modulus of elasticity

The compressive strength and static modulus of elasticity of 136 of the 6- by 12-in. concrete cylinders were determined. One cylinder from each of the 28 concrete batches was tested at each of five ages: 3, 7, 28, 91, and "N" days. Test results are given in table 10.

The compressive strength test results from table 10 are summarized in the following tabulation.

No. Specimens Tested	Water:Cement Ratio gal per bag		Compressive Strength, psi 3 Days	7 Days	28 Days	35 Days	45 Days	91 Days	365 Days
			Air-Entrained Concrete						
2	5.64	Max	3570	5110	7140			7300	
		Min	3520	4460	6890			7000	
		Avg	3545	4785	7015			7150	
20	5.85	Max	4390	4980	6570	5070	6390	7250	7650
		Min	2990	3930	4820	5040	5480	5710	5910
		Avg	3540	4405	5695	5670*	5830*	6545	6925
			Nonair-Entrained Concrete						
6	6.22	Max	3860	5410	7290	6640	6360	7220	
		Min	3070	4140	5430	6540	6040	6360	
		Avg	3525	4540	6385	6590**	6200**	6820	

* Average of five specimens: only five specimens were tested at these ages.

** Average of two specimens; only two specimens were tested at these ages.

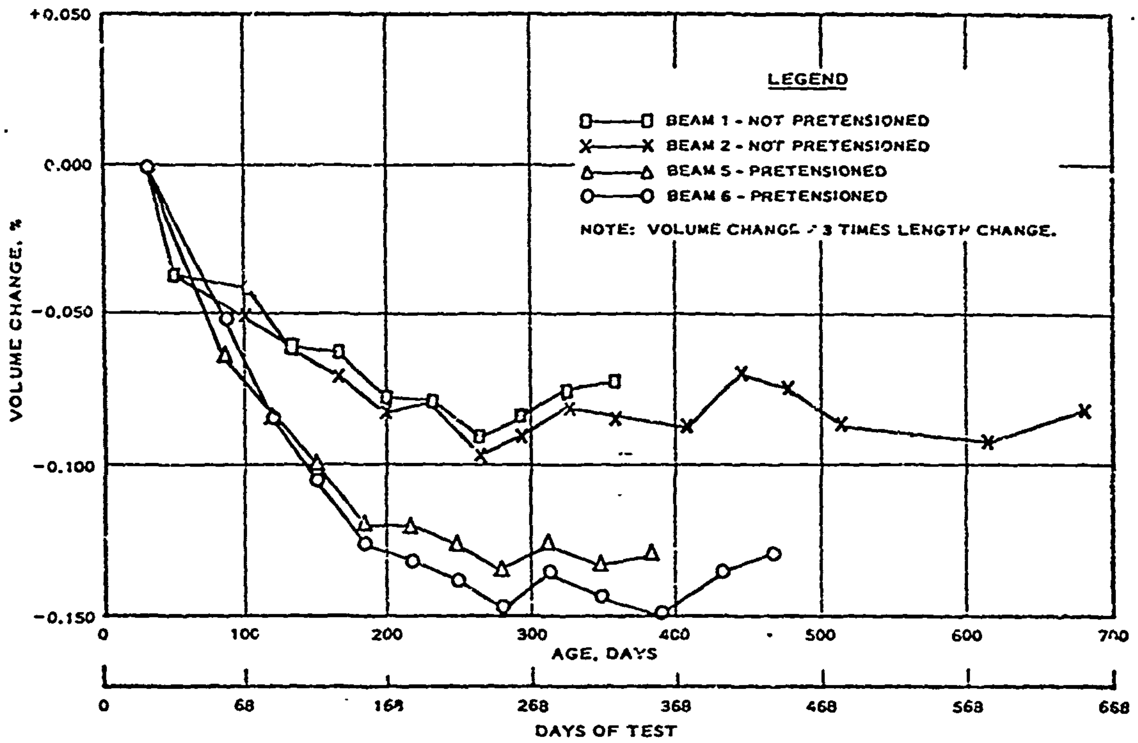


Fig. 9. Results of laboratory volume-change tests

The indicated average compressive strength of the air-entrained concrete with a water:cement ratio of 5.64 gal per bag was greater than that of the concretes made with the other two water cement ratios at all ages tested; however, only two specimens of this concrete were tested at each age. The average compressive strength of the nonair-entrained concrete with a water: cement ratio of 6.22 gal per bag was greater than that of the air-entrained concrete with a water:cement ratio of 5.85 gal per bag at 7, 28, 35, 45, and 91 days age; the average compressive strengths of these two concretes were essentially the same at 3 days age.

The apparent decrease in strength of the nonair-entrained concrete between 35 and 45 days age is not regarded as significant. It may have resulted from improper consolidation of one or both of the two test specimens which were tested at 45 days age; but since only two specimens were tested, no definite conclusions are believed warranted.

As shown in the following tabulation, the air-entrained concrete with a water:cement ratio of 5.64 gal per bag had the highest percentage increase in compressive strength between 3 and 91 days, and the nonair-entrained concrete had a higher percentage increase than the air-entrained concrete with a water:cement ratio of 5.85 gal per bag.

No. Specimens Tested	Water:Cement Ratio gal per bag	Percent Increase in Concrete Compressive Strength with Age				
		3-7 Days	7-28 Days	28-91 Days	3-91 Days	91-365 Days
Air-Entrained Concrete						
2	5.64	38	47	2	102	
20	5.85	24	29	15	85	6
Nonair-Entrained Concrete						
6	6.22	29	41	7	93	

The increase in compressive strength of the three concretes between 3 and 7 days age ranged from 24 to 38%, between 7 and 28 days age from 29 to 47%, and between 28 and 91 days age from 2 to 15%. The smaller increase between 28 and 91 days is presumably characteristic of high-early-strength concrete.

The strength-gain characteristics of the nonair-entrained concrete and the 5.85-gal-per-bag air-entrained concrete are shown in fig. 10. The rate of strength gain by each concrete apparently decreases greatly when the average compressive strength reaches a level of approximately 6500 psi. Since concrete compressive strengths in excess of 6000-7000 psi would be advantageous for some applications involving pretensioning, it would be desirable to learn what factors brought about the indicated compressive strength plateau. Among those that may have been responsible are (a) approximate completion of effective hydration of the cement by self-desiccation and other processes; (b) effective decline in efficiency of curing; (c) attainment of a strength level that made the effective strength of the aggregate a critical factor; and (d) elastic properties of the testing machine.

The average static modulus of elasticity of the air-entrained concrete with a water:cement ratio of 5.64 gal per bag was generally lower than that of the other two concretes and ranged from 360×10^6 psi at 3 days age to 4.92×10^6 psi at 91 days age (see table 10). The average static modulus of elasticity of the air-entrained concrete with a water:cement ratio of 5.85 gal per bag ranged from 3.82×10^6 psi at 3 days age to 5.35×10^6 psi at 91 days age, and was higher than that of the other two concretes at 3 and 91 days age. The average static modulus of elasticity of the nonair-entrained concrete was 3.78×10^6 psi at 3 days age and

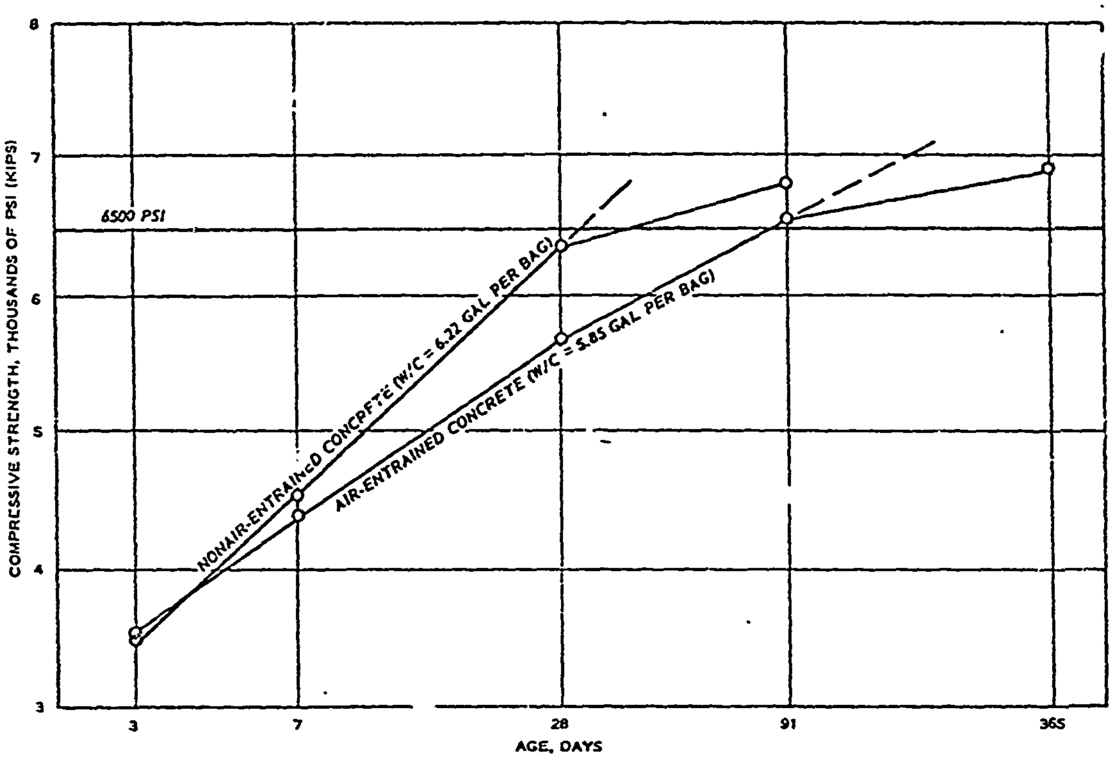


Fig. 10. Strength gain of concrete

5.12×10^6 psi at 91 days age, and was higher than that of the other two concretes at 28 days age, and higher than that of the air-entrained concrete with a water:cement ratio of 5.85 gal per bag at 35 and 45 days age.

Dynamic properties

Young's dynamic modulus of elasticity, the dynamic modulus of rigidity, and Poisson's ratio of 120 of the small concrete beams were determined. One small beam from each of 24 concrete batches was tested at each of five ages: 3, 7, 28, 91, and "N" days. Results are given in table 11, which shows the following. The average dynamic modulus of elasticity and the average modulus of rigidity of the nonair-entrained concrete were greater than those of the 5.85-gal-per-bag air-entrained concrete at all ages tested. The average Poisson's ratio of the nonair-entrained concrete was greater than that of the air-entrained concrete at four of the six ages tested, i.e. at 28, 35, 45, and 91 days age. At 3 days age, the average Poisson's ratio of the two concretes was equal; at 7 days age, the air-entrained concrete had a greater average Poisson's ratio.

Creep

Four of the 6- by 16-in. concrete cylinders containing embedded strain meters, two air-entrained and two nonair-entrained, are being subjected to laboratory creep tests. These specimens were loaded in compression to 1000 psi at an age of 10 days; this load is being maintained by steel springs. The other four 6- by 16-in. concrete cylinders containing embedded strain meters, two air- and two nonair-entrained, are being tested for autogenous length change,concurrently with the creep-test specimens, to serve as controls. One each of the air- and nonair-entrained creep cylinders is being tested in a sheathed condition (outside surface of the cylinder covered with a neoprene jacket), and the other two without sheaths; the same is true of the autogenous-length-change cylinders. Creep equations for data obtained after approximately one year of testing, and from which autogenous length change has been subtracted, are shown in the following tabulation. Creep curves are plotted in figs. 11 and 12.

1000-psi Load at 10 Days Age

Batch No.	Air Content of Concrete, %	Specimen Sheathed	Creep Equation
2	4.0	No	$\epsilon = 0.158 + 0.0791 \ln (t + 1)$
		Yes	$\epsilon = 0.195 + 0.0381 \ln (t + 1)$
16	2.2	No	$\epsilon = 0.128 + 0.0808 \ln (t + 1)$
		Yes	$\epsilon = 0.0718 + 0.0331 \ln (t + 1)$

Note: ϵ = elastic plus creep strain, millionths of an inch per pound per square inch
t = time after loading, days
ln = natural logarithm

The sheathed air-entrained specimens have exhibited more creep to date than the sheathed nonair-entrained specimens. The creep of the unsheathed specimens is essentially the same.

Laboratory freezing-and-thawing

Seventy-two of the small concrete beams, three from each of 24 batches, were subjected to rapid laboratory freezing-and-thawing tests in water, beginning at 14 days age. Results are given in table 12. The average durability factor (DFE) of the air-entrained concrete beams was 87, whereas that of the nonair-entrained concrete was 4.

Pulse velocity

As shown on page 25, nonair-entrained concrete beams had slightly higher initial pulse velocities than the air-entrained beams.

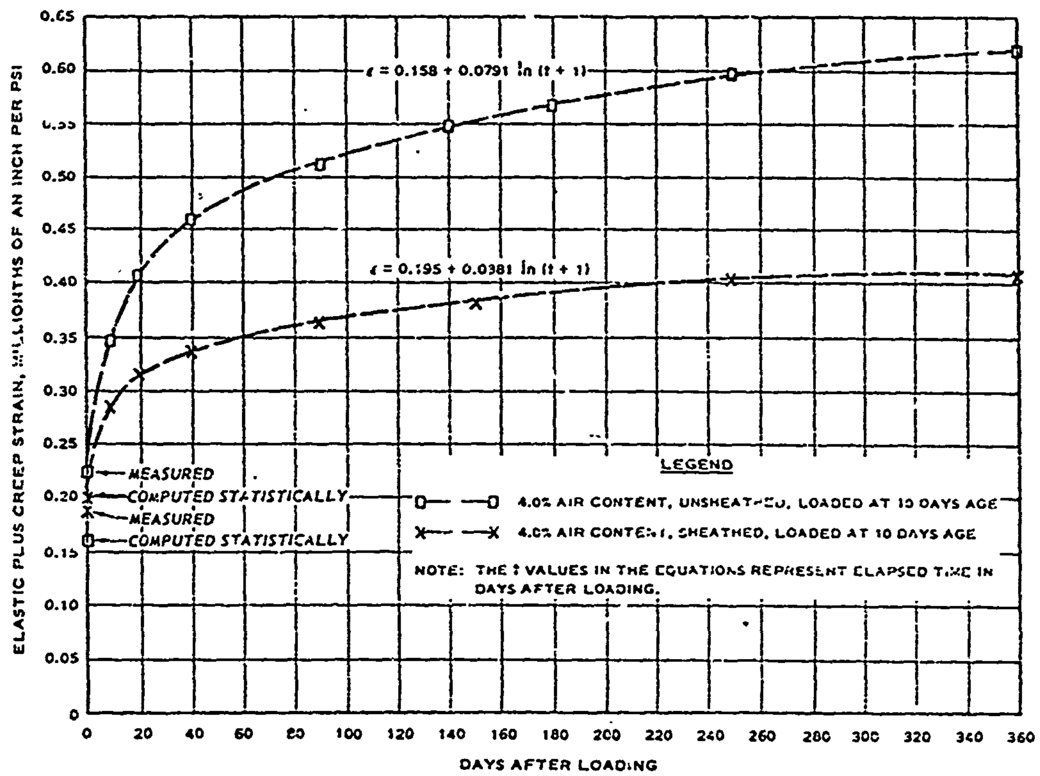


Fig. 11. Creep of air-entrained concrete, batch 2

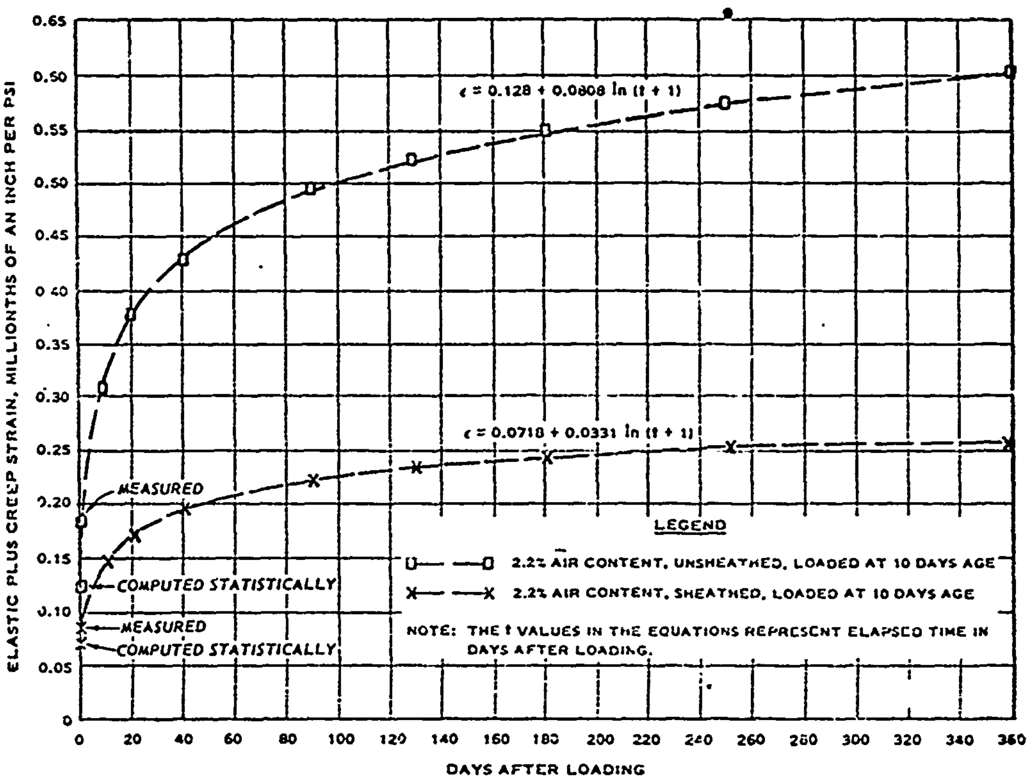


Fig. 12. Creep of nonair-entrained concrete, batch 16

No. Beams Tested	Type Beam	Water:Cement Ratio gal per bag	Pulse Velocity, fps
12	Air-entrained	5.85	Max 15,555 Min 14,965 Avg 15,225
4	Nonair-entrained	6.22	Max 15,590 Min 15,375 Avg 15,445

Field Exposure Tests

Resistance of the concrete beams and auxiliary specimens to natural weathering is being determined by means of exposure of the specimens at Corps of Engineers exposure stations located at Treat Island, Maine, and St. Augustine, Florida. At Treat Island the principal factor affecting durability is freezing-and-thawing; at St. Augustine it is sulfate attack.

Specimens exposed to sulfate attack

Three beams were installed at half-tide elevation at St. Augustine[5] in October 1959. Two of the beams were installed in a loaded condition (loaded to cracking, i.e. to 189% of prestress); the other beam was installed unloaded. The beams are inspected biennially, at which time length changes are determined using an external strain gage, and pulse velocity tests are conducted.

Specimens exposed to freezing-and-thawing

Seventy-two of the small concrete beams (three beams from each of 24 batches) were installed at Treat Island in October 1958. These beams are annually inspected and tested for fundamental flexural frequency. Test results obtained to date are given in table 12. No significant differences have been noted in the physical appearance of the small field exposure beams made from the two concretes. The average durability factor of the air-entrained concrete after four winters of exposure was 101, whereas that of the nonair-entrained concrete was 97. Therefore, it can be seen that the air-entrained concrete is exhibiting slightly more resistance to freezing-and-thawing than the nonair-entrained concrete. When more data are available, these field results will be compared with results of the laboratory freezing-and-thawing tests.

Sixteen large beams were installed at half-tide elevation at Treat Island in October 1958. Four were not loaded; the other 12 were loaded, six to 100% of prestress and six to 108% of prestress. The channels, springs, and rollers used on the loaded beams were painted to protect the metal from corrosion, and stainless steel rods and nuts were used. The embedded gage points were protected by stainless steel cones. The beams are inspected annually, at which time length changes are determined with an external strain gage, and pulse velocity tests are made using a soniscope. These pulse velocity readings are taken (one per beam) through the 81-in. dimension of the beam, and the square of the pulse velocity obtained at any time is expressed as a percentage of the initial pulse velocity squared. Results of the inspections, and of the length-change and velocity tests are given in table 13.

The 12 beams of air-entrained concrete have survived four winters of exposure at Treat Island; the 1962 condition of these beams ranged from "good" to "very good" (table 13). The four nonair-entrained beams failed structurally during the first winter of exposure; this failure occurred considerably earlier than had been expected.

The weekly condition of the nonair-entrained pretensioned beams during the winter of 1958-1959 until structural failure is given below:

	Yoked Pair Loaded to 108% of Prestress		Yoked Pair Loaded to 100% of Prestress	
Date	Beam 15	Beam 16	Beam 23	Beam 24
12 Dec 1958	Sound	Sound	Sound	Sound
19 Dec 1958	Slight scaling	Sound	Sound	Sound
26 Dec 1958	Slight scaling	Sound	Sound	Sound
2 Jan 1959	Failed	Sound	Sound	Failed
9 Jan 1959		Moderate spalling	Sound	
16 Jan 1959	*	Heavy spalling	Moderate spalling	**
23 Jan 1959	*	Failed	Moderate spalling	**
30 Jan 1959	*		Heavy spalling	**
6 Feb 1959	*		Heavy spalling	**
13 Feb 1959	*		Failed	**

* All steel wires exposed one-half of their length.
** All steel wires exposed one-fourth of their length.

The foregoing results indicate that even though one beam of each pair deteriorated and failed first, thereby releasing the third-point flexural load, the other beam continued to deteriorate until it failed also. Beams 15 and 24 failed simultaneously (week ending 2 Jan 1959). Beam 23, which had less initial pretensioning load than beam 16 (5662 lb per strand versus 5744 lb per strand), outlasted beam 16.

Paragraph 301(b) of the 1956 American Concrete Institute (ACI) Building Code[10] states "Concrete without air entrainment which will be exposed to the action of freezing weather shall have a water content not exceeding 6 gal per sack of cement." It will be noted that the nonair-entrained concrete used in this investigation had a water content of less than 6 gal per bag of cement.

Lin[2] wrote "Air entrainment of 3 to 5% improves workability and reduces bleeding. When well-recognized air-entraining agents are employed, there is no evidence of increased shrinkage or creep. Hence proper application of air entrainment is considered beneficial for prestressed concrete." The Bureau of Public Roads[6] stated that "any portland cement and aggregate may be used which is suitable for ordinary concrete" in prestressed concrete bridges. The ACI[1] recommendations list air-entraining portland cement among the types of acceptable portland cements, but fail to comment on when or whether air entrainment should be employed; no mention of air entrainment is contained in the paragraph on admixtures. This failure by the writers of authoritative guides to prestressed concrete construction practice to mention whether or not entrained air is needed in prestressed concrete exposed to weathering has apparently led some to conclude that entrained air is not needed in prestressed concrete. This opinion was expressed during the discussion of an unpublished paper presented at the 1960 ACI convention in New York.

Most authorities, however, believe that air entrainment is necessary in prestressed concrete exposed to freezing-and-thawing. Based on laboratory tests, Klieger[7] concluded: "All concretes require intentionally entrained air to provide a high degree of resistance to freezing and thawing and de-icer scaling." In a discussion of a paper by Gutzwiller and Musleh,[8] Kunze[9] stated: "For most concretes used in prestressing, air content of 5 ± 1% is required to assure a high degree of resistance to freezing and thawing, along with low water-cement ratio and adequate curing."

The results of the field exposure tests reported herein appear to provide conclusive evidence that properly entrained air is necessary to provide resistance in saturated prestressed members to severe freezing-and-thawing. These results confirm the wisdom of the new requirement of ~~proposed change in~~ the 1963 ACI Building Code[11] ~~to require~~ that "Concrete that is to ~~which will~~ be subject ~~exposed~~ to ~~the action of~~ freezing temperatures while wet ~~weather~~...shall contain entrained air," (Section 501(c)).

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Directors of the Waterways Experiment Station during this investigation were Col. A. P. Rollins, Jr., CE, Col. Edmund H. Lang, CE, and Col. Alex G. Sutton, Jr., CE. Technical Director was Mr. J. B. Tiffany.

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11. ________, "ACI standard ~~Proposed revision of~~ building code requirements for reinforced concrete (ACI 318-63)." American Concrete Institute Proceedings, vol 60 (1963), pp ~~[illegible]~~ 809-815; issued as a separate publication, 144 pp.; and in 1963 ACI Book of Standards.

Table 1

Physical Properties and Grading of Crushed Limestone Aggregates

Test	Fine Aggregate	Coarse Aggregate
Physical Properties		
Bulk specific gravity, saturated surface dry	2.66	2.70
Absorption, %	1.2	0.7
Soundness, $MgSO_4$, % loss	10.0	2.4
Los Angeles abrasion, % loss	--	23.6
Mortar strength, %		
3-day	163	--
7-day	158	--
Percent Passing Standard Sieves		
Sieve:		
1-in.		100
3/4-in.		99
1/2-in.		55
3/8-in.		31
No. 4	100	4
No. 8	92	
No. 6	62	
No. 30	36	
No. 50	19	
No. 100	9	
Fineness modulus	2.82	

Table 2

Properties of Steel Pretensioning Strands

Property	Description or Value
Type of strand*	Stress-relieved 7-wire strand
Nominal strand diameter*	1/4 in.
Strand construction*	1 by 7
Approximate weight per 1000 ft*	121 lb
Cross-section area*	0.0352 sq in.
Minimum ultimate tensile strength*	238,000 psi
Approximate yield strength* (as determined by 0.7% elongation)	67% of ultimate strength
Ultimate tensile load and strength:	
Manufacturer**	10,300 lb (292,615 psi)
WES†	9,600 lb (272,725 psi)
Elongation (in 24-in. lengths)**	7.92% (at ultimate load)
Strain at stress of 166,600 psi††	0.00626 in. per in.
Modulus of elasticity:	
Manufacturer††	26.6×10^6 psi
WES†	23.7×10^6 psi
Relaxation††	6.7% loss in 1000 hr (at stress of 166,600 psi)

* Taken from table in reference 2.

** From manufacturer's report.

† As determined by Waterways Experiment Station on three strands, each about 5 ft long.

†† Interpolated from curve for 1/4-in. strand furnished by manufacturer.

Table 3

Concrete Mixture Data*

Batch No.**	Type Concrete	Theoretical Unit Weight lb/cu ft	Cement Factor bags/cu yd	Water: Cement Ratio gal/bag	Sand: Aggregate Ratio, %	Air Content %	Slump in.	Bleeding, %	Ball Penetration, in.	Temperature, °F: Concrete Laboratory	Concrete Casting Bed	Air Laboratory	Air Casting Bed
A	Air	146.9	6.34	5.64	41	4.0	1-1/2	1.0	1-1/2 to 1-3/4	83	--	82	--
B	Air	146.9	6.34	5.64	41	4.0	1-1/4	1.2	1-1/4 to 1-1/2	84	--	83	--
C	Nonair	148.5	5.97	6.22	45	2.2	1-1/2	1.1	1-1/4 to 1-1/2	84	--	84	--
D	Nonair	149.3	5.97	6.22	45	2.1	1-1/4	1.3	1-1/4 to 1-1/2	85	--	84	--
1	Air	144.9	6.04	5.85	45	4.2	2	1.5	1-1/4 to 1-1/4	84	--	84	--
2	Air	145.3	6.05	5.85	45	4.0	1-3/4	1.5	1-1/4 to 1-1/4	84	--	83	--
3	Air	145.3	6.04	5.85	45	4.2	1-3/4	1.4	1-1/4 to 1-1/4	86	--	87	--
4	Air	145.5	6.05	5.85	45	4.0	1-3/4	1.5	1-1/4 to 1-1/4	86	--	86	--
5	Air	144.9	6.01	5.85	45	4.6	1-3/4	1.0	1-1/4 to 1-1/2	84	--	83	--
6	Air	145.7	6.03	5.85	45	4.3	1-3/4	1.1	1-1/4 to 1	84	85	84	80
7	Air	145.3	6.02	5.85	45	4.5	1-3/4	1.1	1-1/2 to 1-1/4	87	86	85	87
8	Air	145.5	6.01	5.85	45	4.6	1-1/4	1.3	1-1/4 to 1	87	86	86	88
9	Air	145.3	6.00	5.85	45	4.7	1-1/2	0.7	1-1/4 to 1	88	86	87	85
10	Air	145.5	6.00	5.85	45	4.7	1-3/4	1.0	1-1/2 to 1-1/4	88	87	87	85
11	Air	144.9	5.99	5.85	45	4.9	2	1.1	1-1/2 to 1-1/2	89	--	85	--
12	Air	145.1	5.99	5.85	45	4.9	2	1.2	1-1/2 to 1	88	89	86	88
13	Air	145.3	6.00	5.85	45	4.7	1-3/4	1.0	1-1/4 to 1-1/4	87	90	86	89
14	Air	145.3	6.00	5.85	45	4.7	1-1/4	1.0	1-1/4 to 1	87	88	86	89
15	Nonair	148.5	5.95	6.22	49	2.4	1-1/2	0.9	1-1/2 to 1-1/4	88	88	86	86
16	Nonair	148.7	5.97	6.22	49	2.2	1-1/2	1.0	1-1/4 to 1	88	87	87	88
17	Air	144.9	6.00	5.85	45	4.8	1-1/2	0.7	1-1/2 to 1-1/2	90	88	88	92
18	Air	145.1	6.00	5.85	45	4.8	1-1/2	0.6	1-1/2 to 1-1/2	90	88	88	92
19	Air	144.9	6.00	5.85	45	4.8	2	1.0	1-3/4 to 1-1/2	80	82	78	80
20	Air	145.7	6.03	5.85	45	4.3	1-3/4	0.9	1-1/2 to 1	81	84	79	80
21	Air	146.1	6.04	5.85	45	4.2	1-1/2	0.8	1-3/4 to 1-3/4	81	83	79	82
22	Air	144.9	6.00	5.85	45	4.8	1-1/2	1.1	1-3/4 to 1-1/2	80	83	79	80
23	Nonair	148.7	5.97	6.22	49	2.1	1-1/2	1.4	1-1/4 to 1-1/4	80	83	79	84
24	Nonair	148.7	5.96	6.22	49	2.3	1-1/2	1.3	1-1/4 to 1-1/4	82	84	79	82

* The following test methods (reference 3) were used in making these determinations: unit weight, CRD-C 7-57; air content, CRD-C 8-55; slump, CRD-C 5-57; bleeding, CRD-C 9-51; ball penetration, CRD-C 46-57.

** Batch numbers are also the numbers of the large beams made from that batch.

Table 4

Test Data, Concrete Beams*

Beam No.	Type Con-crete	Water:Cement Ratio gal/bag	Casting Date 1958	Average (of 9 Strands) Tension Load on Strand, lb	Percent of Ultimate Tensile Strength of Strand	Camber (Avg of 2 Readings) at Center of Beam, in.	Sink-in of Strands (Avg of 3 Read-ings), in.
A	Air	5.64	26 May	5928	70.8	--	---
B	Air	5.64	26 May	5928	70.8	--	---
C	Nonair	6.22	26 May	5928	70.8	--	---
D	Nonair	6.22	26 May	5928	70.8	--	---
1	Air	5.85	30 June	106	1.3	--	---
2	Air	5.85	30 June	106	1.3	--	---
3	Air	5.85	30 June	106	1.3	--	---
4	Air	5.85	30 June	106	1.3	--	---
5	Air	5.85	14 July	5791	69.1	0.0055	0.012
6	Air	5.85	14 July	5791	69.1	0.0193	0.014
7	Air	5.85	14 July	5791	69.1	0.0148	0.014
8	Air	5.85	14 July	5791	69.1	0.0474	0.021
9	Air	5.85	14 July	5791	69.1	0.0221	0.021
10	Air	5.85	14 July	5791	69.1	0.0192	0.024
11	Air	5.85	28 July	5786	69.1	0.0316	0.011
12	Air	5.85	28 July	5786	69.1	0.0114	0.022
13	Air	5.85	28 July	5786	69.1	0.0238	0.014
14	Air	5.85	28 July	5786	69.1	0.0028	0.016
15	Nonair	6.22	11 Aug	5744	68.6	0.0250	0.021
16	Nonair	6.22	11 Aug	5744	68.6	0.0200	0.032
17	Air	5.85	11 Aug	5744	68.6	0.0034	0.026
18	Air	5.85	11 Aug	5744	68.6	0.0126	0.022
19	Air	5.85	26 Aug	5662	67.6	0.0125	0.022
20	Air	5.85	26 Aug	5662	67.6	0.0322	0.017
21	Air	5.85	26 Aug	5662	67.6	0.0227	0.024
22	Air	5.85	26 Aug	5662	67.6	0.0031	0.026
23	Nonair	6.22	26 Aug	5662	67.6	0.0138	0.019
24	Nonair	6.22	26 Aug	5662	67.6	0.0304	0.019

* These determinations were made outdoors on the casting bed.

Table 5

Types of Tests Conducted on, and Disposition of Beams

Beam No.*	Water: Cement Ratio gal/bag	Pretensioned to 70% of Ultimate Strand Strength	Laboratory Tests			Field Exposure Tests	
			Midspan Deflection Flexural Loading	Length and Volume Change	Flexural Loading to Destruction	Location	Condition
			Air-Entrained				
A	5.64	Yes	No	No	Yes		
B	5.64	Yes	No	No	Yes		
1	5.85	No	No	Yes	Yes		
2	5.85	No	No	Yes	No	**	
3	5.85	No	No	No	No	Maine	Unloaded
4	5.85	No	No	No	No	Maine	Unloaded
5	5.85	Yes	No	Yes	Yes		
6	5.85	Yes	No	Yes	No	Florida	Unloaded
7	5.85	Yes	No	No	No	Maine	Unloaded
8	5.85	Yes	No	No	No	Maine	Unloaded
9	5.85	Yes	Yes	Yes	Yes		
10	5.85	Yes	Yes	Yes	No	Florida	Loaded, 189% of prestress
11	5.85	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
12	5.85	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
13	5.85	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
14	5.85	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
17	5.85	Yes	Yes	Yes	Yes		
18	5.85	Yes	Yes	Yes	No	Florida	Loaded, 189% of prestress
19	5.85	Yes	Yes	No	No	Maine	Loaded, 100% of prestress
20	5.85	Yes	Yes	No	No	Maine	Loaded, 100% of prestress
21	5.85	Yes	Yes	No	No	Maine	Loaded, 100% of prestress
22	5.85	Yes	Yes	No	No	Maine	Loaded, 100% of prestress
			Nonair-Entrained				
C	6.22	Yes	Yes	No	Yes		
D	6.22	Yes	Yes	No	Yes		
15	6.22	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
16	6.22	Yes	Yes	No	No	Maine	Loaded, 108% of prestress
23	6.22	Yes	Yes	No	No	Maine	Loaded, 100% of prestress
24	6.22	Yes	Yes	No	No	Maine	Loaded, 100% of prestress

* The beam numbers of these beams are also their batch numbers.

** This beam was retained in the laboratory for continuation of length-change tests; see fig. 8.

Table 6

Results of Flexural Loading Tests on Concrete Beams

Beam No.	Type Concrete	Water:Cement Ratio gal/bag	Pretensioned to 70% of Ultimate Strand Strength		Flexural Load Tests: Age at Loading Days	Flexural Load Tests: Load Each End, lb (Nominal)	Flexural Load Tests: Loading % of Prestress	Flexural Load Tests: Avg Fiber Strain (External Gage)* in. per in. × 10⁴ Compression Side	Flexural Load Tests: Avg Fiber Strain (External Gage)* in. per in. × 10⁴ Tension Side	Flexural Load Tests: Avg Outer Fiber Strain (Resistance-Wire Gage)* in. per in. × 10⁴	Flexural Load Tests: Avg Midspan Deflection* in.	Flexural Load Tests to Destruction: Age at Destruction Test Days	Flexural Load Tests to Destruction: Ultimate Load Each End, lb	Flexural Load Tests to Destruction: Avg Midspan Deflection* in.	Flexural Load Tests to Destruction: Loading % of Prestress	First Cracks Appeared at: Load Each End, lb	First Cracks Appeared at: % of Prestress
A	Air	5.64	Yes		--	---	---	---	---	--	--	115	14,935	0.0536 at 8700 lb	256	--	---
B	Air	5.64	Yes		--	---	---	---	---	--	--	120	14,355	0.0484 at 5800 lb	246	--	---
C	Nonair	6.22	Yes	Yoked	84	5,833	100	-2.9	+3.0	--	0.0559	113	16,240	---	278	9,135	157
D	Nonair	6.22	Yes	pair	84	5,833	100	-3.4	+3.1	--	0.0517	106	13,775	---	236	10,150	174
1	Air	5.85	No		--	---	---	---	---	--	--	366	2,320**	0.0087 at 2030 lb	40	--	---
5	Air	5.85	Yes		--	---	---	---	---	--	--	380	13,920	0.0503 at 5800 lb	239	11,600	199
9	Air	5.85	Yes	Yoked pair	45	6,319	108	-3.6	+3.9	+5.16	0.0720	381	14,500	0.1102 at 8700 lb	249	10,150	174
10	Air	5.85	Yes		45	6,319	108	-3.8	+4.4	+5.21	0.0618	---	--	---	---	--	---
11	Air	5.85	Yes	Yoked	45	6,319	108	-3.9	+3.4	--	0.0642	---	--	---	---	--	---
12	Air	5.85	Yes	pair	45	6,319	108	-4.0	+3.9	--	0.0628	---	--	---	---	--	---
13	Air	5.85	Yes	Yoked	45	6,319	108	-3.8	+3.8	--	0.0712	---	--	---	---	--	---
14	Air	5.85	Yes	pair	45	6,319	108	-3.8	+3.2	--	0.0460	---	--	---	---	--	---
15	Nonair	6.22	Yes	Yoked	45	6,319	108	-3.6	+3.0	--	0.0649	---	--	---	---	--	---
16	Nonair	6.22	Yes	pair	45	6,319	108	-3.5	+3.3	--	0.0642	---	--	---	---	--	---
17	Air	5.85	Yes	Yoked pair	35	5,833	100	-3.8	+3.6	+4.62	0.0194	355	13,630	0.0404 at 8700 lb	234	10,875	186
18	Air	5.85	Yes		35	5,833	100	-4.1	+3.5	+4.75	0.0535	---	--	---	---	--	---
19	Air	5.85	Yes	Yoked	35	5,833	100	-4.0	+3.4	--	0.0458	---	--	---	---	--	---
20	Air	5.85	Yes	pair	35	5,833	100	-3.6	+3.8	--	0.0555	---	--	---	---	--	---
21	Air	5.85	Yes	Yoked	35	5,833	100	-2.8	+2.8	--	0.0534	---	--	---	---	--	---
22	Air	5.85	Yes	pair	35	5,833	100	-3.0	+3.0	--	0.0361	---	--	---	---	--	---
23	Nonair	6.22	Yes	Yoked	35	5,833	100	-3.0	+2.8	--	0.0640	---	--	---	---	--	---
24	Nonair	6.22	Yes	pair	35	5,833	100	-3.4	+3.0	--	0.0578	---	--	---	---	--	---
10	Air		†	Yoked	473	11,020	189	-7.6	+16.2	+16.78	--	---	--	---	---	--	---
18	Air		†	pair	501	11,020	189	-8.0	+12.0	+16.78	--	---	--	---	---	--	---

* Average of two readings.

** This beam was load-tested to destruction with its prestressing strands on the compression side. All other beams were load-tested with the strands on the tension side.

† Second loading; beams 10 and 18 were yoked and loaded at St. Augustine, Fla., until cracks appeared. This loading took place after tests to destruction of beams 9 and 17 with which these beams were originally yoked.

Table 7

Flexural Strength Determinations

Batch No.	Type Concrete	Water:Cement Ratio gal/bag	Flexural Strength,* psi, at 3 Days Age	7 Days Age	28 Days Age	35 Days Age	45 Days Age	91 Days Age	1-Yr Age
1	Air	5.85	925	1065	1180	--	--	900	1060
2	Air	5.85	925	1025	1185	--	--	1050	940
3	Air	5.85	865	1095	1145	--	--	1050	1075
4	Air	5.85	955	920	1155	--	--	1035	905
5	Air	5.85	995	1040	1290	--	--	1100	770
6	Air	5.85	960	--	1185	--	--	980	955
7	Air	5.85	810	1065	1240	--	--	1135	1010
8	Air	5.85	1015	1085	1075	--	--	1005	895
9	Air	5.85	1000	965	1155	--	--	1095	765
10	Air	5.85	940	1000	1110	--	1150	1155	--
11	Air	5.85	920	995	1225	--	1160	1050	--
12	Air	5.85	880	995	1000	--	1120	860	--
13	Air	5.85	890	1055	1120	--	1200	910	--
14	Air	5.85	845	895	1110	--	1055	885	--
15	Nonair	6.22	970	1025	1005	--	830	860	--
16	Nonair	6.22	840	1120	1085	--	920	830	--
17	Air	5.85	780	1020	1055	--	--	980	1175
18	Air	5.85	780	945	955	1140	--	830	--
19	Air	5.85	920	1110	960	890	--	995	--
20	Air	5.85	920	1065	970	870	--	850	--
21	Air	5.85	875	990	960	800	--	1025	--
22	Air	5.85	770	890	1015	880	--	960	--
23	Nonair	6.22	935	920	1055	1150	--	960	--
24	Nonair	6.22	900	940	1045	860	--	1000	--

* Flexural strength determined on one 3-1/2- by 4-1/2- by 16-in. beam from each batch, using Method CRD-C 17-58 (using simple beam with center-point loading, reference 3).

Table 8

Results of Laboratory Tests of Length Change in Outer Fiber of Pretensioned Concrete Beams of Air-Entrained Concrete

Beam No.	Outer Fiber Length Change,* % at 45 Days Age	52 Days Age	67 Days Age	87 Days Age	119 Days Age	150 Days Age	163 Days Age	214 Days Age	247 Days Age	277 Days Age	310 Days Age	344 Days Age	381 Days Age	Disposition of Beams After Length-Change Tests
							Loaded 100%, Tension Side**							
9	±0.0000	+0.0070	+0.0060	+0.0130	+0.0148	+0.0160	+0.0135	+0.0120	+0.0108	+0.0088	+0.0095	+0.0132	+0.0152	Loaded to destruction
10	±0.0000	+0.0038	+0.0070	+0.0120	+0.0132	+0.0148	+0.0120	+0.0105	+0.0098	+0.0075	+0.0072	+0.0092	+0.0088	Transported to St. Augustine, Fla.

Beam No.	35 Days Age	39 Days Age	59 Days Age	91 Days Age	122 Days Age	155 Days Age	186 Days Age	219 Days Age	249 Days Age	282 Days Age	316 Days Age	365 Days Age	Disposition of Beams After Length-Change Tests
							Loaded 100%, Neutral Side**						
17†	±0.0000	+0.0025	+0.0050	+0.0070	+0.0070	+0.001[illegible]	±0.0000	-0.0010	-0.0045	-0.0055	+0.0020	+0.0096	Loaded to destruction
18	±0.0000	-0.0022	-0.0055	+0.0018	+0.0015	-0.0028	-0.0052	-0.0062	-0.0100	-0.0115	-0.0077	-0.0102	Transported to St. Augustine, Fla.

* Average of two readings taken with resistance-wire strain gages mounted on outer fiber of beam. Plus sign indicates expansion; minus sign indicates shrinkage.
** Tension side: side of beam which is in tension. Neutral side: side of beam which is in neither tension nor compression.
† Average of one strain gage only.

Table 9

Results of Laboratory Deflection Tests of Pretensioned Concrete Beams of Air-Entrained Concrete

Beam No.	Condition of Loading	Average Change in Beam Deflection After Flexural Loading,* in. 39 Days Age	59 Days Age	91 Days Age	122 Days Age	155 Days Age	186 Days Age	219 Days Age	249 Days Age	282 Days Age	316 Days Age	365 Days Age	Disposition of Beams After Length-Change Tests
9 or 10, Yoked pair	Loaded 100%	±0.0000	+0.0003	+0.0005	+0.0010	+0.0009	+0.0010	+0.0012	+0.0013	+0.0013	+0.0012		Unloaded for other tests
17 or 18, Yoked pair	Loaded 100%	±0.0000	+0.0007	+0.0011	+0.0014	+0.0013	+0.0014	+0.0016	+0.0015	+0.0017	+0.0020	+0.0022	Unloaded for other tests

* Average of two readings. The readings were taken at beam midspan with dial gages, one on each side of a yoked pair. The average readings therefore indicate the deflection change of two beams, and when divided by 2 gave the changes given above. Plus sign indicates increase in beam deflection.

Table 10

Compressive Strength and Static Modulus of Elasticity of Concrete Cylinders at Various Ages

Compressive Strength,* psi, and Static Modulus of Elasticity** x 10^{-6}, psi, at

Batch No.	3 Days Age		7 Days Age		28 Days Age		35 Days Age		45 Days Age		91 Days Age	
	Comp	Static E	Comp	Static E	Comp	Static E	Comp	Static E	Comp	Static E	Comp	Static E
Air-Entrained Concrete, w:c 5.64												
A	3570	--	5110	--	7140	4.71	--	--	--	--	7300	4.90
B	3520	3.60	4460	4.29	6890	4.65	--	--	--	--	7000	4.95
Nonair-Entrained Concrete, w:c 6.22												
C	3640	--	5410	--	7290	4.81	--	--	--	--	6930	4.90
D	3710	3.75	4440	4.62	7070	4.92	--	--	--	--	6870	4.50
15	3540	4.19	4290	4.29	5520	4.37	--	--	6040	5.39	6360	5.23
16	3660	3.87	4140	4.28	5430	4.18	--	--	6360	5.01	6570	5.22
23	3070	3.55	4210	4.16	6290	5.20	6640	5.36	--	--	7220	5.57
24	3340	3.52	4360	4.09	6700	5.31	6540	5.11	--	--	6960	5.29
Air-Entrained Concrete, w:c 5.85												
1	3790	3.84	4950	4.03	6570	4.59	--	--	--	--	7150	5.05
2	3290	3.57	4980	4.15	5230	4.39	--	--	--	--	6520	5.40
3	3270	3.59	4070	4.16	5340	4.23	--	--	--	--	5710	4.90
4	3250	3.82	4140	4.02	5480	5.00	--	--	--	--	6230	5.15
5	4290	4.24	4910	4.34	5580	4.34	--	--	--	--	7180	5.29
6	4390	3.85	4110	4.41	5710	4.62	--	--	--	--	6650	5.59
7	3750	3.94	4790	4.37	5820	4.58	--	--	--	--	6760	5.25
8	3890	3.82	4910	4.31	6430	4.41	--	--	--	--	7050	5.68
9	3960	4.00	4430	4.30	6320	4.55	--	--	--	--	7250	5.81
10	3800	4.17	4440	4.26	5850	4.25	--	--	6390	4.75	6960	5.41
11	3500	3.78	4390	4.02	5540	4.65	--	--	5570	4.30	6640	5.23
12	3430	3.66	4100	3.94	5790	4.25	--	--	6210	4.15	6960	5.26
13	3700	3.81	3930	3.79	5090	4.30	--	--	5500	4.49	5750	4.99
14	3610	4.13	4430	4.29	5710	4.45	--	--	5480	4.44	6340	5.59
17	3300	3.47	4070	3.96	4830	4.19	--	--	--	--	6860	5.26
18	3320	3.83	4180	4.00	4820	4.45	5040	4.39	--	--	6210	5.13
19	3070	3.56	4230	4.01	5300	4.95	5640	5.00	--	--	6250	5.32
20	2990	3.75	4250	4.01	5360	4.89	6020	4.71	--	--	6250	5.08
21	3010	3.63	4110	4.05	5930	5.06	6070	5.08	--	--	6610	5.94
22	3160	3.92	4210	4.09	5660	5.00	5570	5.08	--	--	6540	5.34

Batch No.	106 Days Age		113 Days Age		115 Days Age		130 Days Age		1 Year Age	
	Comp	Static E	Comp	Static E	Comp	Static E	Comp	Static E	Comp	Static E
Air-Entrained Concrete, w:c 5.64										
A	--	--	--	--	5960	5.31	--	--	--	--
B	--	--	--	--	--	--	6700	5.71	--	--
Nonair-Entrained Concrete, w:c 6.22										
C	--	--	6930	5.25	--	--	--	--	--	--
D	6870	4.62	--	--	--	--	--	--	--	--
Air-Entrained Concrete, w:c 5.85										
1	--	--	--	--	--	--	--	--	6460	5.71
2	--	--	--	--	--	--	--	--	6960	5.57
3	--	--	--	--	--	--	--	--	6350	5.29
4	--	--	--	--	--	--	--	--	6700	5.73
5	--	--	--	--	--	--	--	--	7460	5.71
6	--	--	--	--	--	--	--	--	7120	5.71
7	--	--	--	--	--	--	--	--	7290	4.93
8	--	--	--	--	--	--	--	--	7650	5.22
9	--	--	--	--	--	--	--	--	7370	5.45
17	--	--	--	--	--	--	--	--	5910	5.45

* Compressive strength determined on one 6- by 12-in. cylinder at each age (Test Method CRD-C 14-57).

** Modulus determined on one 6- by 12-in. cylinder at each age. This modulus is the chord between 250 and 1000 psi (Test Method CRD-C 19-55).

Table 11

Results of Determinations of Young's Dynamic Modulus of Elasticity, Dynamic Modulus of Rigidity, and Poisson's Ratio

Batch No.	Type Concrete	Water: Cement Ratio gal/bag	Dynamic Modulus of Elasticity, E × 10^{-6} psi at 3 Days Age	7 Days Age	28 Days Age	35 Days Age	45 Days Age	91 Days Age	1-Yr Age	Dynamic Modulus of Rigidity, G × 10^{-6} psi, at 3 Days Age	7 Days Age	28 Days Age	35 Days Age	45 Days Age	91 Days Age	1-Yr Age	Poisson's Ratio, μ, at 3 Days Age	7 Days Age	28 Days Age	35 Days Age	45 Days Age	91 Days Age	1-Yr Age
1	Air	5.85	5.05	5.51	6.19	--	--	6.59	6.73	2.08	2.26	2.37	--	--	2.54	2.57	0.21	0.22	0.31	--	--	0.30	0.31
2	Air	5.85	5.14	5.57	6.41	--	--	6.67	6.56	2.09	2.32	2.43	--	--	2.54	2.51	0.23	0.20	0.32	--	--	0.26	0.31
3	Air	5.85	5.12	5.45	6.17	--	--	6.60	6.73	2.09	2.33	2.48	--	--	2.60	2.64	0.22	0.22	0.24	--	--	0.27	0.27
4	Air	5.85	5.12	5.86	6.26	--	--	6.69	6.87	2.08	2.37	2.55	--	--	2.68	2.62	0.23	0.24	0.23	--	--	0.25	0.31
5	Air	5.85	5.29	5.77	6.09	--	--	6.81	6.82	2.13	2.32	2.60	--	--	2.63	2.84	0.24	0.24	0.17	--	--	0.29	0.20
6	Air	5.85	5.31	4.62*	5.90	--	--	6.45	6.72	2.18	1.87*	2.55	--	--	2.69	2.82	0.22	0.24*	0.16	--	--	0.20	0.19
7	Air	5.85	5.00	5.47	5.90	--	--	6.30	6.79	1.99	2.20	2.46	--	--	2.59	2.69	0.26	0.24	0.20	--	--	0.22	0.26
8	Air	5.85	5.47	5.58	6.21	--	--	6.61	6.56	2.24	2.35	2.70	--	--	2.56	2.68	0.22	0.19	0.15	--	--	0.30	0.22
9	Air	5.85	5.15	5.65	5.95	--	--	6.36	6.78	2.05	2.30	2.55	--	--	2.55	2.65	0.26	0.23	0.17	--	--	0.25	0.22
10	Air	5.85	5.03	5.66	5.86	--	5.86	6.65	--	2.00	2.24	2.57	--	2.47	2.66	--	0.26	0.26	0.14	--	0.19	0.25	--
11	Air	5.85	5.17	5.28	5.93	--	5.94	6.57	--	2.06	2.11	2.38	--	2.47	2.58	--	0.25	0.25	0.25	--	0.20	0.27	--
12	Air	5.85	4.89	5.24	5.86	--	5.93	6.47	--	1.95	2.14	2.48	--	2.39	2.73	--	0.25	0.22	0.18	--	0.24	0.18	--
13	Air	5.85	5.01	5.37	5.79	--	5.82	6.36	--	2.00	2.20	2.37	--	2.33	2.53	--	0.25	0.22	0.22	--	0.22	0.27	--
14	Air	5.85	5.14	5.52	5.97	--	5.97	6.51	--	2.02	2.25	2.44	--	2.41	2.65	--	0.27	0.23	0.22	--	0.24	0.23	--
15	Nonair	6.22	5.31	5.78	6.59	--	6.62	7.05	--	2.05	2.44	2.54	--	2.60	2.82	--	0.30	0.18	0.30	--	0.27	0.25	--
16	Nonair	6.22	5.36	5.54	6.46	--	6.72	6.87	--	2.11	2.29	2.53	--	2.66	2.82	--	0.27	0.21	0.28	--	0.26	0.22	--
17	Air	5.85	5.22	5.52	6.05	--	--	6.31	6.91	2.13	2.22	2.34	--	--	2.49	2.69	0.20	0.24	0.29	--	--	0.27	0.22
18	Air	5.85	5.14	5.45	6.33	5.96	--	6.62	--	2.12	2.31	2.50	2.53	--	2.68	--	0.21	0.18	0.27	0.18	--	0.24	--
19	Air	5.85	5.14	5.43	6.39	5.55	--	6.46	--	2.22	2.36	2.49	2.59	--	2.60	--	0.16	0.15	0.28	0.26	--	0.24	--
20	Air	5.85	5.10	5.55	6.15	6.37	--	6.82	--	2.13	2.41	2.40	2.49	--	2.70	--	0.20	0.15	0.28	0.28	--	0.26	--
21	Air	5.85	5.11	5.52	6.26	6.50	--	7.27	--	2.13	2.30	2.42	2.55	--	2.65	--	0.20	0.20	0.29	0.27	--	0.37	--
22	Air	5.85	5.36	5.40	6.34	6.40	--	6.73	--	2.16	2.26	2.53	2.58	--	2.76	--	0.24	0.19	0.25	0.24	--	0.22	--
23	Nonair	6.22	5.21	5.78	6.84	6.89	--	7.23	--	2.25	2.44	2.69	2.70	--	2.69	--	0.16	0.18	0.28	0.28	--	0.34	--
24	Nonair	6.22	5.50	5.66	6.48	6.34	--	6.77	--	2.29	2.42	2.53	2.47	--	2.55	--	0.20	0.17	0.28	0.28	--	0.33	--

* This beam was badly honeycombed.

Table 12

Results of Freezing-and-Thawing Tests on Small Beams

Batch No.	Type Concrete	Water: Cement Ratio gal/bag	Laboratory Tests* Avg DFE** at 0 Cycles	Laboratory Tests* Avg DFE** at 300 Cycles	Field Tests* Avg DFE** at 0 Cycles	Field Tests* Avg DFE** at 150 Cycles	Field Tests* Avg DFE** at 221 Cycles	Field Tests* Avg DFE** at 362 Cycles	Field Tests* Avg DFE** at 451 Cycles	Field Tests* 1959 Avg Condition	Field Tests* 1960 Avg Condition	Field Tests* 1961 Avg Condition	Field Tests* 1962 Avg Condition
1	Air	5.85	100	92	100	106	105	99	103	Sound	Sound	Sound	Sound
2	Air	5.85	100	89	100	107	104	98	101	Sound	Sound	Sound	Sound
3	Air	5.85	100	64	100	107	104	98	102	Sound	Sound	Sound	Sound
4	Air	5.85	100	86	100	106	104	98	101	Sound	Sound	Sound	Sound
5	Air	5.85	100	91	100	107†	105	99	102	Sound	Sound	Sound	Sound
6	Air	5.85	100	86	100	106†	103	98	100	Sound	Sound	Sound	Sound
7	Air	5.85	100	89	100	106	101	93	94	Sound	Sound	Sound	Sound
8	Air	5.85	100	84	100	103	101	95	97	Sound	Sound	Sound	Sound
9	Air	5.85	100	89	100	107	104	97	102	Sound	Sound	Sound	Sound
10	Air	5.85	100	95	100	107	105	98	101	Sound	Sound	Sound	Sound
11	Air	5.85	100	88	100	107	105	99	101	Sound	Sound	Sound	Sound
12	Air	5.85	100	93	100	107	104	98	101	Sound	Sound	Sound	Sound
13	Air	5.85	100	93	100	107	104	97	100	Sound	Sound	Mod sp††	Hy sp‡
14	Air	5.85	100	90	100	107	105	99	102	Sound	Sl sp‡‡	Mod sp	Hy sp
15	Nonair	6.22	100	4§	100	105	104	98	100	Sound	Sound	Mod sp	Mod sp
16	Nonair	6.22	100	3§	100	105	104	96	97	Sound	Sl sp	Mod sp	Mod sp
17	Air	5.85	100	91	100	107	105	99	103	Sound	Sound	Sl sp	Mod sp
18	Air	5.85	100	70	100	107	106	100	103	Sound	Sound	Sound	Sl sp
19	Air	5.85	100	91	100	105	103	97	100	Sound	Sound	Sl sp	Sl sp
20	Air	5.85	100	91	100	107	105	99	103	Sound	Sound	Sl sp	Sl sp
21	Air	5.85	100	87	100	105	103	98	101	Sound	Sound	Hy sp	Hy sp
22	Air	5.85	100	89	100	104	102	97	101	Sound	Sound	Mod sp	Mod sp
23	Nonair	6.22	100	5§	100	107	106	93	95	Sound	Sound	Sound	Sl sp
24	Nonair	6.22	100	5§	100	106	103	97	97	Sound	Sl sp	Sl sp	Sl sp

* Each DFE value given is the average of the DFE's of three beams made from the same batch of concrete; the readings and calculations were performed in accordance with Test Method CRD-C 20-55 for the laboratory specimens and Test Method CRD-C 18-55 for the field specimens (reference 3).

** Durability factor of elasticity (reference 3).

† Average of two beams only; the third beam in this set was lost overboard.

†† Moderate spalling.

‡ Heavy spalling.

‡‡ Slight spalling.

§ Failed.

Table 13

Results of Field Exposure Tests of Concrete Beams, Treat Island Exposure Station

(All Beams Installed in October 1958)

Beam No.	Type Concrete	Water: Cement Ratio gal/bag	Pretensioned to 70% of Ultimate Strand Strength	Condition of Loading	Pulse Velocity fps (1958)	% V^2 (1958)	% V^2 (1959)	Length Change, %: Compression Side* (1959)	Length Change, %: Tension Side* (1959)	Length Change, %: Neutral Side* (1959)	Condition (1959)	% V^2 (1960)	Length Change, %: Compression Side* (1960)	Length Change, %: Tension Side* (1960)	Length Change, %: Neutral Side (1960)	Condition (1960)
3	Air	5.85	No	Unloaded	15,100	100	106	+0.014	+0.018	--	Very good	108	+0.005	+0.012	--	Good
4	Air	5.85	No	Unloaded	15,235	100	106	+0.009	+0.008	--	Very good	107	+0.004	+0.010	--	Very good
7	Air	5.85	Yes	Unloaded	15,270	100	102	+0.013	+0.023	--	Excellent	103	+0.008	+0.024	--	Excellent
8	Air	5.85	Yes	Unloaded	15,205	100	104	+0.009	+0.012	--	Excellent	107	-0.004	+0.005	--	Excellent
11	Air	5.85	Yes	Loaded 100%	15,235	100	106	+0.008	+0.004	--	Excellent	105	+0.003	+0.006	--	Very good
12	Air	5.85	Yes	Loaded 100%	15,135	100	105	±0.000	+0.010	--	Excellent	106	-0.003	+0.008	--	Very good
13	Air	5.85	Yes	Loaded 100%	15,170	100	104	-0.001	-0.002	--	Excellent	104	-0.008	±0.000	--	Very good
14	Air	5.85	Yes	Loaded 100%	15,555	100	104	-0.010	+0.011	--	Excellent	104	-0.012	+0.012	--	Excellent
15	Nonair	6.22	Yes	Loaded 100%	15,375	100	**	--	--	--	---	---	--	--	--	---
16	Nonair	6.22	Yes	Loaded 100%	15,375	100	**	--	--	--	---	---	--	--	--	---
19	Air	5.85	Yes	Loaded 100%	14,965	100	107	-0.004	--	+0.012	Very good	107	-0.015	--	+0.009	Very good
20	Air	5.85	Yes	Loaded 100%	15,205	100	106	-0.006	--	+0.012	Excellent	103	-0.013	--	±0.000	Excellent
21	Air	5.85	Yes	Loaded 100%	15,340	100	106	+0.012	--	+0.012	Very good	107	+0.002	--	+0.005	Very good
22	Air	5.85	Yes	Loaded 100%	15,270	100	106	+0.010	--	+0.020	Excellent	104	-0.001	--	+0.010	Very good
23	Nonair	6.22	Yes	Loaded 100%	15,445	100	**	--	--	--	---	---	--	--	--	---
24	Nonair	6.22	Yes	Loaded 100%	15,590	100	**	--	--	--	---	---	--	--	--	---

Beam No.	Type Concrete	Water: Cement Ratio gal/bag	Pretensioned to 70% of Ultimate Strand Strength	Condition of Loading	% V^2 (1961)	Compression Side* (1961)	Tension Side* (1961)	Neutral Side* (1961)	Condition (1961)	% V^2 (1962)	Compression Side* (1962)	Tension Side* (1962)	Neutral Side (1962)	Condition (1962)
3	Air	5.85	No	Unloaded	104	+0.020	+0.021	--	Good	105	+0.007	+0.010	--	Good
4	Air	5.85	No	Unloaded	105	+0.009	+0.012	--	Good	104	±0.000	+0.008	--	Good
7	Air	5.85	Yes	Unloaded	103	+0.014	+0.025	--	Good	102	±0.006	+0.022	--	Good
8	Air	5.85	Yes	Unloaded	105	+0.003	+0.006	--	Good	97	-0.010	-0.001	--	Good
11	Air	5.85	Yes	Loaded 100%	106	+0.014	+0.008	--	Good	99	+0.004	-0.004	--	Good
12	Air	5.85	Yes	Loaded 100%	106	-0.003	+0.012	--	Good	96	-0.007	+0.004	--	Good
13	Air	5.85	Yes	Loaded 100%	109	-0.008	+0.002	--	Good	98	-0.019	-0.005	--	Good
14	Air	5.85	Yes	Loaded 100%	104	-0.011	+0.018	--	Good	94	-0.022	+0.009	--	Good
15	Nonair	6.22	Yes	Loaded 100%	---	--	--	--	---	---	--	--	--	---
16	Nonair	6.22	Yes	Loaded 100%	---	--	--	--	---	---	--	--	--	---
19	Air	5.85	Yes	Loaded 100%	107	-0.006	--	+0.004	Good	98	-0.016	--	-0.005	Good
20	Air	5.85	Yes	Loaded 100%	105	-0.016	--	+0.008	Good	97	-0.024	--	+0.002	Good
21	Air	5.85	Yes	Loaded 100%	105	-0.002	--	+0.004	Good	94	-0.008	--	±0.000	Good
22	Air	5.85	Yes	Loaded 100%	104	±0.000	--	+0.014	Very good	96	-0.014	--	+0.004	Very good
23	Nonair	6.22	Yes	Loaded 100%	---	--	--	--	---	---	--	--	--	---
24	Nonair	6.22	Yes	Loaded 100%	---	--	--	--	---	---	--	--	--	---

Note: Compression side: gage points were located on the side of the beam which was in compression. Tension side: gage points were located on the side of the beam which was in tension. Neutral side: gage points were located on the side of the beam which was neither in tension nor compression. Plus sign indicates expansion. Minus sign indicates shrinkage.

* Average of two readings.

** Beam failed during first winter of exposure.

APPENDIX A: DESIGN COMPUTATIONS

Notations Used in Computations

A Cross-sectional area of beam, in.^{2}

A_c Cross-sectional area of concrete, in.^{2}

A_s Cross-sectional area of steel, in.^{2}

b Width of beam, in.

d Depth of beam, in.

D Diameter of strand, in.

e Eccentricity, in.

E_c Modulus of elasticity for the concrete, psi

E_s Modulus of elasticity for the steel, psi

f_c Compressive stress in concrete, psi

f'_c Compressive strength in concrete, psi, at 28 days age

f_e Effective prestress in steel, psi

f_i Initial prestress in steel, psi

F Force, lb

I Moment of inertia of section, in.^{4}

I_t Moment of inertia transformed, in.^{4}

L Effective length of beam, in.

L_t Length of transfer, in.

m Coefficient of friction

M Bending moment, lb-in.

M_c Poisson's ratio for concrete

M_s Poisson's ratio for steel

n Modular ratio, steel to concrete (i.e. E_s/E_c)

APPENDIX A: DESIGN COMPUTATIONS

Notations Used in Computations

A Cross-sectional area of beam, $in.^2$

A_c Cross-sectional area of concrete, $in.^2$

A_s Cross-sectional area of steel, $in.^2$

b Width of beam, in.

d Depth of beam, in.

D Diameter of strand, in.

e Eccentricity, in.

E_c Modulus of elasticity for the concrete, psi

E_s Modulus of elasticity for the steel, psi

f_c Compressive stress in concrete, psi

f'_c Compressive strength in concrete, psi, at 28 days age

f_e Effective prestress in steel, psi

f_i Initial prestress in steel, psi

F Force, lb

I Moment of inertia of section, $in.^4$

I_t Moment of inertia transformed, $in.^4$

L Effective length of beam, in.

L_t Length of transfer, in.

m Coefficient of friction

M Bending moment, lb-in.

M_c Poisson's ratio for concrete

M_s Poisson's ratio for steel

n Modular ratio, steel to concrete (i.e. E_s/E_c)

P Load, lb

Q Statical moment, $in.^3$

S_t Principal tensile stress, psi

u Bond stress, psi

v Shearing stress, psi

V Total shear, lb

V_c Total shear carried by concrete, lb

y Perpendicular distance from center of gravity (centroid) of concrete section to outer fiber, in.

Δf_s Loss of prestress in steel, psi

Design Assumptions

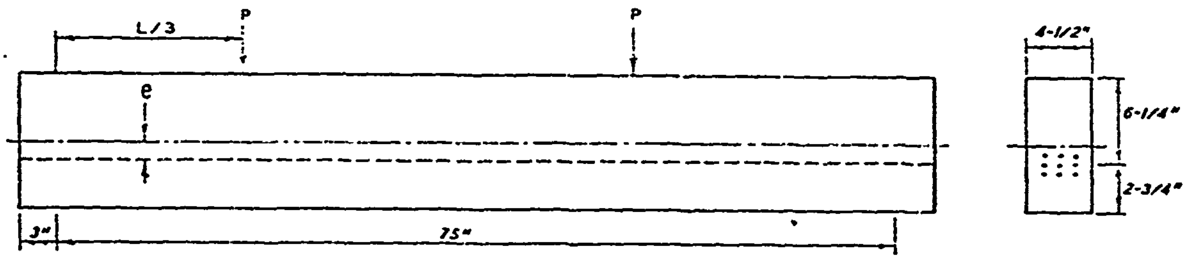
Steel: Cross-sectional area per strand = 0.0352 in.^{2}
Minimum ultimate tensile strength = 238,000 psi
Maximum tensioning stress = 70% ultimate strength
Yield strength at 0.7% elongation = 67% ultimate strength

Concrete: Compressive strength at 28 days age = 6000 psi
Poisson's ratio = 0.24
Modulus of elasticity (E_c) = 5×10^6 psi

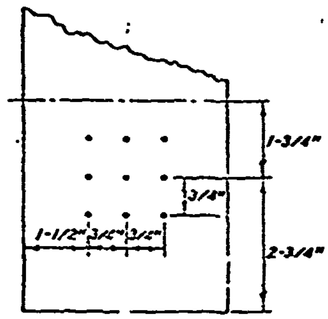
Loss of prestress: 15% due to creep and relaxation

Computations

Stress distribution $f_c = \frac{F}{A} \pm \frac{Fey}{I} \pm \frac{My}{I}$



$F = 238{,}000 \times 0.7 \times 0.3168 = 52{,}779 - 15\%^{*}$ loss (7917)
$= 44{,}862$ lb



$A = 4.5 \times 9 = 40.5$ sq in.

$e = 1.75$ in.

$y = d/2 = 4.5$ in.

$I = bd^3/12 = 273.4$ in.^{4}

$M = \frac{PL}{3}$

$L = 75$ in.

$P = 6319$ lb at 108% of prestress (exceeds compression in bottom fibers)

$P = 5833$ lb at 100% of prestress (equals compression in bottom fibers)

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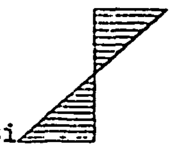
* Estimated 15% loss of prestress due to creep and relaxation.

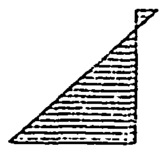
At transfer

$\frac{F}{A} = \frac{-52,779}{40.5} = -1303$ psi, $\frac{Fey}{I} = \frac{52,779 \times 1.75 \times 4.5}{273.4} = \pm 1520$ psi



Top = -1303 + 1520 = +217 psi

Bottom = -1303 - 1520 = -2823 psi

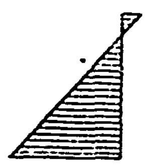


After creep and relaxation

$\frac{F}{A} = \frac{-44,862}{40.5} = -1108$ psi, $\frac{Fey}{I} = \frac{44,862 \times 1.75 \times 4.5}{273.4} = \pm 1292$ psi

Top = -1108 + 1292 = +184 psi

Bottom = -1108 - 1292 = -2400 psi



Stress due to F + P
after creep and relaxation

At 108% (2400 x 1.08 = 2592, use 2600), $\frac{My}{I} = \frac{157,975 \times 4.5}{273.4} = 2600$ psi

At 100%, $\frac{My}{I} = \frac{145,825 \times 4.5}{273.4} = 2400$ psi

(At 108%, P = 6319, M = 6319 x 25 = 157,975 lb-in.)

(At 100%, P = 5833, M = 5833 x 25 = 145,825 lb-in.)

At 108%

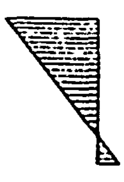
Top = +184 - 2600 = -2416 psi

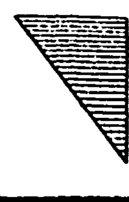
Bottom = -2400 + 2600 = +200 psi

At 100%

Top = +184 - 2400 = -2216 psi

Bottom = -2400 + 2400 = 0





Shear

$$v = \frac{V_c Q}{Ib} = \frac{6319 \times 45.6}{273.4 \times 4.5} = 234 \text{ psi max}$$

V_c = total shear = 6319 lb

Q = statical moment, at ℄ $= \frac{bd^2}{8} = 45.6 \text{ in.}^3$

234 psi

Principal tension
(occurs 6 in. from top)

$S_t = \sqrt{v^2 + (f_c/2)^2} - (f_c/2)$, f_c = compressive stress at level

4.5 in. from top, $S_t = \sqrt{234^2 + 554^2} - 554 = 47$ psi

5 in. from top, $S_t = \sqrt{230^2 + 492^2} - 492 = 51$ psi

6 in. from top, $S_t = \sqrt{208^2 + 369^2} - 369 = 54$ psi

7 in. from top, $S_t = \sqrt{164^2 + 246^2} - 246 = 50$ psi

Bond stress (applies
only to uncracked beams)

$$u = \frac{V_c ynD}{4I_t} = \frac{6319 \times 1.75 \times 6 \times 0.25}{4 \times 273.4} = 15 \text{ psi max}$$

V_c = total shear carried by concrete, lb

n = modular ratio, steel to concrete = 6

y = distance from centroid to steel = 1.75 in.

D = diameter of strand = 0.25 in.

I_t = moment inertia transformed

Length of transfer of prestress*

$$L_t = \frac{D}{2a} (1 + M_c) \left(\frac{n}{M_s} - \frac{f_i}{E_c}\right) \frac{f_e}{2f_i - f_e}$$

$$L_t = \frac{0.25}{2 \times 0.3} (1 + 0.24) \left(\frac{6}{0.3} - \frac{166,600}{5,000,000}\right) \frac{158,781}{2(166,600) - 158,781} = 9.4 \text{ in.}$$

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* See T. Y. Lin, Design of Prestressed Concrete Structures, 1st ed. John Wiley and Sons, Inc. (New York, N. Y., 1955).

where

D = diameter of strand = 0.25 in.

m = coefficient of friction = 0.3 (assumed)

M_c = Poisson's ratio, concrete = 0.24

M_s = Poisson's ratio, steel = 0.30

E_c = modulus of elasticity, concrete = 5×10^6 psi

f_i = initial prestress in steel

f_e = effective prestress in steel

$$f_e = f_i - \Delta f_s$$

$$\Delta f_s = \frac{nF}{A_c} = \frac{6 \times 166,600 \times 0.3168}{40.5} = 7819 \text{ psi}$$

n = modular ratio, steel to concrete = 6.0

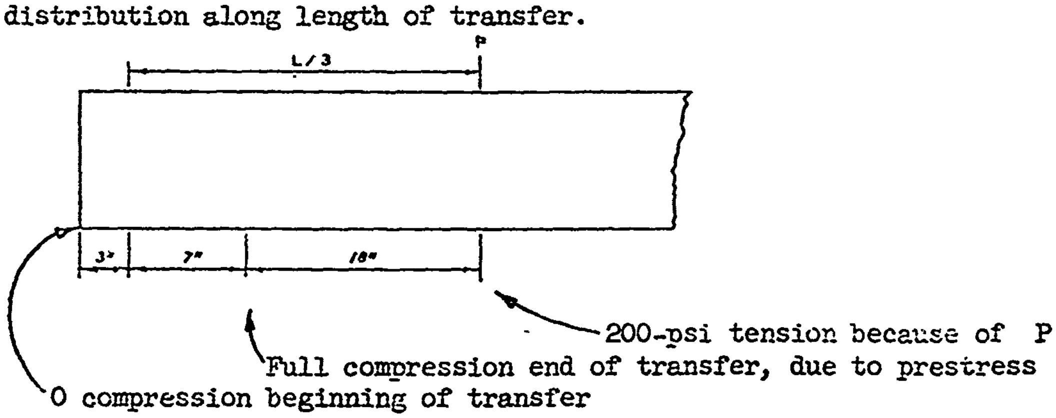
$F = f_i A_s$

A_s = area of steel = 0.3168 sq in.

A_c = area of concrete = 40.5 sq in.

End condition due to loading

Assume 10-in. length of transfer from 0 to full prestress with linear distribution along length of transfer.



Graphically (at 108% load)

Distance, in. From End	Distance, in. From Reaction	Compression Due to Prestress (-), psi	Tension Due to Moment (+), psi	Residual Stress at Bottom Fiber, psi
28	25	-2400	+2600	+200
26	23	-2400	+2392	-8

(Continued)

Distance, in. From End	Distance, in. From Reaction	Compression Due to Pre-stress (-), psi	Tension Due to Moment (+), psi	Residual Stress at Bottom Fiber, psi
10	7	-2400	+728	-1672
8	5	-1920	+520	-1400
6	3	-1440	+312	-1128
4	1	-960	+104	-856
2	0	-480	0	-480
End	-	0	0	0

End condition appears safe.

Summary

Compressive stress concrete

At transfer = 0.47 f'_c

Design = 0.37 f'_c (100% loading)

Design = 0.40 f'_c (108% loading)

Tensile stress steel

At transfer = 0.70 ultimate strength

Design = 0.60 ultimate strength

Tensile stress concrete

At transfer = 217 psi = 0.036 f'_c

Design = 0 psi (100% loading)

Design = 200 psi (108% loading)

Shear = 234 psi = 0.039 f'_c

Bond = 15 psi

Transfer length = 9 in.