A STUDY OF PRESTRESSED CONCRETE CONTAINING LIGHT WEIGHT AGGREGATE

by

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INTRODUCTION

In recent years there has been a great deal of development in prestressed concrete. This development has proceeded more rapidly in Europe than in the United States because of the economic factors involved. Prestressed concrete in practice utilizes the materials to their fullest extent while the amount of labor and technical skill required is increased. The saving in material which is realized in prestressed concrete is very attractive to Europeans because of their limited supply of raw materials. In the United States ordinary reinforced concrete is still preferred in most instances because of the relatively high cost of labor in this country. There are other factors involved however, which make prestressed concrete desirable in any area of construction. In ordinary reinforced concrete a structure may become cracked and still perform the functions it was designed for. However, where cracks occur, water claims access to the concrete and through cycles of freezing and thawing and through chemical action the structure is slowly broken down. In prestressed concrete the cracks are not allowed to develop. The prestressing wires put the concrete in compression on the entire face of the cross section thus never allowing the cracks to form. Even in structures which are over loaded and caused to crack due to that overload the cracks close as soon as the over load is removed and the structure is not damaged.

Since prestressed concrete has so many good qualities a method will be found eventually to produce it economically. In the United States this economy can probably be obtained by producing prestressed members in a factory where the weather cannot interfere with operations and assembly line methods can be used. With prestressed concrete being produced in factories and shipped to the job site the factor of freight enters the picture. It seems that prestressed concrete could be made more economical if the weight could be reduced. A reduction in weight would also be welcomed at the job site. Because of these factors manufacturers of prestressed concrete are using, in many cases, light weight aggregates such as expanded shale and mica. By using light weight aggregates the weight is reduced from 150 lb. per cu. ft. to 105 lb. per cu. ft.

Up to the present time very little research has been done on light weight prestressed concrete. Therefore a need was felt for investigation of some of the properties of this structural medium.

In prestressed concrete the steel reinforcing units are stretched until the desired prestressing force is attained and then, by various means, this load is transferred to the concrete member. The effect is that of an eccentrically loaded column as far as stresses are concerned. At this point a problem arises which does not occur in ordinary reinforced concrete. As the concrete cures it has a tendency to shrink. This shrinkage of the concrete allows the steel to shorten and cause a loss in the original prestress force. At the same time plastic flow or creep is taking place, not only in the concrete, but also in the steel. This creep adds to the loss of prestress already noted as due to shrinkage. The creep in the steel might be called a relaxation of the reinforcing units in which the force decreases over a period of time for a constant strain.

The factors mentioned above have been investigated by researchers in ordinary prestressed concrete, but very little has been done with light weight concrete.

Rosov (3) has stated that the design prestress shall be fixed by deducting 30,000 to 40,000 lb. per sq. in. from the yield point value of the steel. The preliminary stress should be from 5,000 to 10,000 lb. per sq. in. less than the yield point value. These values indicate a loss from creep and shrinkage of from 20,000 to 35,000 lb. per sq. in. If the preliminary prestress is taken as 170,000 lb. per sq. in. the percentage loss due to shrinkage and creep would be from 11.75 per cent to 20.50 per cent.

According to Rundlett (4) the design specification of 15 per cent loss in prestressing as used in bridge design proved to be insufficient under full scale tests.

Staley and Peabody (5) stated that for steel stressed to 100,000 or 150,000 lb. per sq. in. the drop due to creep and shrinkage will be 20,000 or 30,000 lb. per sq. in. In each case the drop is 20 per cent. They also showed that for very low prestressing forces the loss may be up to 83 per cent after one year.

Another value for loss in steel due to all factors is given by Magnel (2) to be 15 per cent. He also stated that exception should be taken when the concrete is not of the best quality or when its stress is higher than 1440 lb. per sq. in.

The purpose of this paper is to present the results of research on light weight prestressed concrete with respect to shrinkage, creep, deflection and grouting.

DEFINITION OF NOTATIONS

I - Moment of Inertia

A_c - Area of concrete

e - Eccentricity

f_s - Design steel unit stress, tension

f_c' - Design concrete unit stress, compression

S_t - Stress in extreme fibers, top of beam

S_b - Stress in extreme fibers, bottom of beam

w - Weight of concrete per foot of beam

M_{dl} - Dead load moment

S_{dl} - Dead load stress

TEST SPECIMENS

Twenty Foot Beams

Two 20 foot beams were cast with a cross section as shown in Plate I. High early strength cement and haydite aggregate were used as materials in the beams. The two beams were cast with holes for prestressing steel. The holes were cast by wiring inflated rubber tubes in the forms and pouring the concrete around them. The holes were cast as shown in Plate I to form a constant cross section in the middle one-third of the beam. The tubes were of a size such as to form a hole 1 3/4" in diameter. This area was large enough to hold six 1/4" diameter wires for prestressing.

Ten Foot Beams

Two 10 foot beams were cast with cross sections as shown in Plate III. The same materials were used in the 10 foot beams that were used in the 20 foot beams. Bronze gage plugs were set in opposite sides of the beams and 1 3/4 inch holes were cast down the center of each beam.

TEST PROCEDURE

Twenty Foot Beams

With the beams cast as shown in Plate I the following values were calculated:

Net I of concrete - 6453.9 in^4

e - 5"

A_c - 146.42 in^2

fs - 145,000 lb. per sq. in.

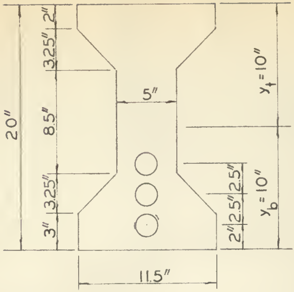
f_c = 2,000 lb. per sq. in.

Using six 1/4" diameter wires per hole the total area of steel was 18 x 0.049 = 0.882 sq. in. The total force on the beams would be 0.882 x 145,000 = 127,890 lb.

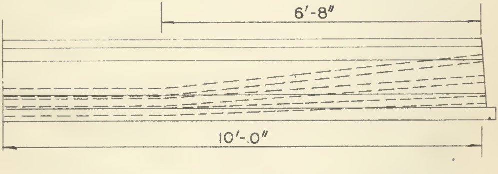
EXPLANATION OF PLATE NO. I

A cross section and side view of the 20 foot prestressed beams tested.

PLATE I



CROSS SECTION OF 20′ BEAM
MIDDLE ONE-THIRD

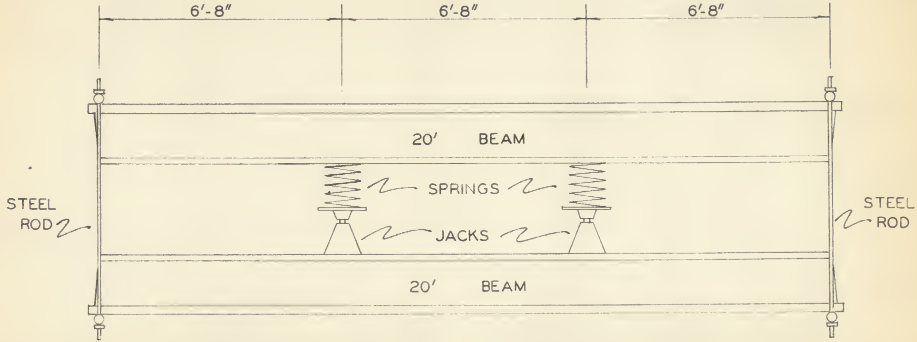


SIDE VIEW OF ONE-HALF OF 20′ BEAM

EXPLANATION OF PLATE NO. II

A sketch of the method of third joint loading of 20 foot prestressed beams for determination of center deflection.

PLATE 11

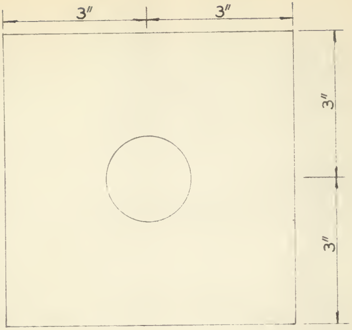


METHOD OF THIRD - POINT LOADING OF 20' BEAMS

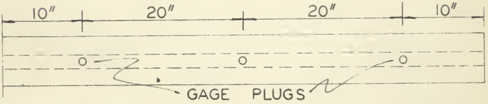
EXPLANATION OF PLATE NO. III

A cross section and side view of the 10 foot beams used in determining shrinkage and creep.

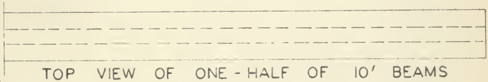
PLATE III



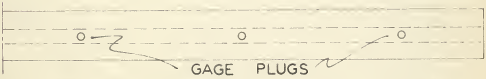
CROSS SECTION OF 10' BEAMS



SIDE VIEW OF ONE - HALF OF 10' BEAMS



TOP VIEW OF ONE - HALF OF 10' BEAMS



SIDE VIEW OF ONE - HALF OF 10' BEAMS

$$S_t = -\frac{P}{A} + \frac{Mc}{I} = -\frac{127,890}{146.42} + \frac{127,890x5x10}{6453.9} = +118 \text{ lb. per sq. in.}$$

$$S_b = -\frac{P}{A} - \frac{Mc}{I} = -\frac{127,890}{146.42} - \frac{127,890x5x10}{6453.9} = -1,864 \text{ lb. per sq. in.}$$

$$M_{dl} = \frac{wl^2}{8}$$

$$w = \frac{105x146.42}{144} = 106.5 \text{ lb. per ft.}$$

$$M_{dl} = \frac{106.5x400x12}{8} = 64000 \text{ in. lb.}$$

$$S_{dl} = \frac{64000x10}{6453.9} = 99.2 \text{ lb. per sq. in.}$$

Net stresses when the beam is supported at the ends is as follows.

$S_t = 118 - 99.2 = +18.8$ lb. per sq. in.

$S_b = -1864 + 99.2 = -1764.8$ lb. per sq. in.

The 20 foot beams were to be loaded as calculated above or as nearly so as possible. After the loads were applied to the beams they were laid on their sides and loaded against each other at the third points as indicated in Plate II. The force applied at the third points was 13,300 lb. The loading device consisted of two jacks and two calibrated springs. A constant load was maintained through keeping the deflection of each spring as nearly constant as possible. With the loads thus applied measurements were taken periodically to determine the center deflection and the loss in steel stress in the prestressing wires.

Some difficulty was encountered in getting the prescribed load of 145,000 lb. per sq. in. in the steel. Consequently the final loads differed from the original calculated figures as shown in plates V to X.

In holes 1, 2, and 3 the prestress loads were 46,000, 42,000, and 42,600 lbs. respectively. With eccentricities of holes 1, 2, and 3: 2.5 inches, 5.0 inches and 7.5 inches respectively the final stresses were found to be + 107 lbs. per sq. in. at the top of the beam and - 1893 lb. per sq. in. at the bottom of the beam.

In the other 20 foot beam the final stresses were - 139 lb. per sq. in. at the top of the beam and - 2065 lb. per sq. in. at the bottom of the beam. These figures do not differ appreciably from those calculated.

Ten Foot Beams

The cross section of the 10 foot beams is shown in Plate III. Both beams had an identical cross section. One was loaded, that is prestressed, with an axial load, and the other had no loads applied. With gage plugs on either side of each beam readings could be taken to determine the strain in each case. For the un-prestressed beam this strain or shortening would be caused by shrinkage of the concrete alone. In the prestressed beam the shortening would be a result of shrinkage and creep combined. The results of the tests would show how much of the total shortening was caused by shrinkage and how much was caused by creep. At the same time readings were to be taken on the steel in the prestressed beam to determine the loss in stress in the steel.

RESULTS OF TESTS ON TWENTY FOOT BEAMS

Center Deflection

At zero days before loading at the third points the deflection was - 0.37 inches. The negative deflection indicates that the beams were bowed slightly toward each other as a result of the prestressing force. Immediately after the application of the loads the deflection was measured and was found to be + 0.23 inches. The total deflection due to the third point loads at this time was 0.60 inches. This deflection can be assumed to be elastic.

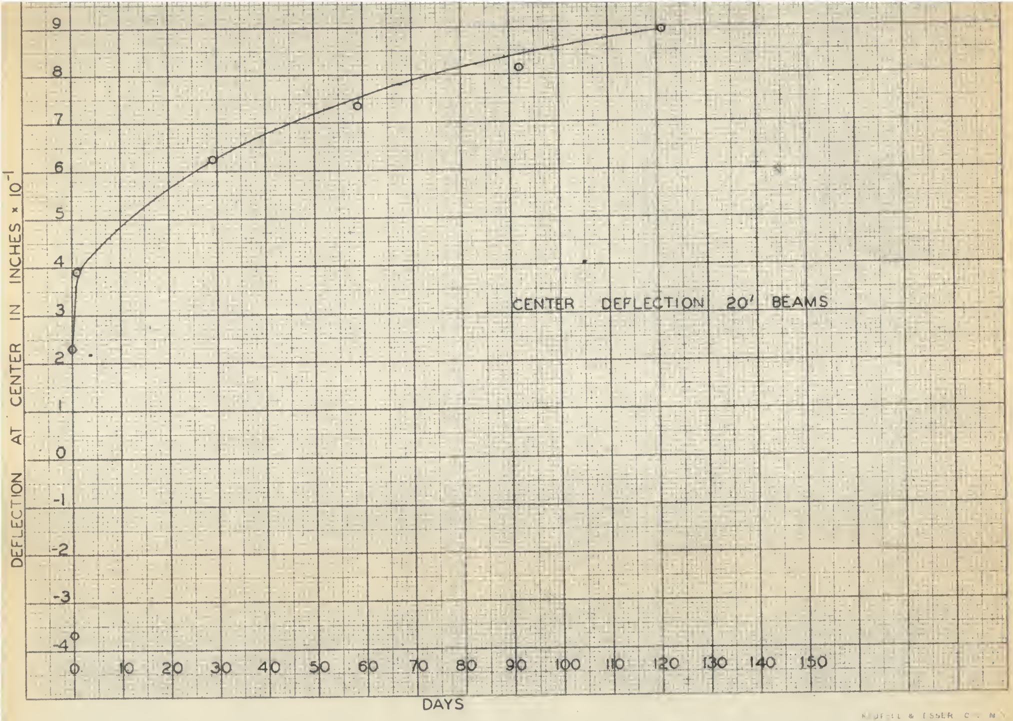
At the end of 121 days the deflection had increased as indicated on Plate IV to a value of + 0.895 inches. This gave a total deflection at this time of 1.265 inches and the curve was definitely leveling off. The deflections as read were the total deflection of the two beams, therefore it can be reasonably assumed that each beam deflected a total of 0.6325 inches in 121 days.

Loss in Steel Stress

The steel stress loss in the 20 foot beams is shown in Plates V to X. The loss was measured in each hole as indicated. The first point recorded was the force necessary to stretch the wires sufficiently to slip the plates behind the loading head. The second point recorded at zero days was the load on the wires when the plates were seated. This load is thus the actual prestressing load. The first point recorded at 4 days was the

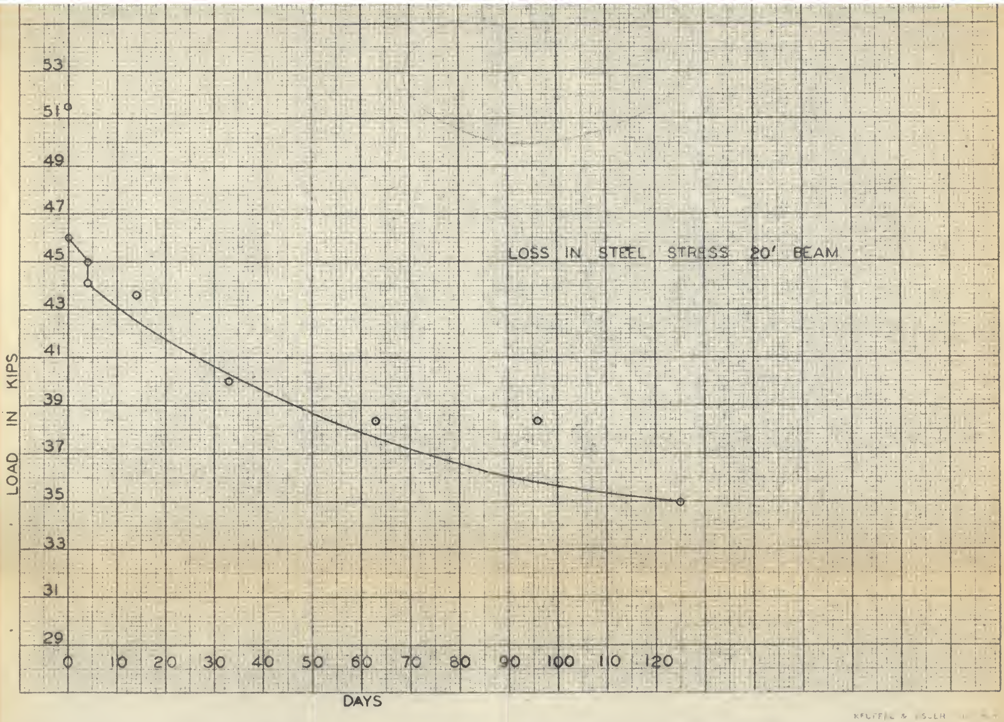
EXPLANATION OF PLATE NO. IV

A graph of the deflection of the 20 foot prestressed beams under third point loading.


CENTER DEFLECTION 20' BEAMS
DEFLECTION AT CENTER IN INCHES × 10⁻¹
DAYS
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

EXPLANATION OF PLATE NO. V

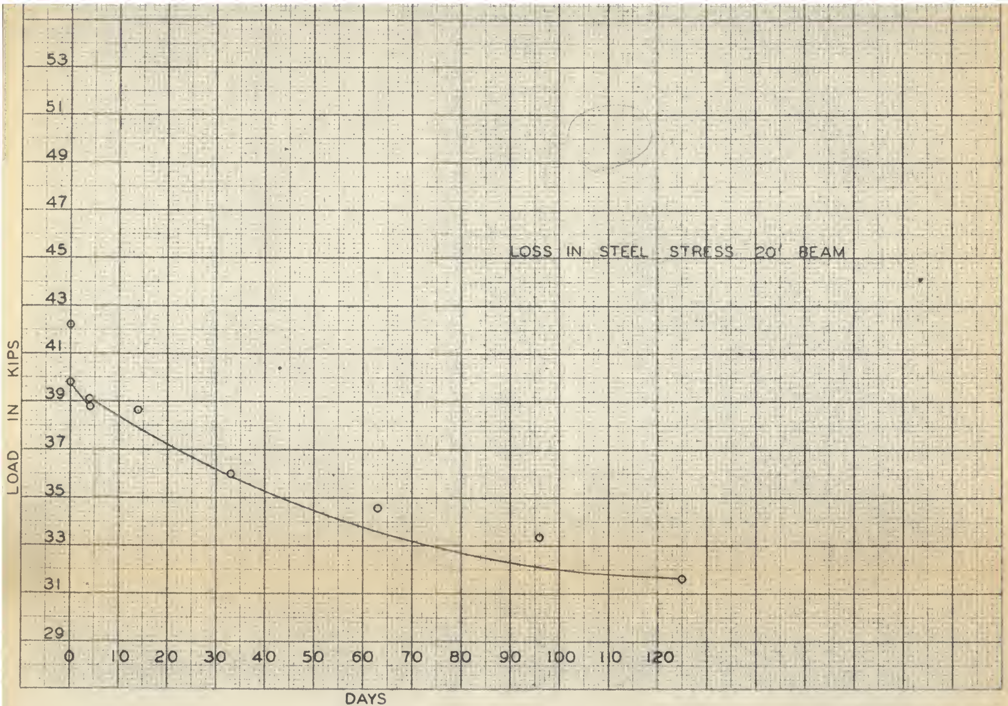
A graph of the loss in steel stress in hole no. 1 of a 20 foot prestressed beam.



LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
0
10
20
30
40
50
60
70
80
90
100
110
120
DAYS

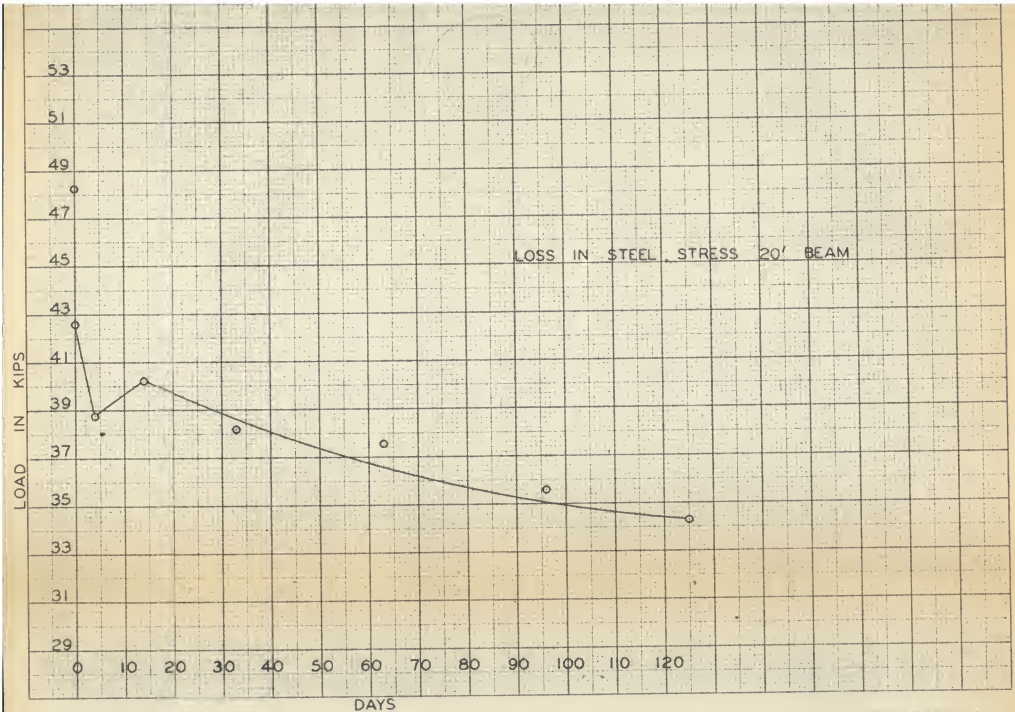
EXPLANATION OF PLATE NO. VI

A graph of the loss in steel stress in hole no. 2 of a 20 foot prestressed beam.


LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
0
10
20
30
40
50
60
70
80
90
100
110
120
DAYS

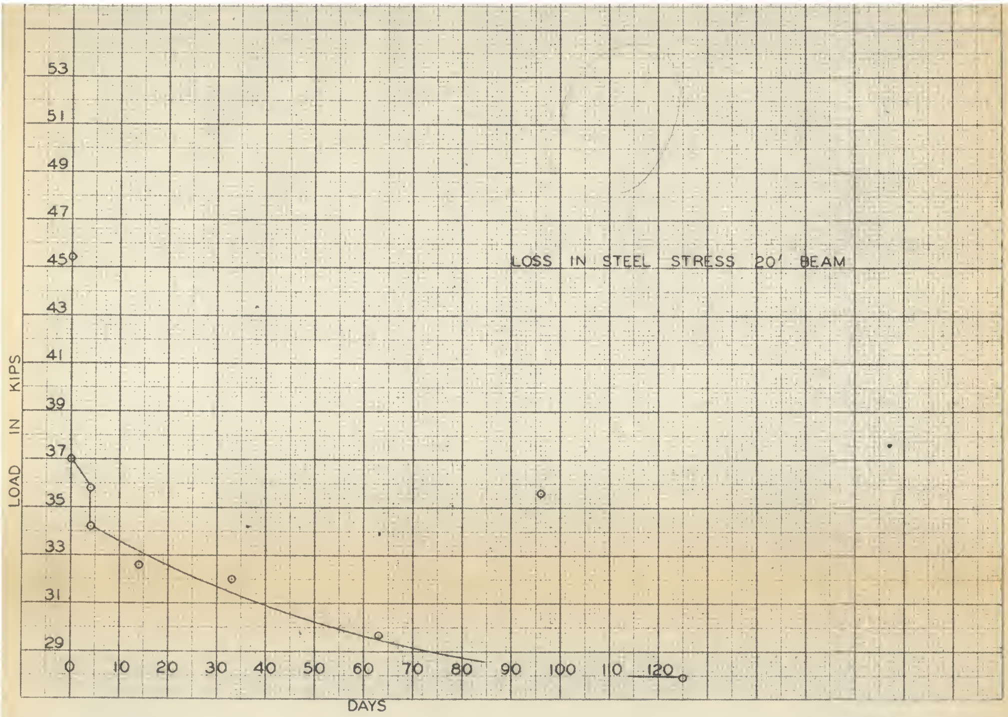
EXPLANATION OF PLATE NO. VII

A graph of the loss in steel stress in hole no. 3 of a 20 foot prestressed beam.


LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
0
10
20
30
40
50
60
70
80
90
100
110
120
DAYS

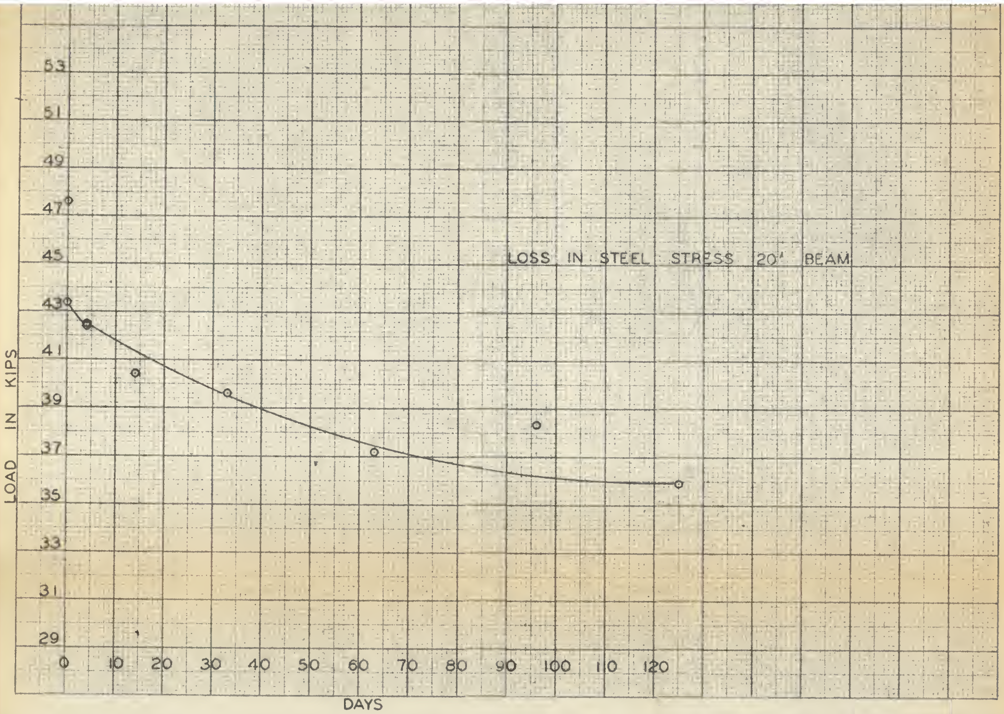
EXPLANATION OF PLATE NO. VIII

A graph of the loss in steel stress in hole no. 4 of a 20 foot prestressed beam.


LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
DAYS
0
10
20
30
40
50
60
70
80
90
100
110
120

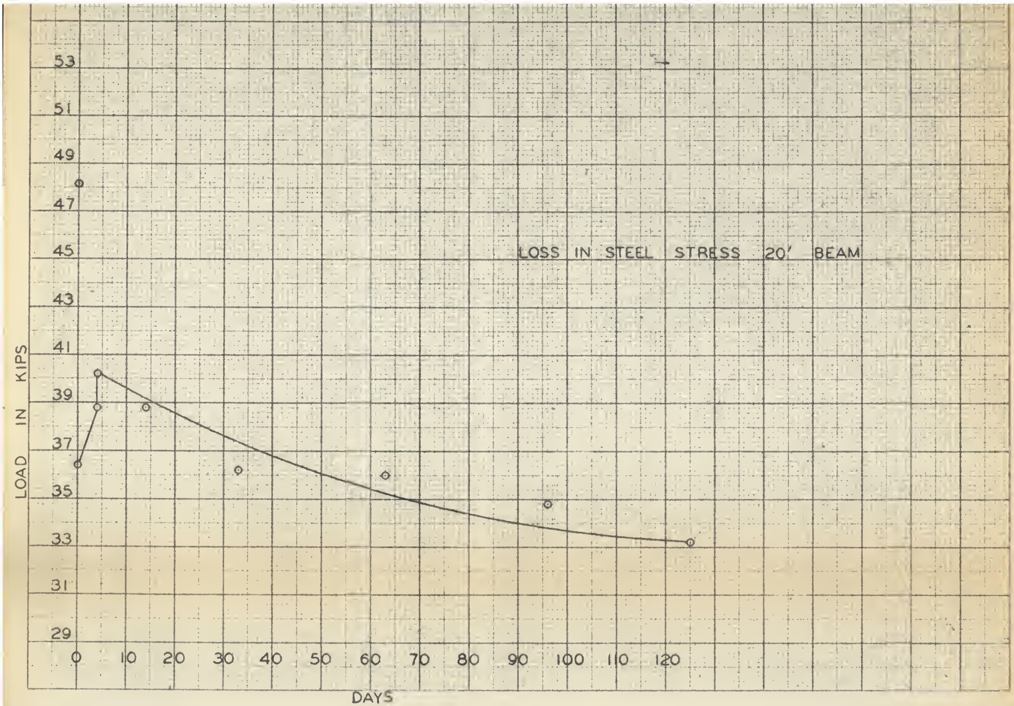
EXPLANATION OF PLATE NO. IX

A graph of the loss in steel stress in hole no. 5 of a 20 foot prestressed beam.


LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
0
10
20
30
40
50
60
70
80
90
100
110
120
DAYS

EXPLANATION OF PLATE NO. X

A graph the loss in steel stress in hole no. 6 of a 20 foot prestressed beam.


LOSS IN STEEL STRESS 20' BEAM
LOAD IN KIPS
53
51
49
47
45
43
41
39
37
35
33
31
29
0
10
20
30
40
50
60
70
80
90
100
110
120
DAYS

amount of original prestressing force left after 4 days of shrinkage and creep. The second point recorded at 4 days is the force in the wires immediately after application of the third point loads.

The average drop from prestressing force to seating of the plates was 13.33 per cent. The average drop, after 125 days, from the seating force was 21.16 per cent. The average drop, at 125 days, from the load immediately after third point loading was 18.2 per cent. These percentage drops were the result of shrinkage and creep in the concrete as well as the creep in the steel. Hole no. 6 was omitted in calculating per cent drop from seating force and hole no. 3 was omitted in calculating per cent drop from third point loading. The plates at the end of the beams in these two cases were badly deformed.

Breaking Load

At 132 days one of the 20 foot beams was subjected to a failure test. It was loaded at the third points with the total span being 19 feet 0.3 inches. Immediately before the test the modulus of rupture and compressive strength of the concrete was obtained from 3 by 4 by 16 inch control beams. These values were 800 lb. per sq. in. and 4490 lb. per sq. in. respectively.

The weight of the beam itself was 108 lb. per ft. and the weight of the loading device was 608 lb. The loads on the prestressing wires at the time of loading were as follows: hole no. 4, 27,900 lb.; hole no. 5, 35,000 lb.; and hole no. 6, 33,200 lb. With these values the cracking load was calculated to compare with the actual test. The calculated cracking load was 38,259 lb. The actual load at which cracks occured was 33,460 lb. The ultimate load was 44,000 lb.

At 141 days, the other 20 foot beam with wires grouted was subjected to the same load test. The calculated cracking load was 39,470 lb. The actual load at which cracks occured was 34,230 lb. The ultimate load was 59,910 lb.

RESULTS OF TESTS ON TEN FOOT BEAMS

The results of tests on the 10 foot beams are shown in Plates XI, XII, and XIII. Plate XI shows the shrinkage on the un-prestressed beam. This plate shows a value of 0.00068 inches per inch at 116 days. Plate XII shows the creep and shrinkage of the pre-stressed beam. At 116 days the value recorded is 0.00122 inches per inch. Plate XIII shows the loss in steel stress in the prestressed beam. This plate shows a drop in steel stress from the seating stress of 35.8 per cent. The three plates indicate that the loss in steel stress can be broken down as 14.7 per cent due to shrinkage of concrete, 11.6 per cent due to creep of concrete, and 9.5 per cent due to creep of the steel.

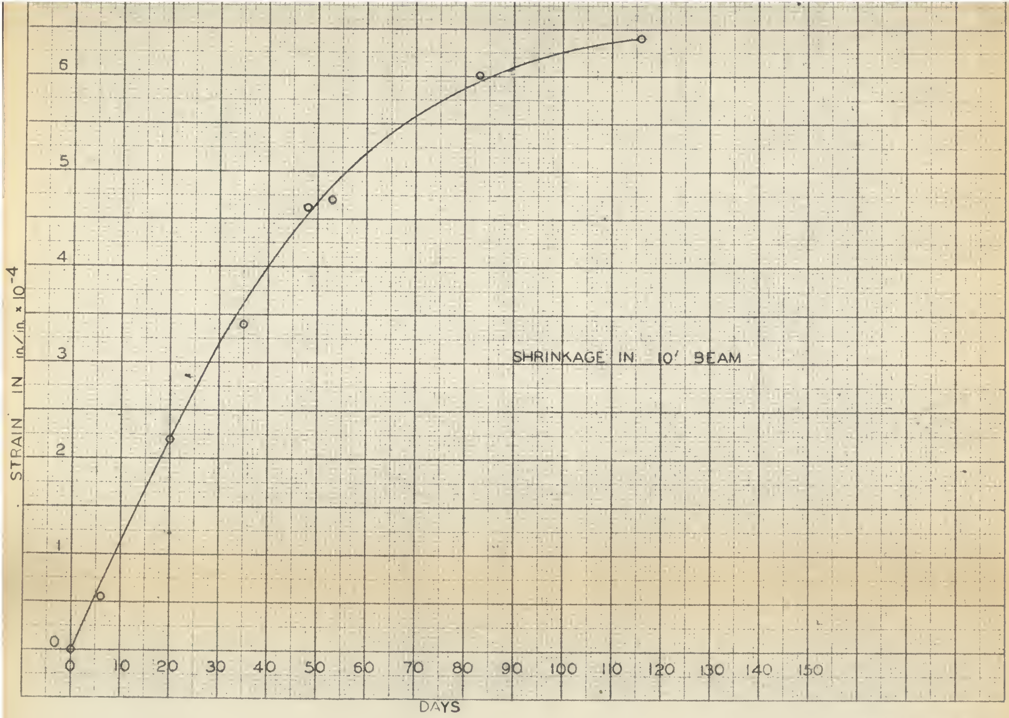
INTERPRETATION OF RESULTS

Deflection

The A.I.S.C. specifications (5) state that for beams and girders supporting plastered ceilings, the deflection due to live load should not exceed 1/360 of the span. For a twenty

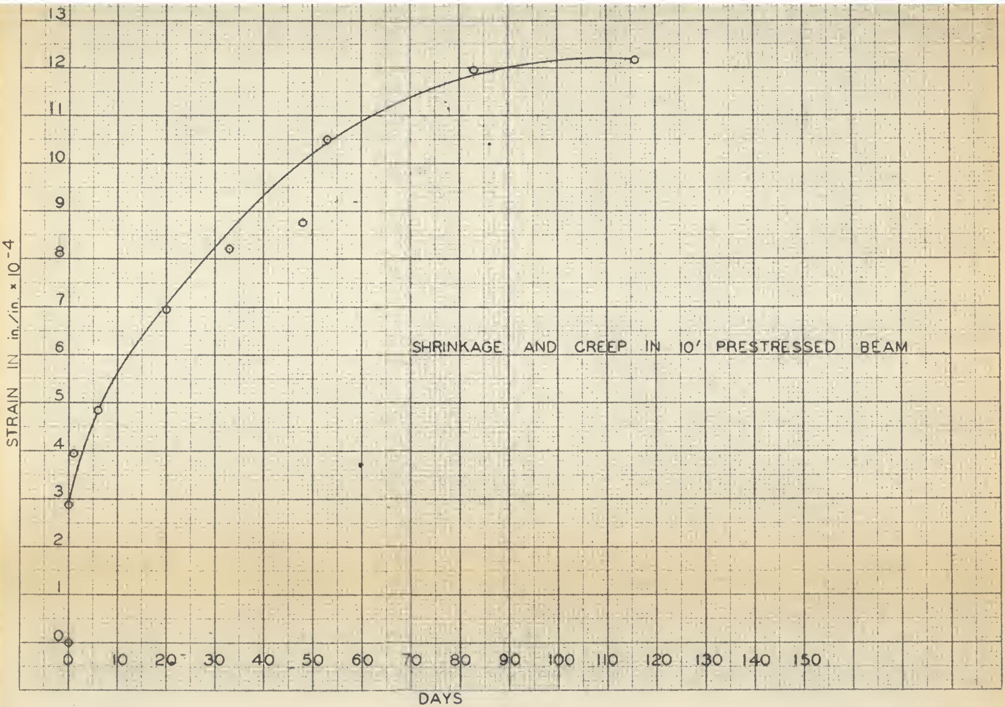
EXPLANATION OF PLATE NO. XI

A graph of the shrinkage of the un-prestressed 10 foot beam with time.


SHRINKAGE IN 10' BEAM
STRAIN IN in/in × 10^-4
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
DAYS

EXPLANATION OF PLATE NO. XII

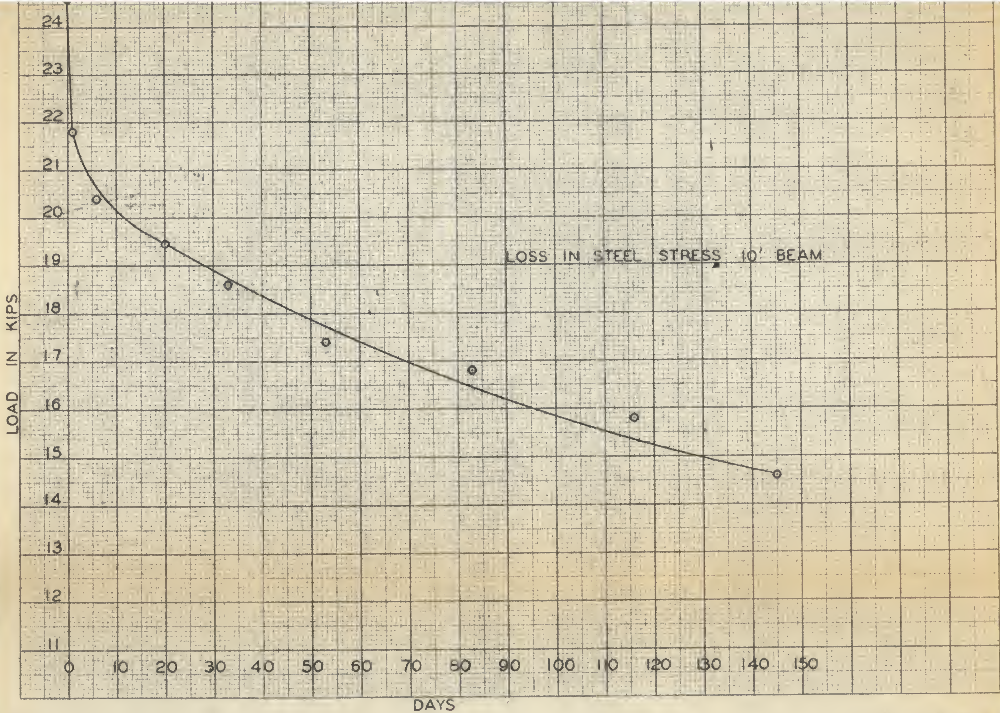
A graph of the shortening of a 10 foot prestressed beam with time.



SHRINKAGE AND CREEP IN 10' PRESTRESSED BEAM
STRAIN IN in./in. x 10^-4
0
1
2
3
4
5
6
7
8
9
10
11
12
13
DAYS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

EXPLANATION OF PLATE NO. XIII

A graph of the loss in steel stress in the 10 foot prestressed beam whose shortening is shown in plate no. XII.


LOSS IN STEEL STRESS 10' BEAM
LOAD IN KIPS
24
23
22
21
20
19
18
17
16
15
14
13
12
11
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
DAYS

foot beam this value would be 0.67 inches. The deflection tests of the 20 foot beams show a maximum value at the end of 121 days of 0.6325 inches. This amount of deflection indicates that this property of prestressed concrete merits some consideration if the beams are to be used in buildings or other places where deflection is a critical factor.

Loss in Steel Stress

In the 20 foot beams the average loss in steel stress from the seating force was 21.16 per cent. In the 10 foot beams the comparable figure was 35.8 per cent. The large beams more nearly approximate the actual load condition. The average stress in the steel was 154,136 lb. per sq. in. In the 10 foot beams the steel stress was 125,510 lb. per sq. in. Since there is a greater per cent drop in the wire with a low initial stress there is a possibility that better results may be obtained by using a steel stress close to the ultimate value.

Grouting

Grouting of the wires in the beam appears to improve the strength in bending. The greatest improvement appears in the ultimate strength where the grouted beam was stronger by 36 per cent. This could be contributed to the fact that the steel acts as ordinary reinforcing steel after the cracking load has been exceeded. The grouting evidently provides a bonding action which makes the steel work as ordinary reinforced concrete steel does. The increased strength due to grouting may be compared with the 18.5 per cent gain as reported by Rundlett (4).

CONCLUSION

The results of these tests were not intended to be conclusive, but only to determine some factors which need investigation. They must be compared with results obtained in ordinary prestressed concrete as very little is yet available on light weight prestressed concrete. This research should not be applied to ordinary prestressed concrete.

As has been pointed out the factor applied to the loss in steel stress varies from 15 to 25 per cent in ordinary prestressed concrete. The results of this test show that to be safe a factor of at least 25 per cent should be considered in light weight concrete where nothing is done to remove the creep in the concrete and steel before loading. The creep in the concrete might be largely overcome by first applying a partial prestressing force and, at a later date, applying the final prestressing. The creep in the steel can be removed, as suggested by Magnel (1), by applying an excessive stressing force for about two minutes before actual prestressing of the beam. These two suggested methods should be tested before use to determine the amount of creep each method removes. The procedure just mentioned may have contributed to the difference in drop in steel stress in the 10 and 20 foot beams. Some difficulty was encountered in applying the prestress force to the 20 foot beams and in the process the wires were subjected to an exceedingly high force. This high stress evidently removed some of the creep in the steel.

The deflection should be investigated in cases where a large deflection could cause injury to the structure. In cases where deflection is not too important the ability to crack and then recover when the overload has been removed is very desirable.

The effect of grouting was well demonstrated in the ultimate load tests. The greater safety factor provided by grouting is, of course, very desirable in all structures.

ACKNOWLEDGMENT

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Without the help and cooperation of the above named individuals this paper could not have been completed.

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Department of Architecture

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OF AGRICULTURE AND APPLIED SCIENCE

1954

The purpose of this paper was to determine some of the characteristics of prestressed concrete containing light weight aggregate, and to determine what factors need further investigation. There has been some research on ordinary prestressed concrete, but very little on light weight prestressed concrete. The research as reported in this paper was not extensive enough to establish any set rules or facts, but only to point out some properties which need investigation. The main points of the research dealt with the loss in prestress due to shrinkage and creep of the concrete and creep of the steel, and the deflection of a full scale beam, under load, with time. The effect of grouting the prestressing wires on the ultimate strength of the beam was also investigated.

Two full scale twenty foot beams and two ten foot beams of rectangular cross section were cast using light weight concrete. The two twenty foot beams were prestressed and loaded against each other to produce the effect of actual loading. The loads were kept as nearly constant as possible and the loss in steel stress along with deflection were measured periodically. After approximately four months these beams were subjected to a failure test, one with the prestressing wires grouted and the other not grouted.

The two ten foot beams were cast with identical cross section and one was prestressed with a direct axial load. These beams were not loaded as beams but were only used as an attempt to separate the three quantities; shrinkage in the concrete, creep in the concrete, and creep in the steel. The ten foot beam which was not prestressed was measured for shrinkage alone. The prestressed ten foot beam gave the shortening due to shrinkage and creep of the concrete. At the same time the loss in steel stress was being recorded.

The results of the tests in most cases were very clear cut. The average loss in steel stress in all wires in the twenty foot beams was about 21 percent. The loss in steel stress in the ten foot beam was about 36 percent. The average original prestressing force in the twenty foot beams was 154,136 lb. per sq. in. while in the ten foot beam the prestressing force was only 125,510 lb. per sq. in. The indication here being that in order to reduce the loss in steel stress a prestressing force near the ultimate strength of the steel should be used. There is evidently an optimum value to use in prestressing.

The results of the deflection test showed that this factor should be investigated in cases where deflection is critical. Where the amount of deflection is not critical the prestressed beams should be satisfactory.

The ultimate load, according to this test, was increased by 36 percent by grouting the prestressing wires. This is a significant value even for one test.

The results of the tests on the ten foot beams showed that the shrinkage in light weight concrete is approximately the same as in ordinary concrete. Of the 35.8 percent loss in steel stress in the prestressed beam it was determined that 14.7 percent was due to shrinkage of concrete, 11.6 percent was due to creep of concrete, and 9.5 percent was due to creep of the steel.