Moving Load Test on Experimental Prestressed Concrete Highway Slab, Part B—Additional Investigations

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This investigation was initiated to determine the loss in prestress in the experimental prestressed concrete highway slab, to determine the extent to which bonding of the strands had been accomplished during the grouting operation and to investigate the effects of corrosion on the strands. Details of the design and construction of the pavement and the results of the static and creep load tests were reported by Moreell et al. (1). The results of the moving load tests were reported by Smith and Lightholder (2).

The investigation was performed about eight years after the pavement was constructed and two years after it was subjected to the moving load tests. Longitudinal cracks had developed over some of the tendons as a result of the moving load tests. Two of these cracks were in the area covered by the present investigation.

The test indicated that there was a loss in prestress in the pavement of about 14 percent. Bond failure occurred between the conduit and the pavement when longitudinal cracks along the conduit were forced open. The developed bond strength between the strands and the grout was about 421 psi. Corrosion covered approximately 30 percent of the surface area of the strands. The average breaking strength of the strands was about 27,200 pounds.

The investigation demonstrated that there was adequate bond developed between the grouted tendons and the concrete to transfer the prestressing loads when transverse cuts are made.

The inherent weakness in the pavement is the longitudinal cracks that develop over the tendons. This condition may be minimized by providing transverse reinforcement or by redistributing the prestressing strands more uniformly across the pavement.

It is recommended that a test section of this pavement be incorporated as a part of a highway system where the performance can be studied under normal traffic conditions.

•IN 1956 and 1957 the Jones and Laughlin Steel Corporation designed and constructed an "Experimental Prestressed Concrete Highway Slab" and ran a series of static and creep load tests on it. During the fall of 1962, the Civil Engineering Department of the University of Pittsburgh placed approximately 580,000 repetitions of moving loads over

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a section of the slab containing an expansion joint. The test was performed to determine the behavior of the slab when subjected to repeated applications of moving loads over an extended period of time.

There are several factors related to prestressed pavements that are of interest in the design and construction of highways. These are (a) the loss of prestress, (b) the developed bond stress, and (c) the effect of corrosion on the strength of the pavement.

PURPOSE AND SCOPE OF RESEARCH

The purpose of this investigation is to determine the amount of prestress remaining in the experimental pavement, to determine the bond resistance between the prestressing strands and the concrete, and to evaluate the corrosion that has taken place since the construction of the slab.

The evaluation was accomplished by progressive destruction of a portion of the pavement. Appropriate instrumentation was used to measure the changes in strain as the work proceeded. This required exposure of the tendons in the early stages so that the changes in strain in the strands could be read directly. It also dictated that sufficient concrete be left between the instrument slots and the severed ends of the strands to develop bond resistance between the tendons and the concrete. The critical bond length was determined by progressively reducing the length of bond to failure. Four of the tendons were removed for further study. The strands from three of these were subjected to the standard tensile test. This, together with visual examination of the conduit, grout core and the tendons, provided the information for the evaluation of the bond strength and corrosion.

It was initially established that one of the tendons was not grouted. This, along with the possibility that bond might not be developed, made it desirable to design anchors for the tendons, so that the remainder of the pavement would retain its prestressed condition. In addition, information about such anchors would be valuable in the event that this pavement or a similar pavement was built into a highway system.

ANCHOR FOR TENDONS

Development of the anchorage device incorporated the use of epoxies, sand and a holding fixture. A series of tests was performed on three different diameter bars and $\frac{7}{16}$-in. diameter prestressing strands, using 1-in. pipe as a holding fixture. The inside surface of the pipe and the surface of the bars and prestressing strands were thoroughly cleaned prior to assembly.

Table 1 of the Appendix gives the results of the pull-out tests to which all of the specimens were subjected with the exception of numbers 16 and 18. Specimens 12 through 18 were subjected to a creep test, the results of which are shown in Figure 14 of the Appendix. Specimen number 16 developed faulty instrumentation and was discarded, and number 18 was a four strand test which exceeded the capacity of the 100,000-lb Universal testing machine.

The knowledge gained from these tests was used in the design of the anchors for the tendons. The anchor consists of a 30-in. length of mechanical tubing with a $1\frac{1}{2}$-in. I.D. and a $2\frac{3}{8}$-in. O.D. The tubes were slotted to fit over the tendons. The slots were covered with mechanical tubing having a $2\frac{3}{8}$-in. I.D. and $3\frac{1}{4}$-in. O.D. which was welded in place. A slotted bearing plate 5 in. wide by $1\frac{3}{4}$ in. thick by 6 in. long, grouted in place with a stiff epoxy sand mixture, was used to transfer the load to the concrete. The tendons were bonded into the fixtures with a mixture of seven parts of epoxy patching compound to 10 parts of silicon sand, 100 percent of which passed a No. 20 sieve and was retained on a No. 30 sieve. The assembly is shown in Figure 1.

TEST AREA

The test area shown in Figure 2 was located within the same area that was used for the moving load test. The site was selected because it had been subjected to a considerable amount of traffic during the previous test and it contained two tendons which had developed longitudinal cracks over them. The center of the area was located 29 ft

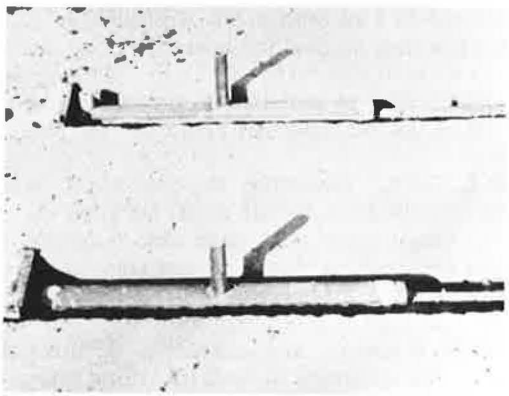


Figure 1. Anchors for the tendons.

west of the expansion joint, midway between the west ramp and the existing holes 15 ft west of the joint.

Access to the tendons was provided by 6- by 49-in. slots. The length was dictated by the anchors and the space needed to manipulate strain measuring instruments. A distance of 81 in. from the end of the slots to the transverse cut was used to insure the development of bond between the tendons and the concrete. The area was covered with a shelter which was heated to maintain the temperature between 55 and 65 F.

INSTRUMENTATION

The instrumentation for the concrete was SR-4, Type A-9 gages surface mounted at the ends of the slots and midway between the slots. These were thoroughly waterproofed and given a protective coating of cerese wax. Each set of gages was wired through a multichannel switch box to a conventional battery-operated strain indicator. The strains in the prestressing strands were taken with a 10-in. Whittemore gage.

OPERATION AND PROCEDURE

The field work began on November 1, 1964. Longitudinal saw cuts were made on each side of the tendons and a 1-in. diameter hole was drilled at each end of the cuts to facilitate the removal of the concrete. The pavement was permitted to dry out thoroughly. The SR-4 strain gages were installed and zero readings were recorded.

The concrete was removed from the slots with light electric chipping hammers. The conduit and grout were stripped from the strands and the anchors were installed in the west slots. Cable clamps were used to provide gage marks for the Whittemore gage.

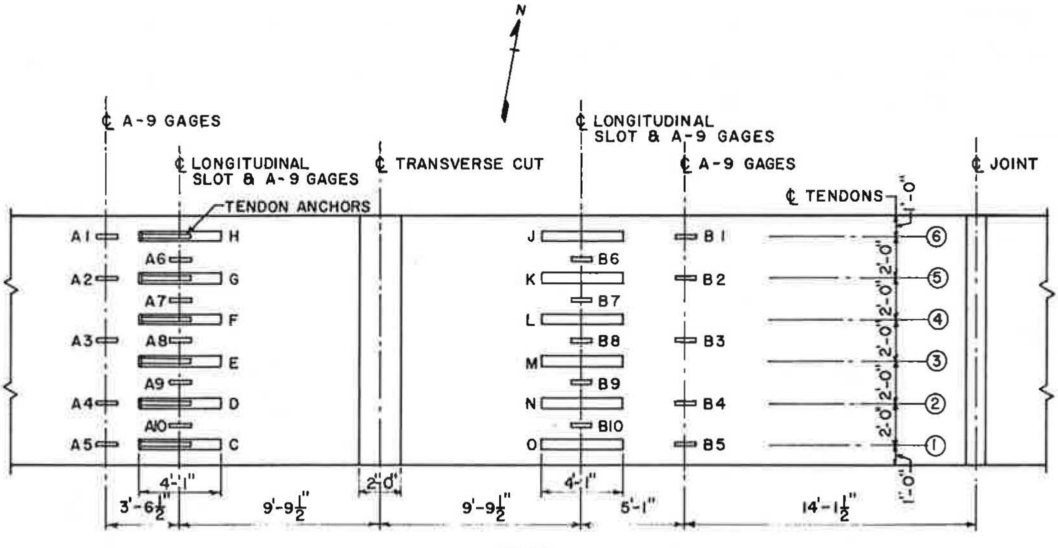


Figure 2. Test area.

The location of the ungrouted tendon was established as tendon No. 2 which ran through slots D and N (Fig. 2). An access slot for this tendon had been provided during construction of the pavement at a point 85 ft west of the transverse cut. The asphalt filler was removed from this hole and it was designated as slot P in Figure 16 of the Appendix. Zero readings were recorded for all of the strands that could be reached with the Whittemore gage.

The transverse cut was made on December 2, 1964. Two cuts, two feet apart, were made across the slab. The saw was permitted to sink down to full depth between the tendons. To facilitate removal of the concrete, longitudinal cuts were also made on each side of the tendons. The concrete between the tendons was removed first and then the concrete, conduit and grout were chipped away from the tendons. Progressive relaxation occurred as each tendon was exposed. The last two tendons to be exposed were the ungrouted tendon No. 2, through slots D, N and P, and tendon No. 3, through slots E and M. As work began on these tendons, the concrete at both locations failed in compression, leaving all but the ungrouted strands relaxed (Fig. 3).

The next step was to cut the tendons. Hack saws, equipped with high-speed tungsten blades, were used. Tendon No. 2 was the first to be cut since it was still highly stressed. The severing of this tendon reduced some of the relaxation in the other tendons (Fig. 4).

The final step was to reduce gradually the length of bond between the transverse cut and the slots until bond failure occurred. Work was started on the east side first. It was decided to remove 12-in. increments of the concrete until a point was reached where bond failure would be impending and then proceed at a slower pace until bond failure was accomplished. Starting at the transverse cut a 12-in. increment was sawed about 1 in. deep. The electric chipping hammers and a sledge were used to break away the concrete. The resulting forces and shock waves caused longitudinal cracks to develop over two additional tendons (Fig. 5). This caused these tendons to relax. The remaining tendons on the east side were released and strain readings on the unstressed strands were recorded.

On the west side the tendon slots were elongated by 6-in. increments with the concrete saw and careful use of the chipping hammers. Strain readings were taken at intervals. Initial failure was indicated at slot F (Fig. 6). About five minutes after the saw cuts were made—work had stopped for the day—the audible failure of the concrete around the conduit was substantiated by visible cracks. This tendon and the one at slot E were the only ones that had longitudinal cracks at the beginning of the tests.

After initial bond failure had been accomplished for the remaining tendons, the strands were freed for total relaxation and the final strain readings were taken. The site was abandoned on December 16, 1964. Graphical representation of the steel and concrete strains is shown in Figures 15 to 20 and Figures 21 to 24, respectively, of the Appendix.

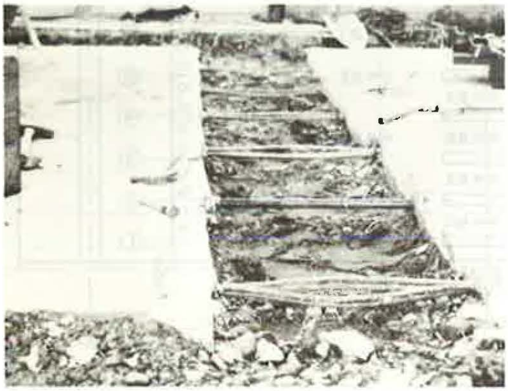


Figure 3. Transverse cut.

Figure 4. Ungrouted tendon severed.

Figure 5. Failure at slot J.

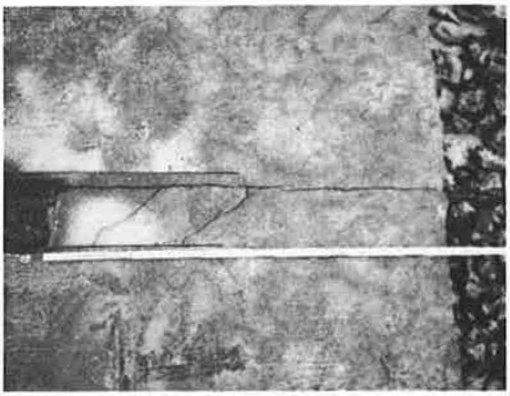


Figure 6. Failure at slot F.

LOSS IN PRESTRESS

Figure 7 shows the average value of the change in stress in the steel and the concrete for each reading. The diagram for the steel stresses shows four separate conditions. C-H and J-O represent the average stress for the grouted tendons to the west and to the east, respectively, of the transverse cut. D and N represent the average stress for the ungrouted tendons west and east of the cut (Fig. 2).

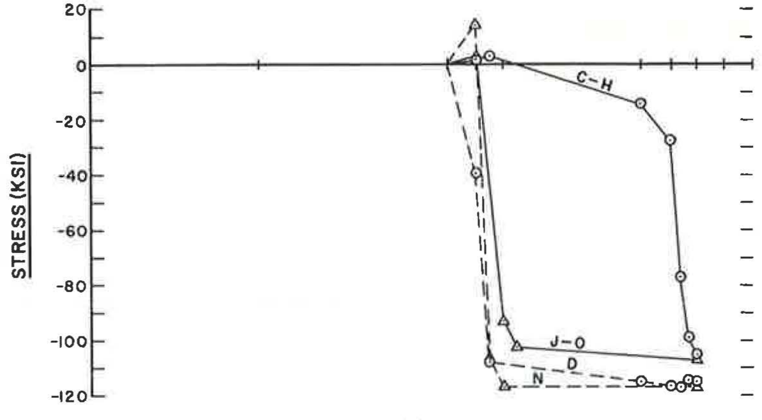
The two curves for each condition agree reasonably well. The final stress for the ungrouted tendon is about 115,700 psi and the average for the grouted tendons is 106,000 psi. One might, at this point, conclude that the loss in prestress would be the difference between the two, since cutting the slots in the pavement would have a negligible effect on the stresses in the ungrouted tendon. However, the stresses reported after the release of the jacks, during the construction of the pavement, indicate a variation in stress from the anchors to the midlength of the slab (1).

The original stresses varied from 116,000 psi at the anchors to 151,000 psi at the
idlength with a value of about 124,000 psi in the vicinity of this test section. It is
med that this variation was locked into the strands due to the grouting of the ten-
The ungrouted tendons, on the other hand, would have had ample opportunity to
ore uniformly stressed over the 8-yr period.
shows the load-deflection relationship between the original area of the slab
ter the slots were cut. The calculations equate δs to δc and indicate
the load ΔP will be the same for the concrete as it is for the steel.
there is no frictional resistance between the concrete and the base

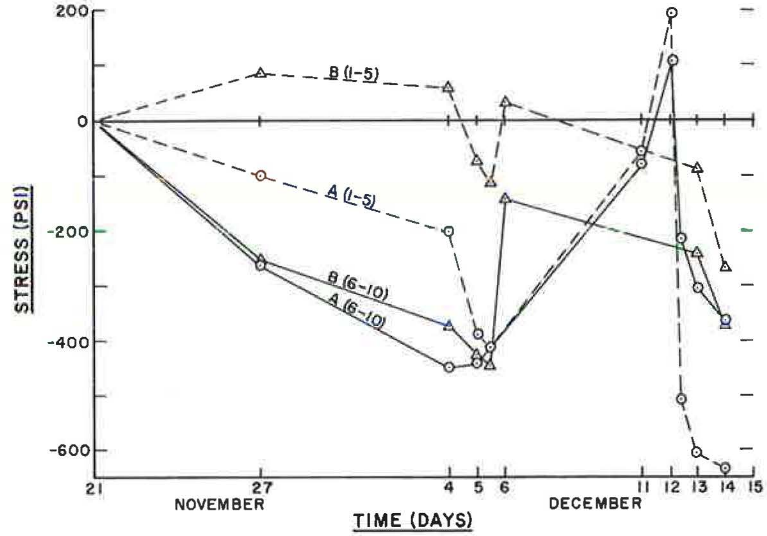
litions the computed prestress in the grouted tendons is about
736 psi. This uses the value P_F = 46,233 lb which is based on the
train in the tendons of 3,870 microinches. The percent loss in
ent which compares favorably with the 15 percent found in the litera-
th frictionless bases.
stresses shown in Figure 7 are not as well grouped as were the steel
lid lines represent the stresses at the end of the slots and the dashed
sses midway between the slots. The (A) values are for those gages
n and the (B) values represent the gages on the east section. The
n slope of these curves indicate that flexural stresses were affecting

BOND

t when the tests were initiated that there would be three different cases
dons were concerned: Case I—the ungrouted tendon, Case II—the



STEEL



CONCRETE

Figure 7. Average change in stress.

grouted tendon with a longitudinal crack, and Case III—the grouted longitudinal crack. The second and third cases are of primary imp is involved.

The tendons were released when the length of bond was about 20 i lustrated in Figure 6 for Case II. Figure 9 shows the cracks that de and is representative of the type of failure for Case III. In both cases in pulling the conduit through the concrete. The wedging action of the the outside of the conduit forced the pavement apart, resulting in longi at those locations which had no previous cracks.

The force in the tendons at this point was approximately 46,537 - 3 The resulting unit stress on the surface of the conduit was 46,223/ (20 491 psi. The approximate bond stress between the grout and the strand (20) (0.4375) (4) (3.14) = 421 psi.

There was an audible adjustment of the load in tendon No. 1, through 31-in. length of bond. This tendon, due to faulty alignment, had one of i

$$P_{ORIGINAL} = P_{OS} = P_{OC} = P_O$$

$$P_{FINAL} = P_{FS} = P_{FC} = P_F$$

ΔP = CHANGE IN LOAD TO EFFECT Δ_S AND Δ_C

$$\delta_S = \delta_C = \Delta_{OS} - \Delta_{FS} = \Delta_{FC} - \Delta_{OC}$$

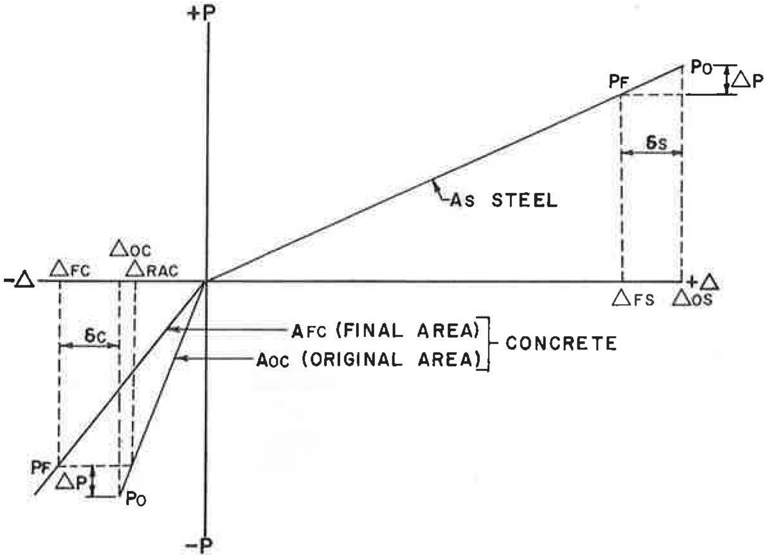
$$\therefore \frac{P_O L_S}{A_S E_S} - \frac{(P_O - \Delta P) L_S}{A_S E_S} = \frac{(P_O - \Delta P) L_C}{A_{FC} E_C} - \frac{P_O L_C}{A_{OC} E_C}$$

$$\frac{L_S}{A_S E_S} \Delta P = \frac{L_C}{A_{FC} E_C} (P_O - \Delta P) - \frac{L_C}{A_{OC} E_C} P_O$$

$$\Delta P = 0.006542 P_O$$

$$P_O = P_F + \Delta P \;;\; P_F = (387)(10^{-5})(27.4)(10^{6})(0.436) = 46{,}233 \text{ LB.}$$

$$P_O = 46{,}537 \text{ LB.} \;;\; \Delta P = 304 \text{ LB.}$$



NO SCALE

Figure 8. Load-deflection relationships.

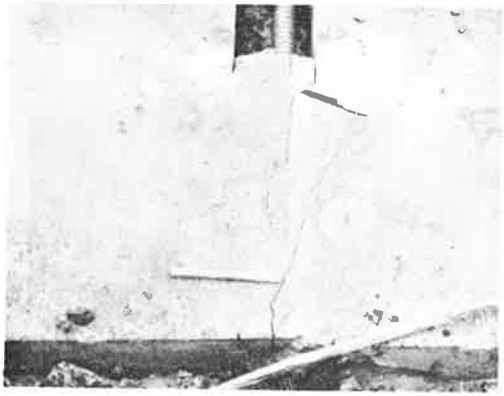


Figure 9. Failure at slot G.

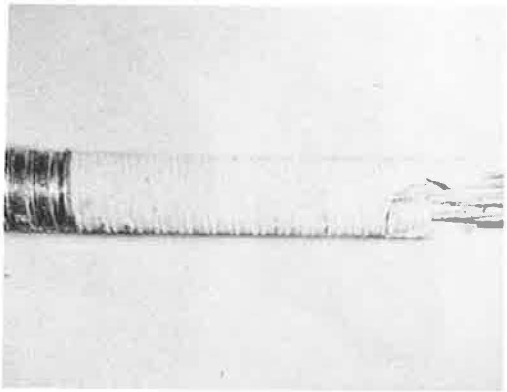


Figure 10. Grout—no initial crack in pavement.

severed during the construction of the slot. Using the same initial load on the tendon and a 31-in. length of bond for three strands, the bond stress would be 362 psi.

The grout was a solid core which completely filled the space inside the conduit (Fig. 10). It was a dark gray with a thin layer of white where it was in contact with the metal conduit. The material was extremely hard and adhered very well to the prestressing strands. It was necessary to use a hammer and cold chisel to remove the grout from the strands. It broke away in segments about 1 in. long. Apparently, cleavage planes had developed normal to the axis of the tendons (Fig. 11). These are probably shrinkage cracks that were pressed together.

Readings taken on the ungrouted tendon at slot P, 85 ft west of the test section, showed little change in strain during the test period. This indicates that the anchors were effective in holding the stress in the tendon. The developed bond stress in the strands was about 306 psi.

CORROSION

Figure 12 shows the condition of the conduit. Case I, at the top of the figure, has from 25 to 30 percent of its surface covered with a light coating of rust. Case II has been completely penetrated with pin holes in the upper area of the picture while the lower area has very little corrosion. In Case III the conduit is free from rust.

Figure 13 shows the condition of the strands. Case I was completely covered with a light film of rust. There was no flaking and very little pitting. In Cases II and III the black oxide coating was very evident. It was spotted with rust which covered as much as 30 percent of the surface in some areas. There was little or no pitting of the base metal. The dark spots on the

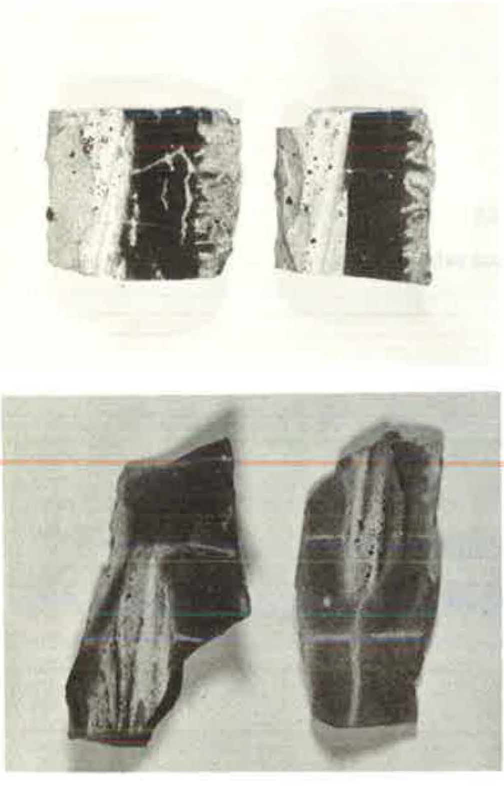


Figure 11. Segments of the grout.

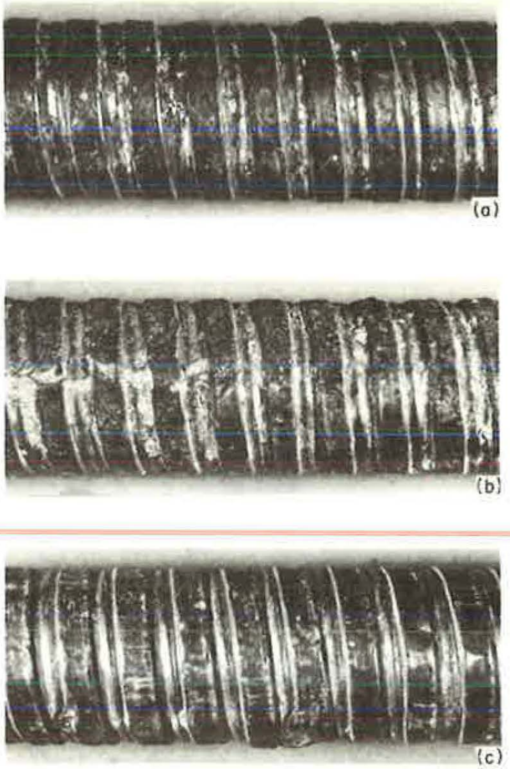


Figure 12. Condition of conduit: (a) Case I, ungrouted tendon; (b) Case II, grouted tendon—initial crack; and (c) Case III, grouted tendon—no crack.

surface of the grout in Figure 11 also illustrate the distribution of the rust.

Each of the strands from the three tendons shown in Figure 13 was subjected to the standard tensile test. The value of the ultimate load ranges from 25, 600 to 28, 80 lb with an average value for the twelve strands of 27, 183 lb. In all of the tests, failure occurred at notches which were caused by the strand vises. The initial tests for these strands indicated an ultimate of 28, 700 lb for one reel and 29, 800 lb for the other. This indicates a loss in strength of from 5 to 9 percent of the initial values.

The modulus of elasticity for the twelve strands varied from 26, 700, 000 to 30, 200, 000 psi with an average value of 28, 200, 000 psi. This is within 3 percent of the 27, 400, 000 psi used in the calculations for the design of the slab. Differences in testing techniques could very well account for the loss in ultimate load and the higher value of the elastic modulus.

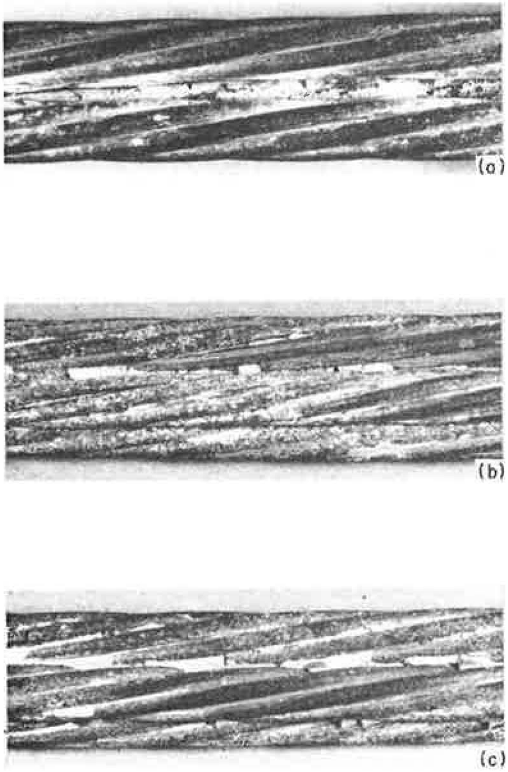


Figure 13. Condition of strands: (a) Case I, ungrouted tendon; (b) Case II, grouted tendon—initial crack; and (c) Case III, grouted tendon—no crack.

SUMMARY AND CONCLUSIONS

This investigation on an existing prestressed concrete highway slab was conducted about eight years after the pavement was constructed and two years after it was subjected to the moving load test. The cracks over the tendons in Case II developed during the moving load tests. The loss in prestress during the ensuing eight years is about 14 percent.

The grout was in excellent condition. Pull-out failure was not due to loss of bond stress between the tendons and the grout, but rather to the rupture of the concrete caused by the wedging action of the conduit on the concrete. This occurred when there was about 20 in. of concrete remaining to effect an anchor. The developed bond stress in the tendons at this time was about 421 psi.

Corrosion was present on the surface of the strands. It covered about 30 percent of the surface area. There was little or no penetration into the base metal. The average ultimate strength of 27, 183 lb compares favorably with the 27, 000 lb specified for ASTM A-416 prestressing strands. It appears that the corrosion had not developed to the extent that it had a detrimental effect on the strength of the pavement.

The test indicates that there was adequate bond to develop the stress in the tendons over a reasonable length. It also illustrates that the plane of weakness that exists in the reduced section of concrete at the tendons is a factor that must be taken into consideration in future designs. This may be minimized by providing transverse reinforcement or by redistributing the prestressing strands more uniformly across the pavement. It also demonstrates that the slab can be successfully cut without destroying the prestressed condition in the remainder of the pavement. It is recommended that a test section of this pavement be incorporated as a part of a highway system where the performance can be studied under normal traffic conditions.

ACKNOWLEDGMENTS

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1. Moreell, Ben, Murray, John J., and Heinzerling, John E. Experimental Prestressed Concrete Highway Project in Pittsburgh. Proc. Highway Research Board, Vol. 37, pp. 150-193, 1958.
2. Smith, John R., and Lightholder, Richard K. Moving Load Test on Experimental Prestressed Concrete Highway Slab. Highway Research Record 60, pp. 59-76, 1964.

Appendix

TABLE 1

BOND STRENGTH OF EPOXY

Test	Rod Dia. (in.)	Perimeter (in.)	Embedded Length (in.)	Load (lb)	Bond Stress (psi)	Slip-Stick Friction (psi)	Remarks
1	0.250	0.785	4	3,700	1,178	–	Bond failure[a]
2	0.375	1.178	4	8,600	1,825	790	Bond failure[a]
3	0.500	1.571	4	1,100	175	–	Bond failure[a]
4	0.250	0.785	4	350	111	–	Bond failure[a]
5	0.375	1.178	4	9,375	1,990	–	Rod failure[a]
6	0.500	1.571	4	2,050	326	–	Bond failure[a]
7	0.375	1.178	3.94	9,100	1,965	–	Bond failure[a]
8	0.500	1.571	4	13,850	2,205	–	Bond failure[a]
9	7/16 strand	1.374	12.5	4,825	280	–	Bond failure[a]
10	7/16 strand	1.374	12.75	16,000	913	456	Bond failure[b]
11	7/16 strand	1.374	12.75	20,700	1,181	684	Bond failure[b]
12	7/16 strand	1.374	13.0	17,475	998	628	Bond failure[b]
13	7/16 strand	1.374	13.0	15,000	857	798	Bond failure[b]
14	7/16 strand	1.374	13.0	21,650	1,237	1,083	Bond failure[c]
15	7/16 strand	1.374	13.0	13,775	786	856	Bond failure[c]
16	7/16 strand	1.374	13.0	–	–	–	No pull-out test[c]
17	7/16 strand	1.374	26.0	28,050	785	–	Strand failure[c]
18	7/16 strand	5.496	26.0	100,000	702	–	No failure (4 strands)[c]

[a] Epoxy bonding compound.
[b] Epoxy patching compound—1 part epoxy to 1 part sand.
[c] Epoxy patching compound—7 parts epoxy to 10 parts sand.

Notes: The perimeter of the prestressing strands is based on that of a 7/16 dia. circle.
Tests 12-18 were subjected to a creep test before loading to failure.
Tests 1-17—the load was transferred by the epoxy to a 1-in. pipe, 1.315 O.D. and 0.957 I.D.
Test 18—the load was transferred to mechanical tubing, 2.375 O.D. and 1.500 I.D.

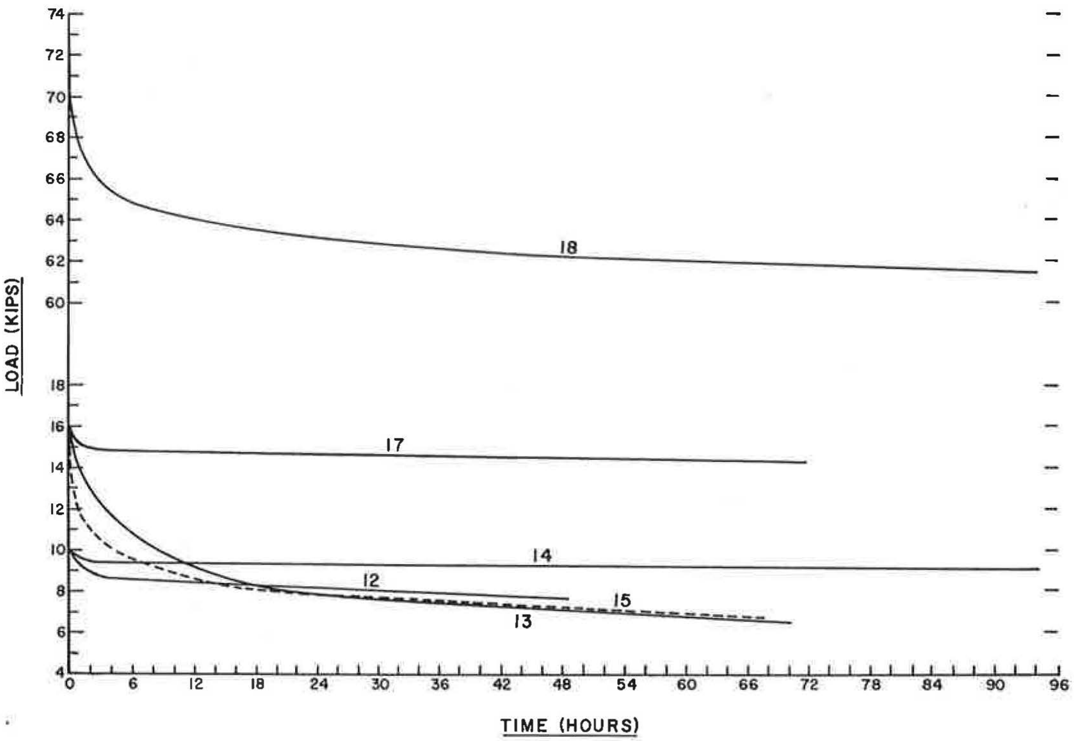

Figure 14. Epoxy creep test.

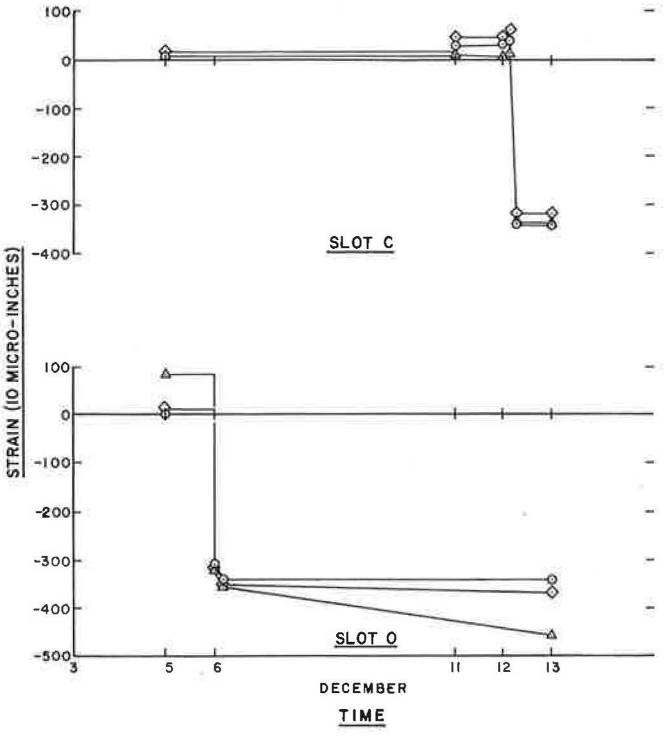

Figure 15. Change in strains, tendon I.

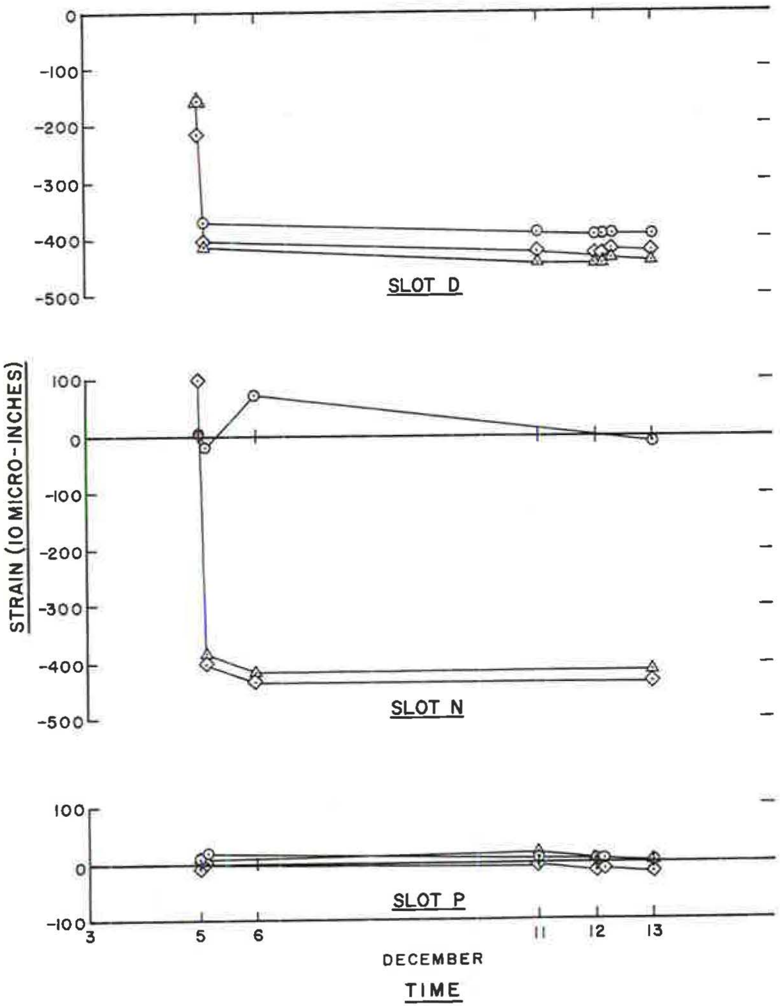

Figure 16. Change in strains, tendon 2.

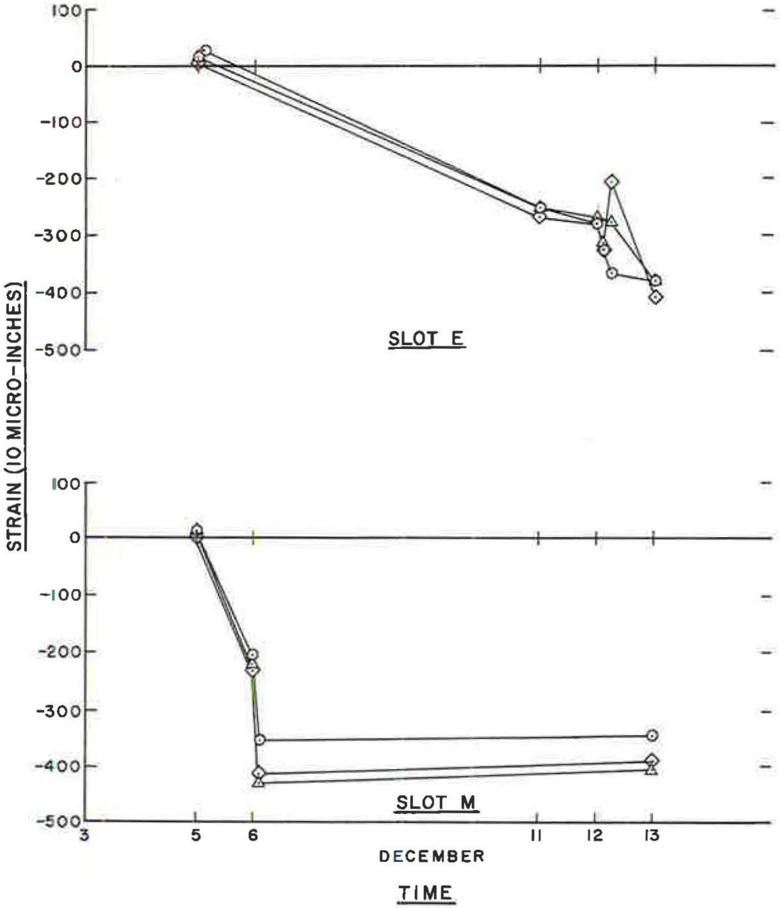

Figure 17. Change in strains, tendon 3.

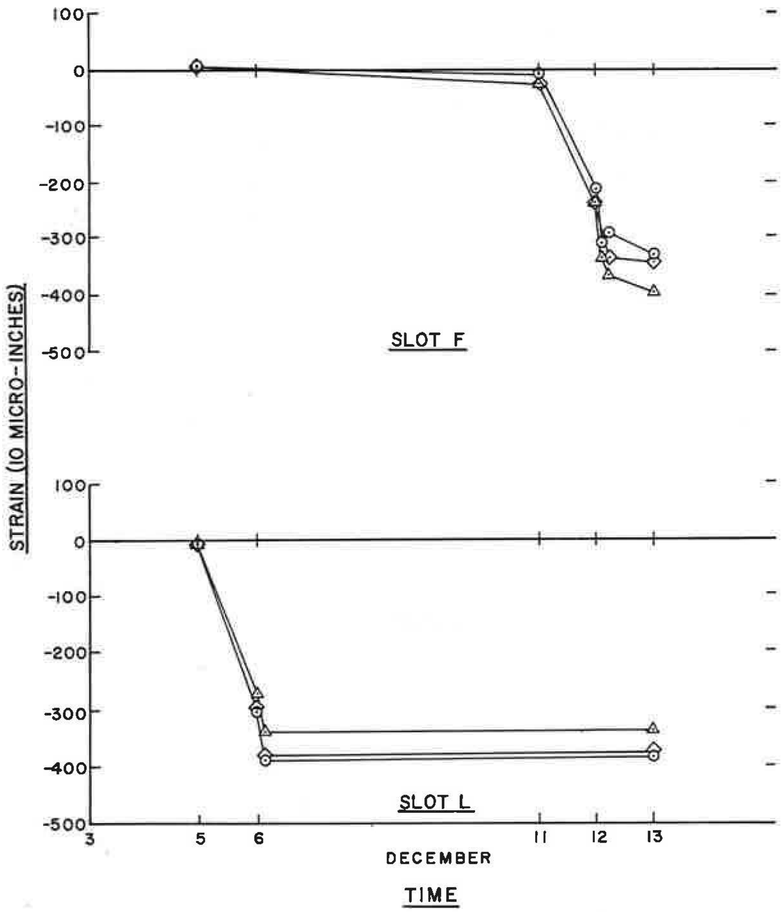

Figure 18. Change in strains, tendon 4.

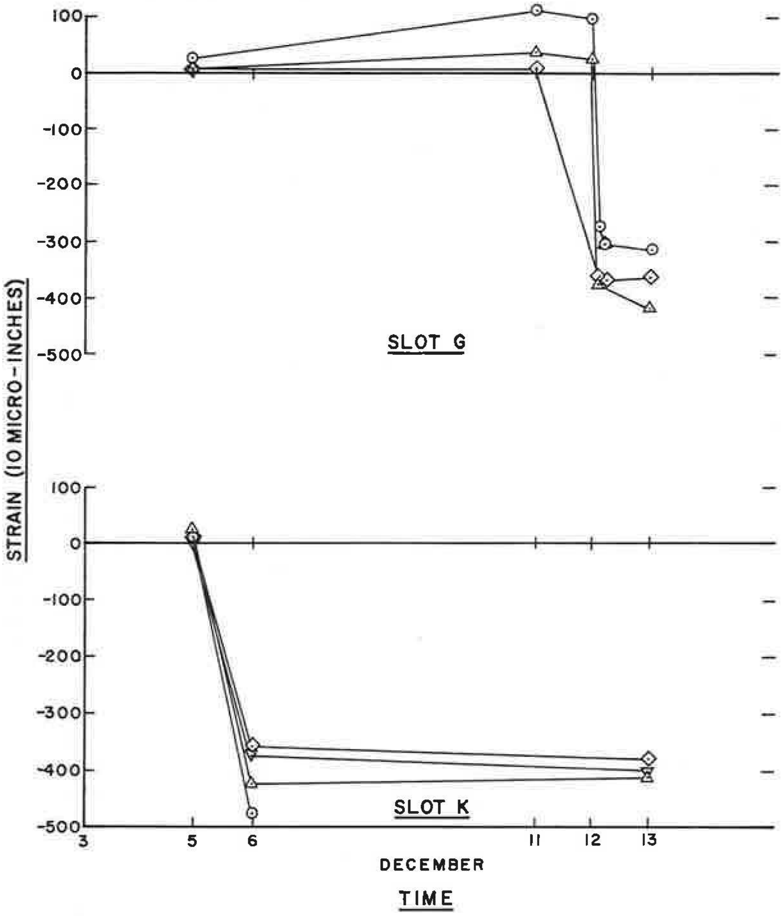

Figure 19. Change in strains, tendon 5.

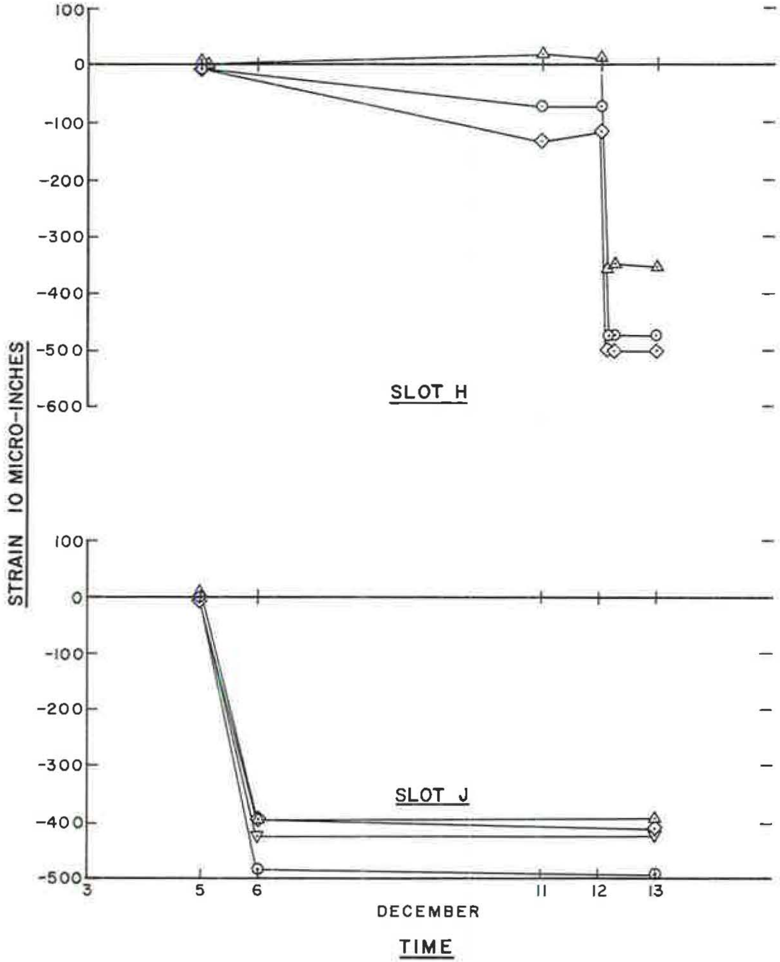

Figure 20. Change in strains, tendon 6.

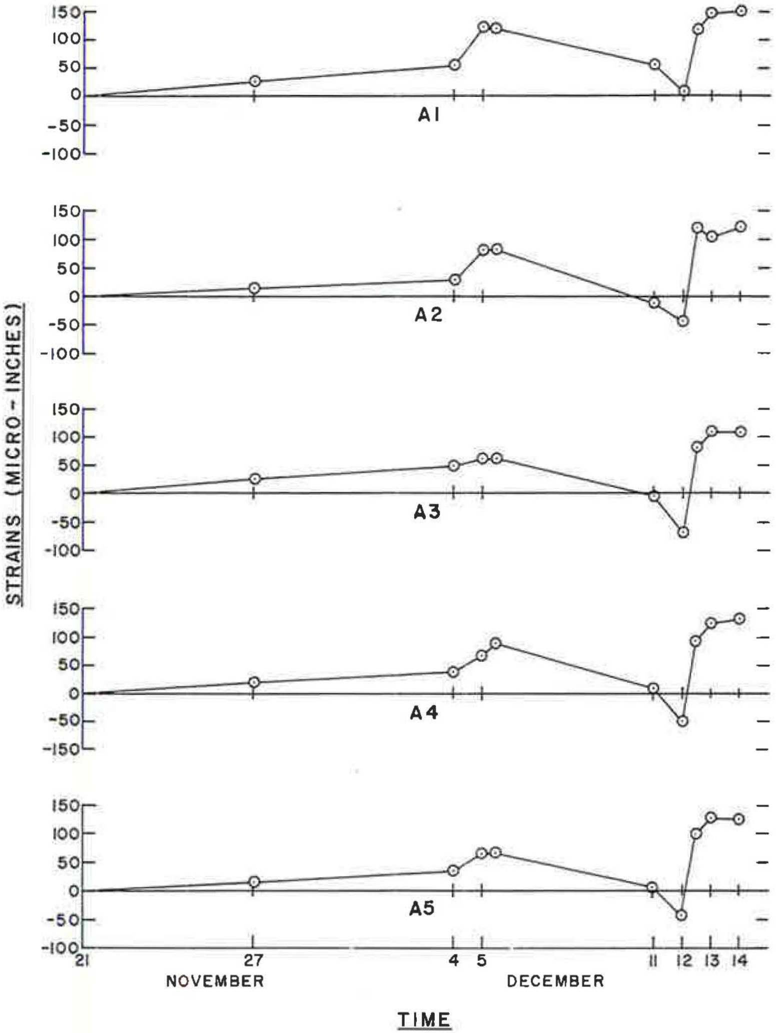

Figure 21. Change in concrete strains, gages A1–A5.

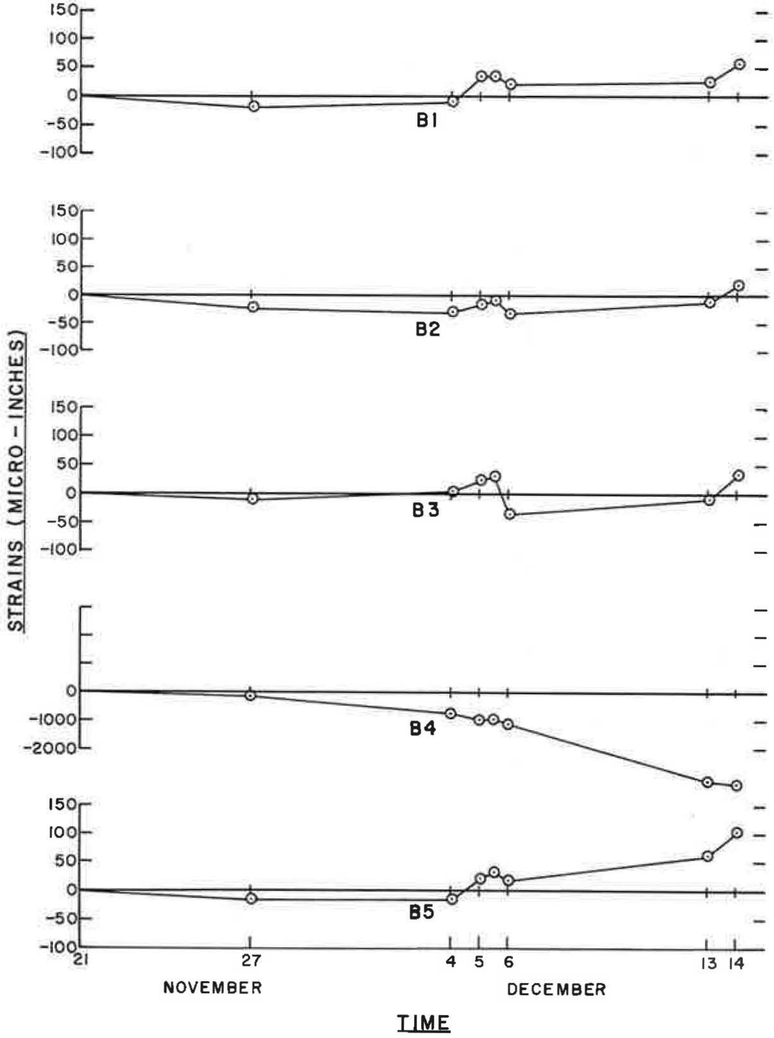

Figure 22. Change in concrete strains, gages B1-B5.

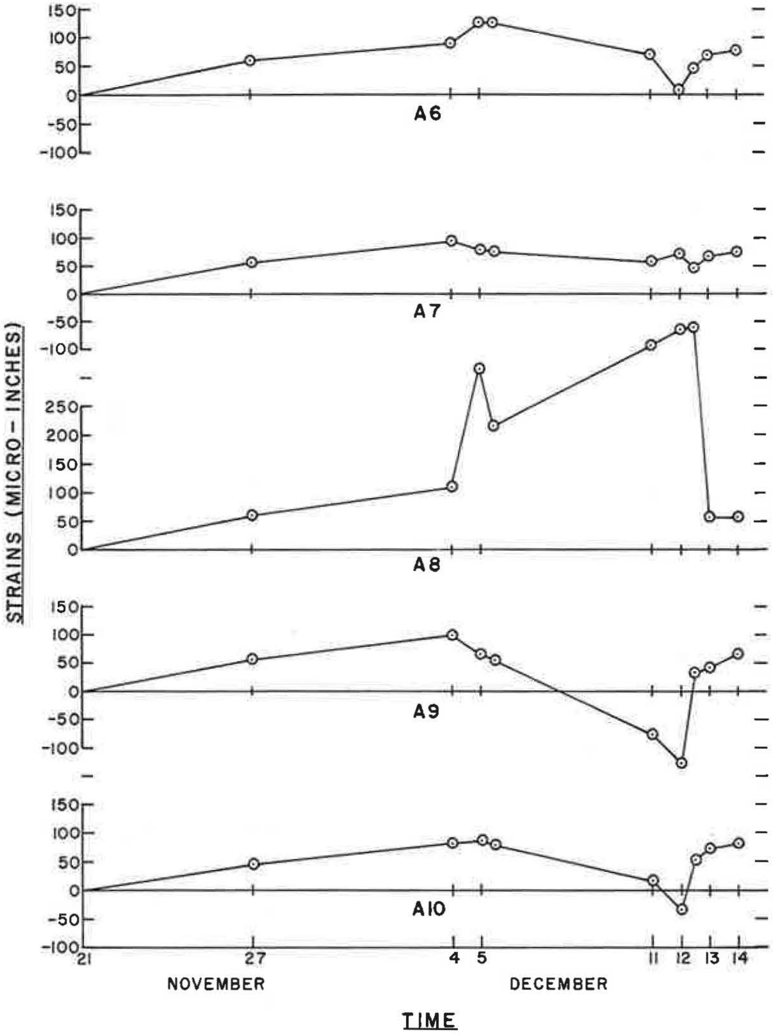

Figure 23. Change in concrete strains, gages A6-A10.

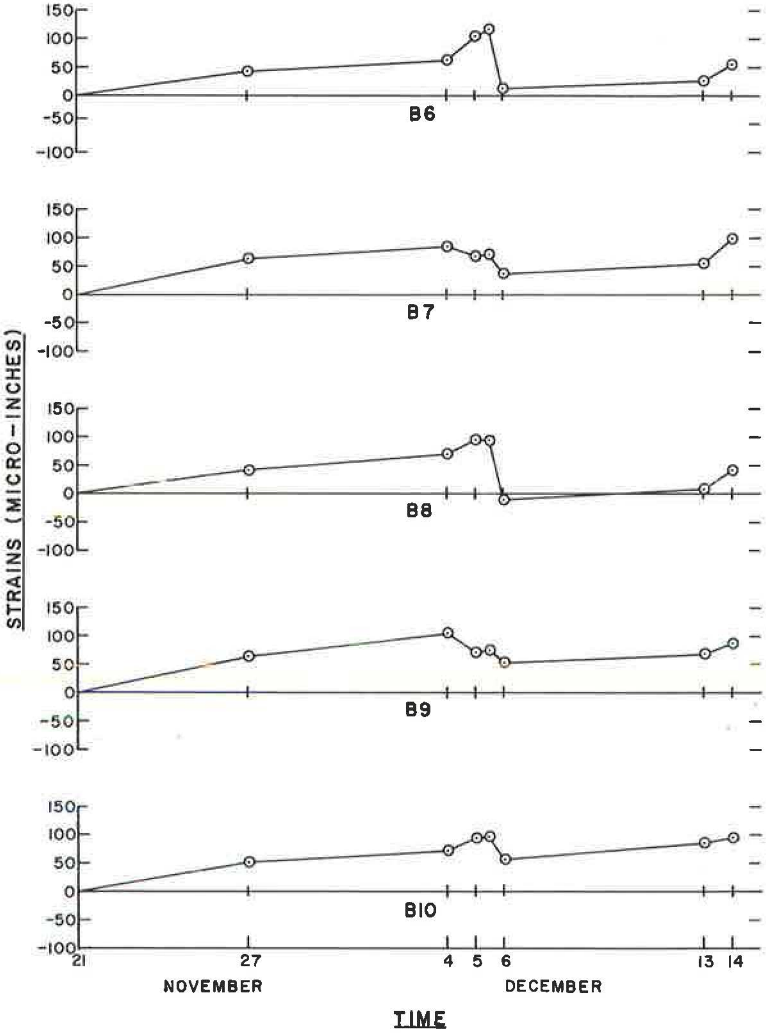

Figure 24. Change in concrete strains, gages B6–B10.