

Theoretical and Practical Aspects of Prestressed Concrete for Highway Pavements

THOMAS CHOLNOKY, Frederic R. Harris, Inc.
Consulting Engineers, New York, N. Y.

● THE INCREASING and successful use of prestressed concrete in this country directed interest toward the possible adoption of this method to highway and airfield pavements.

The apparent theoretical advantages of this novel pavement are still not formulated to the extent where they could be put into practical application in the most economical manner. Theories which were developed to predict the behavior of pavements under loads and volumetric changes therein, proved to be satisfactory only within certain limitations. The task to develop new theories to express the behavior of prestressed concrete pavements becomes even more complex, since it must deal with an increased number of variables.

Testing of such pavement seemed to be the only reasonable way to determine its merits. This made it also possible to cast some light on the practical problems which are to be encountered in future construction.

Following this course of thought, the experimental prestressed concrete slab built at the Patuxent River Naval Air Station was designed and constructed with the main purpose to obtain both theoretical and practical information. This test program, sponsored by the Bureau of Yards and Docks, Department of the Navy, was set up to investigate the adaptability of this new method to airfield pavements. The test results and experience obtained should be valuable, however, for highway engineers as well.

GENERAL THEORY OF PRESTRESSED CONCRETE PAVEMENTS

The apparent advantages of using prestressed concrete for highway pavements are twofold.

First, by using prestressing, pavements can be made continuous, without joints, within certain limitations. Second, by using prestressing, pavements can be made stronger to resist high loads or can be built thinner to resist the same loads, than conventional concrete pavements.

Actually both these features of prestressed concrete pavements can be explained by the inherent compressive energy in the concrete provided by external means. Such external means can be wires or strand under tension and imbedded in the concrete or hydraulic jacks, which can be used with fixed abutments to create compression in the pavement.

The additional strength offered by prestressing tendons when they are used cannot be compared simply with an increase in strength of the concrete. Cracking in a prestressed concrete section does not represent failure. The cracked section is still able to resist increasing loads until the limit condition is reached, similar to that occurring in reinforced concrete slabs.

The increased strength of prestressed concrete pavements points, of course, to the fact that such pavements can be produced with a thinner concrete section than conventional concrete pavements. Such pavements result in greater flexibility and therefore should adapt themselves with less detriment to uneven base conditions. Also, they should be less susceptible to differential thermal conditions, which create severe stress conditions in thick pavements.

The permanent compressive forces applied on prestressed slabs make it possible to build pavements continuous and eliminate thereby a great number of joints. Prestressing also provides a spring effect which will restore continuity in the event cracking in the slab should take place due to accidental reasons such as extreme thermal stresses, shrinkage or excessive loads.

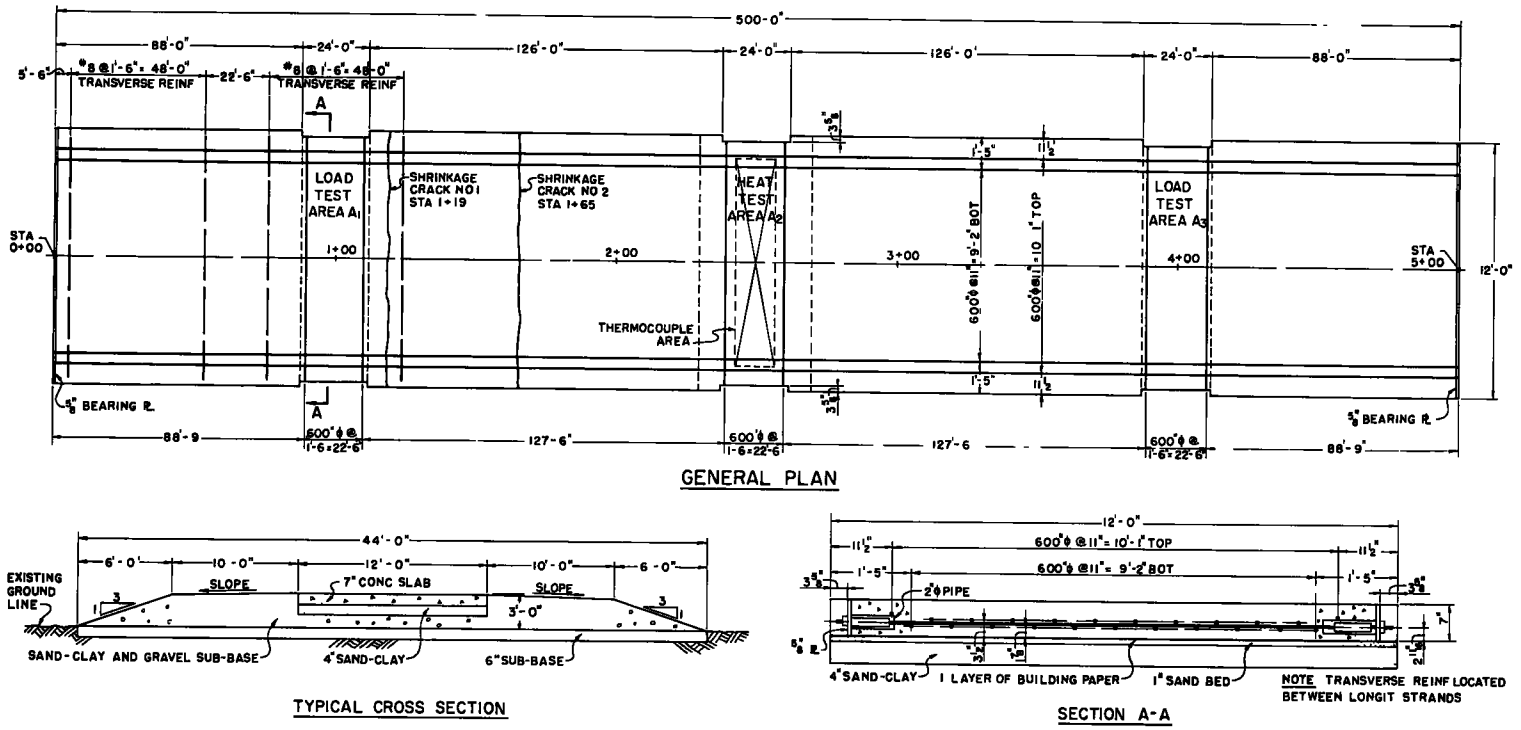


Figure 1. General plan (drawing — courtesy of American Concrete Institute).

DESCRIPTION OF THE TEST SLAB

The test at Patuxent (1) was set up to investigate the general behavior of prestressed concrete pavements with and without loads.

The slab itself is 12 ft wide, 500 ft long and 7 in. thick. Prestressing therein was provided longitudinally by two sets of 0.6 in. dia. strand, which consisted of seven hot-galvanized wires. One of the sets consisted of eleven strands placed at the center of the slab and is referred to as upper ("U") set. The lower ("L") set consisted of twelve strands placed $1\frac{7}{8}$ in. above the bottom of the slab. (See Fig. 1.)

Transverse prestressing was provided in three locations, called test areas, where the same strands as used for the longitudinal direction were placed between the two longitudinal strands.

All strands had standard end fittings for jacking and anchorage. They were designed to allow complete stressing of the strands from either of their ends. It should be noted that the longitudinal strands had to be stressed 36 in. to produce their design load to 30,000 lb.

The majority of strands was covered prior to placing with plastic tubing, the seams of which were sealed with mastic tape. Six longitudinal strands, as shown on Figure 2, were wrapped in "Sisalkraft" paper.

The strands were designed to take an initial stress of 140,000 psi, representing a total of 30,000 lb. Such a load created a compression in the concrete of 360 psi and 330 psi when the upper and lower sets were stressed independently. Applying the same load on each transverse strand exerted 235 lb on each square inch at the test areas.

In addition to the prestressing elements, the slab was reinforced in certain sections with transversally place No. 8 bars, spaced 1 ft 6 in. o.c. as shown in Figure 1.

Concrete used in the slab was designed with seven bags of cement and 34.5 gallons of water for each yard. Crushed limestone with maximum size of 1.5 in. was used for coarse aggregate. To increase strength and workability, $\frac{3}{4}$ lb of Plastiment per bag of cement and Dairex to produce between four and five percent entrained air was also used.

This design gave a rather harsh mix with 1-to $1\frac{1}{2}$ -in. slump which was gradually increased to $3\frac{1}{2}$ in. in the course of the concreting operation.

Results of an extensive test program made at the site are summarized in Table 1.

The slab was placed on a 2 ft 6 in. deep prepared subbase which consisted of a sand and gravel mix. Directly beneath the slab a four inch layer of sandclay was placed.

All material used for the subbase was placed in lifts not exceeding 5 in. and had to be compacted to 100 percent maximum density according to the modified Proctor compaction test. The specification called for a well finished surface, allowing not more than $\frac{1}{8}$ of an inch projections or depressions when measured with a 10-ft straight edge.

The friction reducing layer used under the slab consisted of one inch local sand, covered with building paper. The sand was ideal for this purpose, because of its uniform grain composition. Actually 94 percent of the material was retained on the sieves with meshes from 40 to 80.

CONSTRUCTION OF THE SLAB

During the preparation of the subbase, work began to cover the strands with plastic tubing and paper respectively. This operation proved to be rather time consuming and pointed to the necessity that such work should be eliminated in the field. Tendons if used as post-tensioning elements should be provided with a conduit around them in a factory and shipped so covered to the construction site.

The 500 ft long elements were assembled and covered on a work bench adjacent to the slab-bed. They were handled from there and placed by hand, another operation which created difficulties. Improved methods, such as feeding these elements from reels mounted on a platform, will be necessary in future applications.

Prior to placing the strands, the fine sand layer and sheets of building paper thereon, were laid on the top of the 4 in. sand-clay layer.

To secure proper positioning and alignment of the strands, temporary anchorages were installed at both ends of the slab. By using these anchorages, the strands were

TABLE 1
CONCRETE DATA

AGE OF CONCRETE (DAYS)	FLEXURAL STRENGTH (P.S.I.)	COMPRESSIVE STRENGTH (P.S.I.)	MODULUS OF ELASTICITY (P.S.I.)	SHRINKAGE (MILLIONTHS)	THERMAL EXPANSION (IN./IN.)
3	395	3070	—	—	—
7	610	3560	—	440	—
14	720	4830	3240000	510	—
28	805	5180	3350000	560	.00000616
60	850	5300	3560000	500	—
90	875	5370	3730000	520	—
180	885	5970	4070000	410	—
360	965	6470	4220000	330	.00000654

NOTES: 1. AVERAGE VALUES SHOWN

2. SHRINKAGE VALUES REPRESENT INCREASES AND WERE OBTAINED FROM FIELD CURED SPECIMENS

pulled straight and slightly stiff, applying approximately 1,000 lb on each strand. In addition the strands were supported by metal chairs spaced 6 ft apart.

This arrangement seemed to be satisfactory during casting, as long as concrete was spread in the longitudinal direction of the slab. Unfortunately, since most of the spreading was done by hand, the side pressure of the concrete dislocated some of the strands in the transverse direction. This was corrected as much as possible to maintain the proper alignment of the prestressing elements.

For easier placing and finishing of the concrete, its slump was gradually increased to 3½ in. With such consistency of concrete the operation proved to be much more satisfactory. The casting of the 500 ft long slab took 11½ hours.

The daily temperatures were considerably high, with a maximum of 84 deg F in the shade. The actual temperature in the sun well exceeded 100 deg F.

The slab was cured with paper and burlap for about five days.

The surface of the slab was inspected the morning following casting. At that time two shrinkage cracks developed across the entire width of the slab at Stations 1 + 19 and 1 + 65. No other cracking developed thereafter other than due to the various loadings.

PRESTRESSING OF THE SLAB

The first day following casting of the slab all temporary anchors were released and each strand was slackened to allow a minimum of one inch between the anchor-nut and the anchor-plate. The strands were pulled one by one through their conduits thereafter by using the stressing jack. The gage of the jack was carefully watched to observe any load indications. In none of the cases was any load observed, which would have indicated binding and bounding of the strands in their conduits.

Prestressing of the strands started the third day following casting. First all longitudinal strands were stressed and left under such condition for a period of 35 days. The first stressing of the strands was completed over a longer period and in several steps, mainly because of the various measurements made during these operations.

The lower and upper strands were stressed and released several times after their first stressing and released as shown in Figure 5. This was accomplished partly to create different stress conditions in the slab for the numerous load tests and partly for the general study of the distribution of the introduced stresses along the longitudinal direction of the slab.

As a result of the investigations made during the first stressing operation the following sequence was adopted for stressing the strands thereafter:

1. Introduce one-half of the required load on one end (e.g., Station 0 + 00).
2. Check load on other end (i.e., Station 5 + 00).
3. Introduce difference of final load and checked load at same end.
4. Check load at end where first prestressing was applied at Station 0 + 00.
5. Introduce difference, after checking, for final condition.

The equipment for stressing and release consisted of one hand and one electrically operated hydraulic jack. The latter offered advantages and resulted in considerable time saving.

For future use, jacks are recommended with maximum ram movements equal to the necessary stretching of the prestressing tendons, so that the time consuming re-settings can be eliminated. The average time required to produce 36 in. of elongation of the strands was 80 minutes. With easy jack operation and follow-up of the anchor-

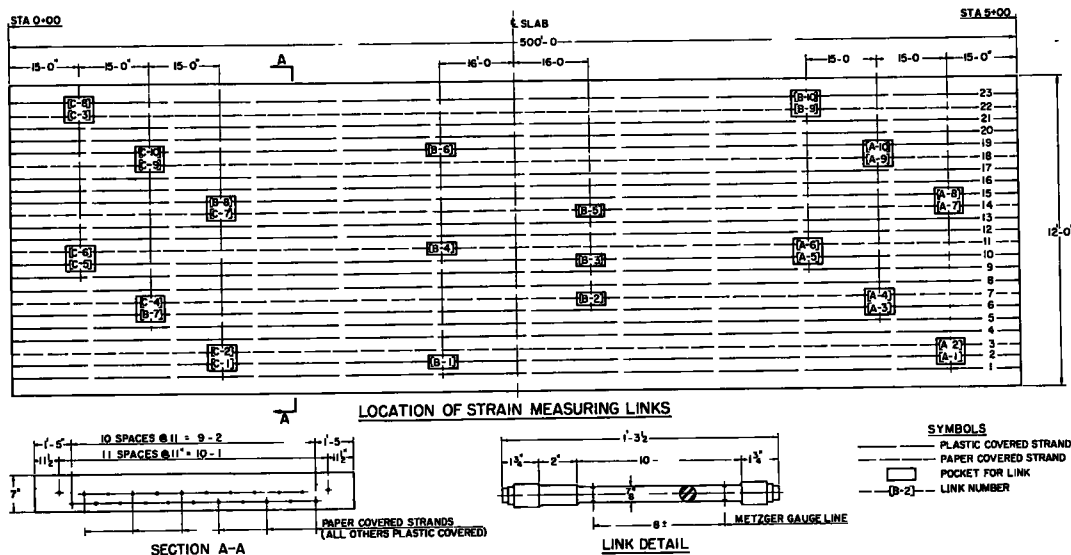


Figure 2. Strand layout.

nut this time could be reduced to about 10 minutes, including connecting and disconnecting the jacks to the elements as used.

TEST PROGRAMS

The test program was centered around two basic problems:

1. How to secure maximum efficiency in providing prestressing in the slab?
2. What is the minimum of prestressing required to secure continuity in the slab and its load-carrying capacity?

The efficiency of prestressing in the slab is affected by the distribution of loads on the prestressing tendons and by the friction resistance of the base underlying the slab.

The distribution of loads on the strands were investigated with the help of calibrated strain measuring links. These links were inserted in certain strands as shown in Figure 2. Loads were measured on these links with Metzger gages which indicate strain variations and these can be converted into loads.

The results of these tests were quite conclusive and pointed to considerable losses in certain cases.

The strain measuring links were mounted on strands belonging to four distinguished groups:

1. Three strands in the upper layer covered with plastic tubing.
2. Three strands in the upper layer wrapped in paper.
3. Same as 1 above, but in the layer above, supporting reinforcing bars and transverse strands in test areas A₁, A₂ and A₃.
4. Same as group 3, but wrapped in paper.

The best results were obtained in the case of strands in the upper layer covered with plastic tubing. The greatest losses were observed in strands in the lower strands covered with paper. Strands belonging to the two other groups showed about the same losses. The losses are expressed in percentage of the differences measured at the two ends, with relation to the introduced loads at the jacking end of the strands. These percentages are:

Group 1 - 5 percent

Group 2 - 19 percent

Group 3 - 15 percent

Group 4 - 62 percent

The results obtained from strands belonging to group 4, point to the importance of providing a proper conduit around the prestressing elements. Paper obviously did not resist the pressure of the concrete, as compared to the more favorable performance of the plastic tubing.

The higher values were registered in case of the lower strands are the result partly of the lower position of the strands, partly of the pressure exerted by the transverse reinforcement which was placed on them.

It is believed, that with presently available sheetmetal conduits applied around the strands in the factory, the losses could have been reduced to much lower value. The actual or possible friction losses should be determined with consideration to the length and position of the elements in future applications.

Since all strands were stressed partly from their both ends, it must be anticipated, that in case of differentials and resulting friction losses the intermediate section of the elements carried less loads than their corresponding ends. This difference produced an equalizing tendency which was observed during the course of testing.

The losses in prestressing after the loads were applied were studied also. Of course in cases where losses due to conduit friction were significant the result would be affected greatly by the leveling off of the differentials.

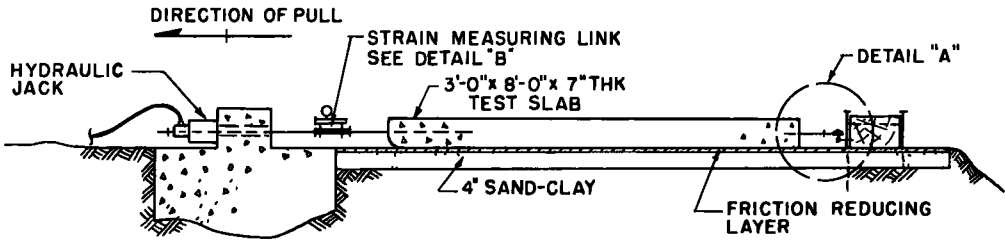
Strands belonging to group 1, with their average conduit friction loss of 5 percent should, however, give satisfactory results.

Losses after prestressing are due to shrinkage and creep in the concrete and creep in the strands. The results represent losses over a period of sixty days, for strands belonging to group 1 and give an average value of 10 percent.

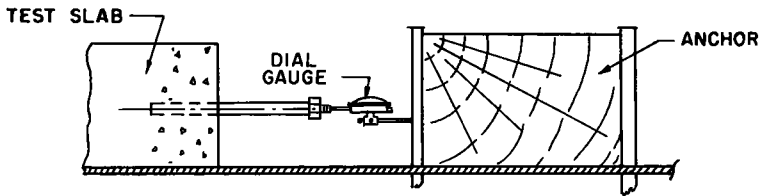
Total shortening of the slab during this sixty day period was not more than two inches. Since prestressing of all strands was completed only after the first 30 days, it may be reasonably assumed that the average shortening of the slab affecting the strands was not more than one inch. Such shortening would represent a loss of approximately 3 percent in the initial load. The relaxation of steel should lead to 6-7 percent loss, and the total result comes close to the measured 10 percent loss.

Losses due to base friction seem to be of greater importance and considerably more difficult to determine. The development of prestressing in the slab creates stresses in the slab accompanied by strain. Series of these strains lead to shortening of the slab, which means that the slab has to move actually in order to develop prestressing in its entire length. Such movements are obviously restrained by the base friction. The lower this base friction, the higher the efficiency of prestressing will be.

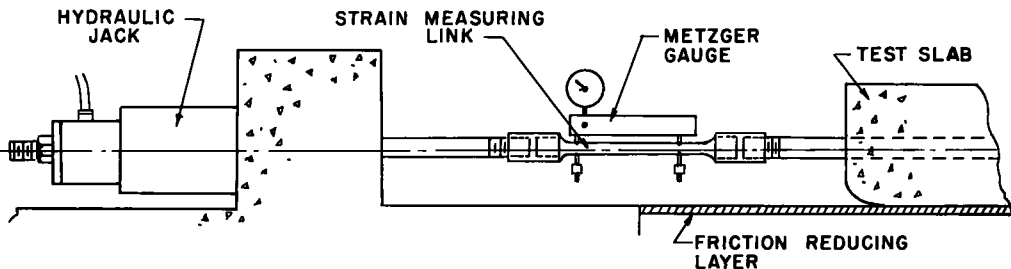
The problem of the resistance to prestressing offered by the base is a rather complex one. It is affected by temperature conditions, moisture content of the base, and not only by absolute values, but possibly even more by the gradient of these variables. It is also affected by thermal differentials existing between the slab and the concrete, and



ELEVATION OF FRICTION TEST



DETAIL "A"



DETAIL "B"

Figure 3. Friction test.

in the concrete itself. The magnitude of the prestressing forces will also have bearing on the friction losses.

It was of primary concern in the design stage of this experimental slab, to find a friction reducing expedient which will offer the lowest friction resistance at minimum construction cost. This problem was deemed important enough to conduct some preliminary testing before the construction of the actual slab.

Therefore concurrently with the base preparation, three experimental slabs, 8 ft by 3 ft and 7 in. thick were built on various friction reducing devices (Fig. 3). A fourth slab was placed directly on the prepared base. The three friction reducing devices were as follows:

1. One inch sand covered with one layer of building paper.
2. Two layers of building paper.
3. Two layers of copper-clad Sisalkraft paper, the copper sides facing and powdered soapstone between them.

The friction values obtained during these tests are tabulated in Table 2. They indicate the extremely high friction coefficient for the slab placed directly on the prepared base. The values obtained for the three slabs with the friction reducing expedient under them seem to be comparable with slab 1, giving the lowest friction values.

Considering cost, the sand and paper layer seemed to be economical and therefore

it was decided, that the 500-ft long slab be built on one inch of sand covered with building paper.

It is obvious, that the friction values obtained during these tests are only indicative as to the friction conditions existing under a 500-ft long prestressed concrete slab.

Failure in the friction layer will occur progressively under a long slab, more than in case of an 8-ft long slab. The presence of such successive friction failure will lower therefore the friction coefficient and probably could be expressed by an average value of those obtained at failure and sliding thereafter.

TABLE 2
FRICTION TESTS

Slab No.	Coefficient of Friction		Movement Before Failure in.
	At Failure	During Sliding	
1	0.72	0.60	0.045
2	1.13	0.55	0.004
3	0.77	0.63	0.018
4	5.15	1.10	0.012

The nature of the forces applied during the preliminary friction tests and of those present in a prestressed concrete slab are quite different also. In a prestressed slab the loads are sustained and therefore the yielding of the base should reduce the actual friction values. The exact determination of the magnitude of the effect of base yielding seems to be extremely difficult because of the presence of several factors.

These are temperature and moisture content variations in both base and concrete.

Test results made on field-cured specimens indicated maximum volumetric changes in the concrete in the order of 470 millionths. Average actual strains measured in the slab showed a maximum variation of 430 millionths.

Compared with these figures prestressing of 300 psi would produce a maximum of 75 millionths, if the modulus of elasticity of 4 millions, as found for the concrete in the slab, was used. This should clearly illustrate that the precision with which losses in prestressing due to base friction can be determined, is rather undetermined, mainly because of the considerable influence on this problem by factors mentioned above.

In addition to these problems, the effect of initial shrinkage developing immediately following casting of the slab must be considered also.

This shrinkage takes place prior to the application of the prestressing forces. It will develop as freely as allowed by base friction. Actually due to the resistance of the base, tensile stresses will develop in the concrete and they will be in equilibrium with the friction forces at any moment. Assuming that the slab remains continuous (i.e., no shrinkage cracks develop and that the friction values are low) the initial shrinkage will dissipate all friction resistance.

Temperature conditions in the concrete are not constant either before the application of the prestressing forces. If they have a decreasing tendency, they will create contraction in the slab and will be similar in effect to shrinkage. Increasing temperatures naturally will decrease the effect of shrinkage. In any case, the combined effect of initial shrinkage and temperature conditions will create a stress condition in the base and the concrete which will be in equilibrium at any time.

If these stresses dissipate the friction resistance of the base, prestressing can be applied, as a superimposed load virtually without loss. This would indicate that losses in prestressing due to base friction cannot be separated from the effect of shrinkage and temperature variations which take place in the slab prior to the application of prestressing.

This rather complex problem was investigated with the help of sixteen strain meters ("L" meters) placed in groups of four at stations as shown in Figure 4. These meters indicated not only strain variations but also temperatures.

Results obtained in connection with the first prestressing of the slab were far from being conclusive. Therefore, a detailed program was set up to study this problem. During this program prestressing was released, then applied again, first by all upper

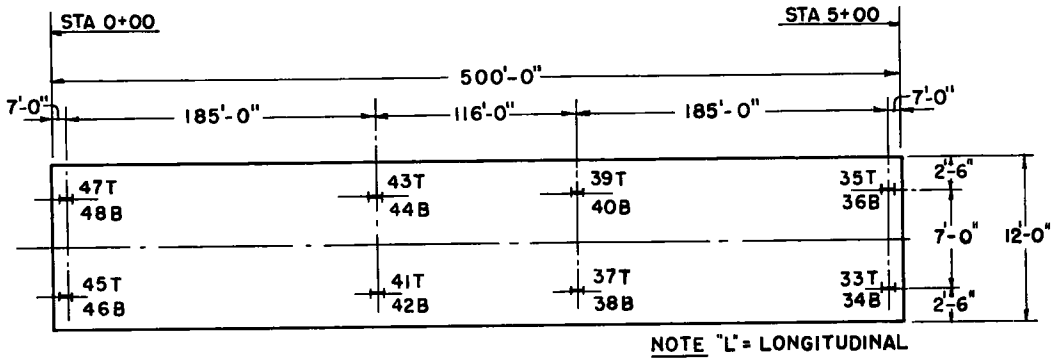


Figure 4. Location of "L" strain meters.

strands, then all lower strands and finally by all strands, with sufficient time intervals provided in between the various stressing operations. Strain meter readings were made after and before the slab was either stressed or released and usually conducted for a period long enough to determine a satisfactory strain condition under day - night variations.

Using the average results obtained from the four meters located at four various stations, the strain variations at the center of the slab were determined by extrapolation.

The results of these tests indicated practically no loss in prestressing, when the set of upper strands were stressed, February 5, 1955. Similar results were obtained when the lower strands were stressed there after April 1, 1955.

At the release of all strands on April 20, 1955, the strain meter readings indicated a drop in strains in the intermediate locations of the slab approximately 12 percent higher than the values observed at the ends of the slab. This greater drop in stresses is obviously the result of restrained volumetric expansions, which were released together with the stresses due to prestressing.

The slab was left unstressed for a week thereafter, and stressed to the maximum possible value of 690 psi, on April 27th. The results registered immediately thereafter indicated a loss of approximately 23 percent at the center of the slab. It should be noted that at this time the tendency of temperature variations was increasing and therefore prestressing forces were opposed by those caused by restrained volumetric changes.

The following release and repeated stressing of strands lead to findings which indicate clearly the effect of time on the friction losses. Immediate observations made after the release of May 1st indicated considerable amount of residual stresses remaining in the center portions of the slab in the order of 45 percent. When the slab was stressed again on May 4th, the maximum losses amounted to approximately 27 percent. The difference should be explained by a drop in residual stresses left after the release.

Repeated prestressing as performed on the slab points, however, to an important problem which if exploited correctly should add to the efficiency in developing prestressing. If prestressing is applied in a slab and released after the introduced stresses and friction forces reached a final state of equilibrium (i. e., after most of the yielding of the base took place) stresses will remain in the center portion of the slab. This will occur because friction will develop and will restrain the expansion of the slab. These interlocked stresses can be increased by applying repeated prestressing in short cycles, allowing time for development of prestressing, but eliminating the drop in residual compression in the unstressed slab. The results obtained clearly indicated the advantageous behavior of a prestressed concrete slab in this respect.

Thermal conditions of the concrete should offer further assistance to secure the most efficient conditions for the development of prestressing forces. Prestressing should be applied whenever temperatures have a decreasing tendency. Seasonal changes seem to have more influence than the day - night variations.

The over-all results did not lead to the finding of an absolute friction coefficient applicable to this test slab. It was found, that proper provisions must be made to keep

friction at a low value when prestressing is introduced, and that this should be applied when the volumetric changes in the concrete create contraction in the slab. A recommended friction coefficient of .5 should be used rather as a yardstick to provide sufficient prestressing, than an absolute figure expressing friction losses.

The effect of prestressing was demonstrated at the two shrinkage cracks at Stations 1 + 19 and 1 + 65. These cracks opened up to somewhat more than $\frac{1}{16}$ of an inch before prestressing and closed gradually thereafter. They remained closed and tight whenever the slab was under compression.

The over-all length variation of the slab was determined from strain measurements performed on the "L" meters. These readings were not continuous and did not coincide with extreme conditions. They should, however, give fairly accurate results.

The maximum shortening of the slab was registered in December, 1954, with 300 psi prestressing in the slab. This amounted to a weighted average of 430 millionths, totaling 2.6 in.

LOAD TESTS

A total of 29 tests were performed on the test slab. These were made under different conditions, varying the amount of prestressing plate size and location. The summary of these tests is shown in Table 3.

The loading equipment with 100,000 lb capacity used at the beginning had to be replaced during the tests with another one having a capacity of 200,000 lb.

Most of the tests were performed at the centers of the two load tests, Areas A₁ and A₃, where strain meters to register concrete stresses and pressure meters to determine base reaction, were placed. Deflections in the area affected by the loads were measured also.

Other tests were made at the edges of the slab, at areas where no transverse strands were placed and also at the two shrinkage cracks.

The first seven load tests were performed on test areas A₁ and A₃, with varying amount of prestressing and plate sizes of 8 and 20 in. in diameter.

The results obtained during these tests did not seem to be affected by the differences in amount of prestressing and size of plate on which the various loads were applied. Deflections and loads were in proportion in the available load range.

To produce a more severe loading condition, the available load of 100,000 lb was applied on a 3 in. and then on a 2 in. plate in diameter. These tests were made at Station 1 + 43, where only 300 psi longitudinal, but no transverse prestressing was available.

Deflections were considerably higher, but recovery of the slab was better than 85 percent after the load was removed. The effect of these loads with extremely high concentration became apparent several months after, when a longitudinal crack was observed on both sides of the point of load application. It is most likely that it was the result of certain initial cracking, which developed on the bottom of the slab and worked its way through the entire section as a result of cyclical volumetric changes.

As soon as the new loading equipment with 200,000 lb capacity became available load tests were performed on test areas A₁ and A₃. The results of two tests, Nos. 15 and 27 were in close agreement. These tests were performed on a 20 in. plate. Two other tests (Nos. 17 and 22) performed at two different locations but on the same 8 in. plate were in agreement also; but the effect of increased load concentration resulted in higher deflections, as compared to those obtained with a 20-in. plate.

It should be noted that during test No. 17, the 8-in. plate punched through the slab under a load of 189,000 lb. This should not be considered as an indication of the strength of the slab, because this failure took place in a location where the concrete section was considerably weakened by the height concentration of various instruments embedded therein.

The effect of the amount of prestressing was not evident during these tests. The registered difference measured during load tests Nos. 15 and 27 is so small that it hardly could be explained by the fact that the amount of prestressing was increased from 250 psi to 600 psi. It is felt that the amount of prestressing would have demonstrated its true effect under considerably higher loads than those available.

Two load tests were performed at portions of the slab, where no prestressing w

TABLE 3
SUMMARY OF LOAD TESTS

TEST NUMBER	DATE	LOCATION	APPLIED LOAD WITH INCREMENT (KIPS)	PLATE	PRESTRESSING IN SLAB (KIPS)		MAXIMUM DEFLECTION (INCHES)	MAXIMUM "K" Psl per in.
					LONGITUDINAL STRANDS	TRANSVERSE STRANDS		
1	10-20-53	A ₃	10-20-30-40-50	20"	550	200	0.36	—
3	12-17-53	A ₃	20-35-50-75-100	20"	250	200	0.63	—
4	12-18-53	A ₃	10-20-30-40-50	8"	250	200	0.32	270
5	4-27-54	A ₃	25-50-75-100	8"	250	200	0.63	420
2	11-17-53	A ₁	10-20-30-40-50	20"	550	200	0.30	—
6	4-28-54	A ₃	12 ⁵ -25-37 ⁵ -50-62 ⁵ -75-87 ⁵ -100	20"	250	200	0.55	—
7	4-28-54	A ₁	25-50-75-100	8"	250	200	0.53	420
11	4-29-54	STA 1+43	10-20-30-40-50-60-70-80-90-100	3"	300	0	0.88	—
12	4-29-54	STA 1+43	50-60-70-80-90-100	2"	300	0	0.76	—
13	4-30-54	STA 1+43	10-20-30-40-50-60	2"	300	0	0.45	—
15	12-8-54	A ₁	50-100-125-150-182-200	20"	250	240	1.57	280
17	12-10-54	A ₃	50-75-100-125-150-175-189	8"	250	240	~ 1.50	400
18	2-1-55	STA 3+60	50-100-150-185	20"	0	0	~ 4.59	—
21	2-3-55	STA 0+83	100-125-150-175	20"	0	0	2.82	—
22	3-29-55	A ₁	200 (6 TIMES)	20"	280	240	2.00	250
23	3-30-55	STA 3+94	200 (12 TIMES)	20"	280	240	2.87	—
24	4-19-55	STA 3+94	200 (18 TIMES)	20"	600	240	2.34	—
26	4-20-55	A ₁	200 (10 TIMES)	20"	600	240	1.57	—
29	4-20-55	A ₁	50-100-150-200	8"	600	240	1.77	—
27	4-20-55	A ₁	50-100-150-200	20"	600	240	1.54	450
8	4-28-54	STA 1+65	12 ⁵ -25-37 ⁵ -50-62 ⁵ -75-87 ⁵ -100	8"	300	0	1.03	—
9	4-29-54	STA 1+65	12 ⁵ -25-37 ⁵ -50-62 ⁵ -75-87 ⁵ -100	8"	300	0	0.86	—
10	4-29-54	STA 1+65	12 ⁵ -25-37 ⁵ -50-62 ⁵ -75-87 ⁵ -100	8"	300	0	0.91	—
16	12-9-54	STA 1+65	50-75-100-125-150-175-200	20"	250	0	2.88	—
20	2-2-55	STA 1+19 875	25-50-75-100-125-150-180	20"	0	0	2.62	—
14	4-30-54	STA 1+45	20-40-60-80-95	8"	300	0	~.250	—
19	2-1-55	STA 3+60	25-37 ⁵ -50-100	8"	0	0	1.92	—
25	4-19-55	STA. 3+94	50-75-100-125-130	8"	600	240	~ 1.77	—
28	4-20-55	STA 1+00	50-100-132	8"	600	240	2.49	—

LOAD APPLIED AT INTERIOR OF SLAB

AT SHRINKAGE
CRACKS

EDGE
LOADING

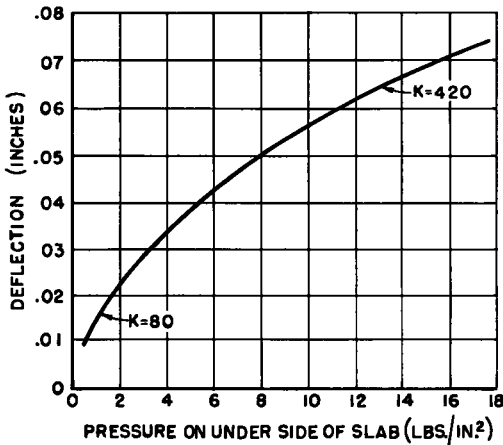


Figure 5. Variation of "K", load test No. 5.

recovery of the slab was never less than 85 percent after the load was removed. There was no cracking observed on the surface, however indications by strain meters located in the bottom part of the slab point to some cracking on the bottom of the slab.

Even if such cracking would have developed, it would not have meant failure and the slab could have resisted considerable additional load before reaching the ultimate condition. It would have been of great interest to obtain information on the behavior of the loaded slab nearing limit conditions. Unfortunately, the estimated loads to produce such conditions were so high that immediately practical means were not at hand.

It is assumed that the slab with prestressing would have offered considerable resistance even after cracks fully developed top and bottom. Such cracking obviously creates a redistribution of moments in the slab, and therefore loads still could be increased considerably thereafter and before failure either in steel or in concrete would take place. If cracks develop without reaching the limit conditions, they will close as soon as the loads are removed and continuity will be restored by the prestressing forces in the slab.

Based on the various deflection characteristics obtained during the various load tests it can be predicted that the slab would not fail under load up to 350,000 lb with 300 psi of prestressing.

Barring the possibility of obtaining the loading equipment of such high capacity, the slab was loaded with 200,000 lb in short cycles during the final plan of the testing.

The measured deflections were higher than those obtained with single loadings during previous tests. It should be noted, however, that in certain tests the load was sustained for a considerable time, as during load test No. 23. In another test, No. 26, when the 200,000 lb load was applied in 10-min. intervals the over-all maximum deflection still remained in the order of those registered with single loadings. As it can be seen the slab did not lose its high recovering ability and in load test No. 26 the instantaneous recovery after the tenth application of the load was over 95 percent.

The deflections observed during these tests may be considered excessive from the point of view of general practice. It was not expected that the base could have followed the concrete slab in its deflections and recoveries. A thorough study was made to determine the magnitude of base reaction under loads of such high order. The pressure meters placed at the two test areas gave valuable information in this respect.

Readings on these meters were made

available. Both tests were performed on 20-in. plates. The locations of these tests were selected so that one was performed where the slab was reinforced transversely with No. 8 bars. The results of these tests indicated the beneficial contribution of reinforcement. The slab without prestressing failed under a load of approximately 125,000 lb, when the deflections increased suddenly. Deflections measured during load test No. 21 were considerably lower, but indicated rapidly increasing deflections and a cracking pattern developing similar to that observed during load test No. 18.

Comparing the results obtained on sections with and without prestressing, it is evident that the prestressed sections had an extremely high load-carrying capacity. Deflections remained fairly proportional in the available range and the instantaneous

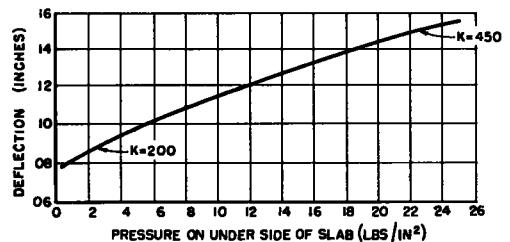


Figure 6. Variation of "K", load test No. 27.

at each load application and thereby relation between loads, deflections and base reactions were established. The relation between pressures and deflections developing under the slab, known as the K value (psi, per in. of deflections) or the supporting value proved to be variable and showed an increasing tendency, with increasing pressures in accompanying each deflection increment.

This finding was in contradiction with the Westergaard theory which assumes a straight proportion between pressures and deflections. A typical case is shown in Figure 5, load test No. 5, where the relation between deflections and pressure indicates a K of 80 in the considerably higher K of 420 for deflections exceeding 0.05 in.

It was also found that after applying high loads, deflections became so excessive that very little recovery took place in the base, and as a result actually a void developed

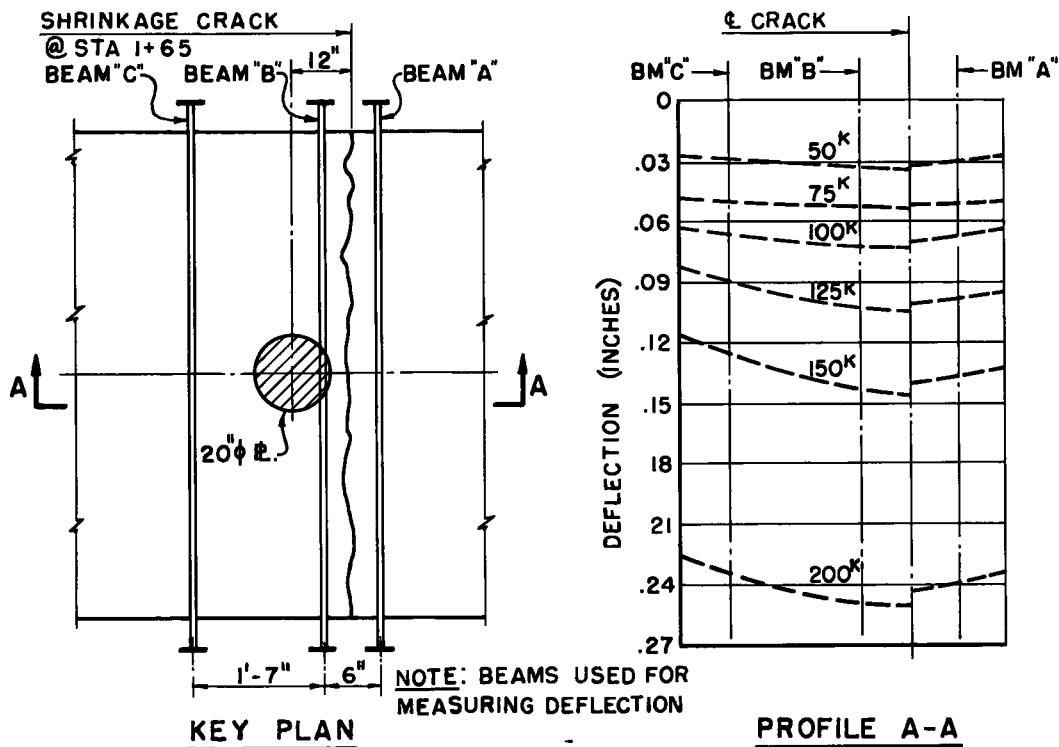
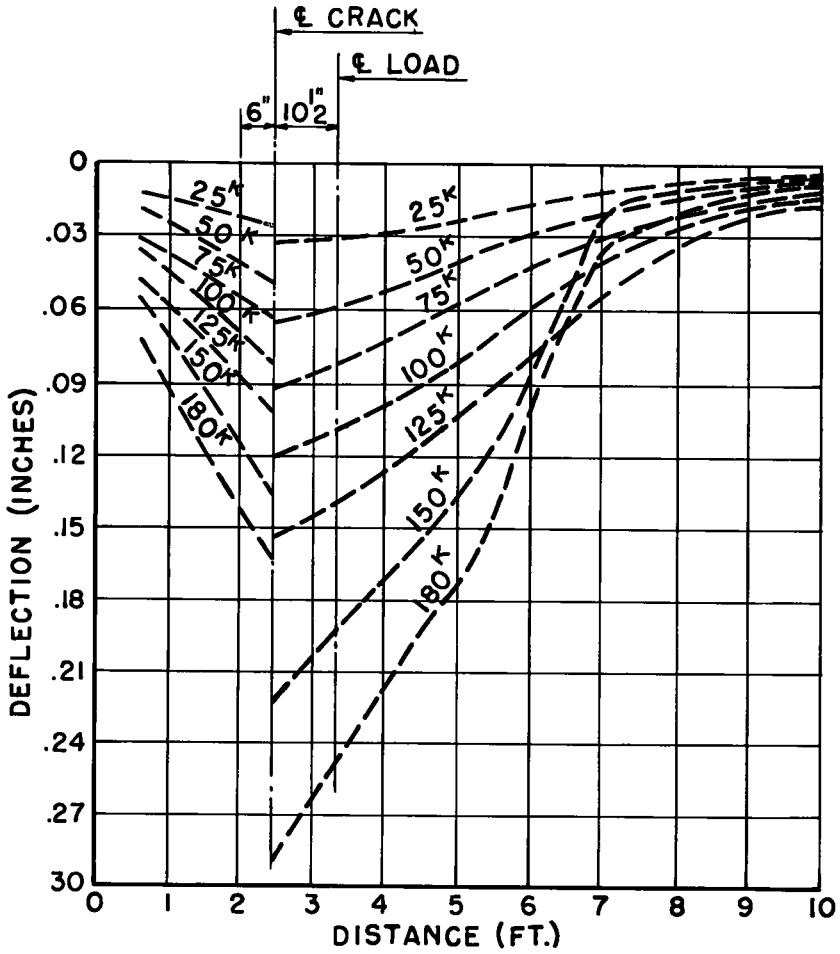


Figure 7. Deflections, load test No. 16; longitudinal prestressing = 250 psi, transverse prestressing = 0 psi.

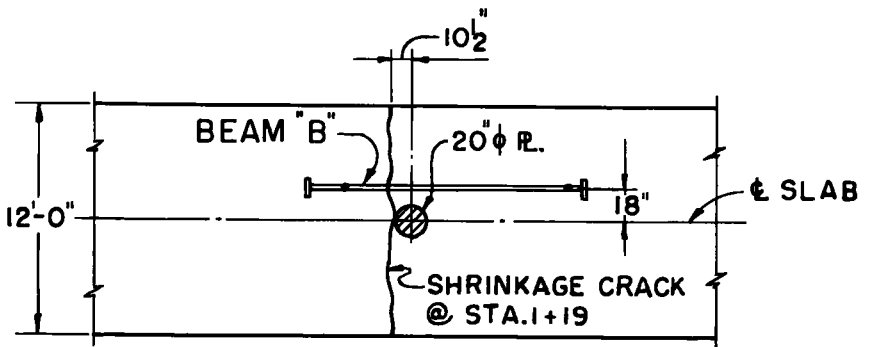
between the bottom part of the slab and the deflected base. This was clearly demonstrated during load test No. 27, when the 200,000-lb load was applied in several increments, measuring simultaneously the maximum deflections and maximum pressure adjacent to and directly under the load. The results revealed that there was no contact between the face of the pressure meter at the bottom surface of the slab and the base until deflections reached 0.08 in. under an approximate load of 100,000 lb. At this point, the initial K was 200 and increased to 450 under the maximum load of 200,000 lb and a deflection of 0.154 (Fig. 6). It should be noted that load test No. 27 was performed immediately after load test No. 26, at the same location, where the maximum load of 200,000 lb was applied ten times in short cycles.

The five load tests performed at the two shrinkage cracks proved also the beneficial contribution of prestressing.

During load test No. 16, which was performed at Station 1 + 65, there was no indication of failure and only a slightly noticeable shifting took place across the crack (Fig. 7).



DEFLECTION UNDER BEAM "B"



KEY PLAN

Figure 8. Deflections, load test No. 20; no prestressing in slab.

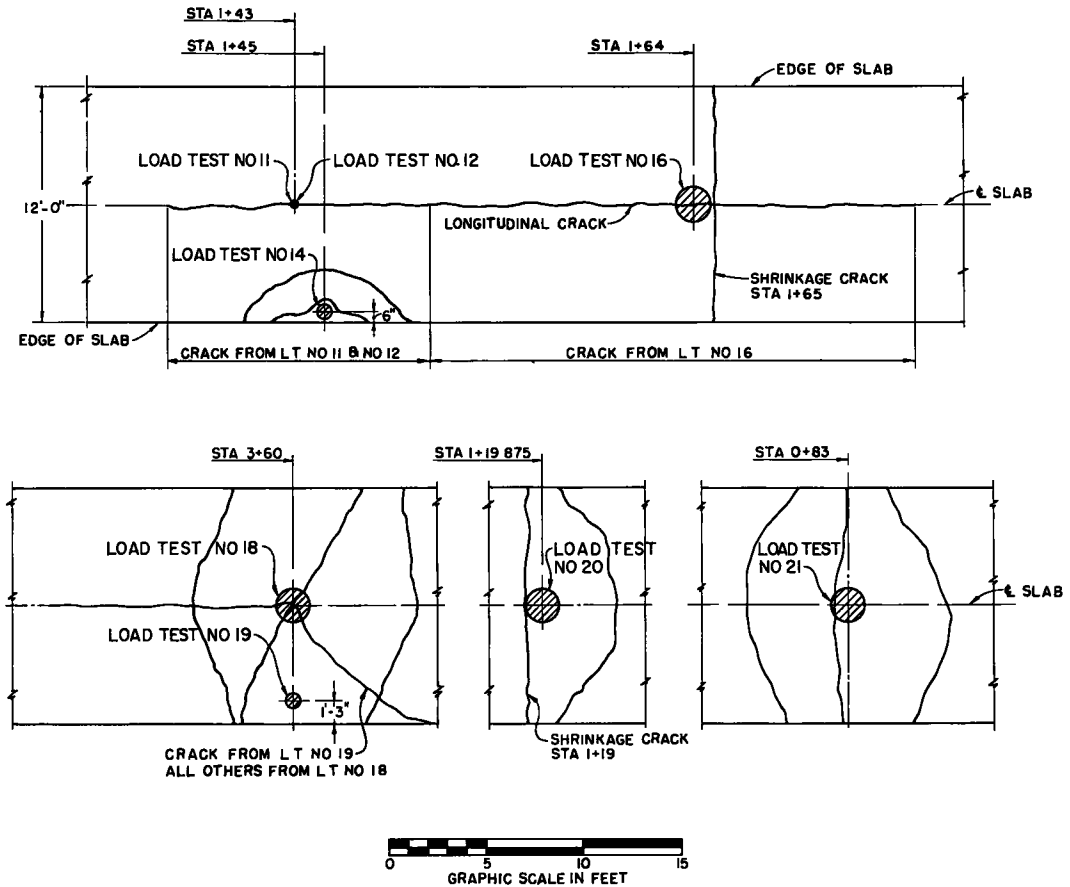


Figure 9. Cracking pattern.

The measured deflections were higher than those registered under similar loads, but at uncracked sections. It should be noted, however, that there was no transverse prestressing at this location. Recovery after removal of the maximum load was 86 percent, which by itself should be good indication as to the strength of the slab.

The results obtained during load test No. 20 indicated shifting across the shrinkage crack after the first load increment was applied. The deflection differential increased thereafter, until the slab failed under a load somewhat over 125,000 lb. The location of the crack which developed can be easily determined from the deflection profile (Fig. 8).

Load tests performed at the edges of the test slab lead to some information on the effect of prestressing on that portion of the slab.

All these tests were performed on an 8-in. plate. During load test No. 14, when the slab was prestressed only longitudinally to about 300 psi, failure occurred after the load exceeded 75,000 lb and deflection 0.12 in. The general cracking pattern is shown in Figure 9. There was no cracking transversely on the bottom of the slab.

The results obtained during load test No. 19 unfortunately cannot be considered of full value because the load was applied in an area where cracking occurred from previous loadings (Fig. 9). It should also be noted that in this case the load was placed 1 ft 3 in. from the edge of the slab as compared to 6 in. in the other cases.

CONCLUSIONS OF THE TESTS

The test indicated the over-all superior behavior of the prestressed concrete slab. Sand and building paper proved an efficient solution to reducing base friction.

Losses due to conduit friction of the strands can be kept to a minimum providing stiff covering material and using suitable placing and spreading of concrete.

Losses in the strands thereafter can be expected not to exceed 10 percent, even in extreme cases.

The problem of developing prestressing in the concrete has not been completely clarified, mainly because of the presence of several factors affecting base friction. It was found, however, that prestressing can be developed under given circumstances in the most efficient manner when the continuously changing volumetric changes in the concrete have a decreasing tendency (i. e., when the concrete tends to contract).

The effect of repeated prestressing in short cycles proved also beneficial.

As far as load-carrying capacity is concerned, the slab could have resisted extremely high loads. The added compressive energy in the concrete provided by prestressing, coupled with its spring effect would make considerable reduction in pavement thickness possible.

Load tests performed at the shrinkage cracks and at the edges also proved the beneficial contribution of prestressing in concrete pavements.

GENERAL CONCLUSIONS

The test program and the following conclusions of course did not cover all problems related to this novel pavement. The possibilities of most economical and most efficient means of providing prestressing in a concrete pavement have not been investigated.

Prestressing in a pavement can be provided either externally by using hydraulic jacks or internally by prestressing elements which are embedded in the slab.

The use of jacks seems to be economical, especially if they could be used in between a series of slabs, with few abutments. The cost of expensive abutments can thereby be spread over a considerable length of pavement section. The cost of wires or strands would be higher, but such elements would offer greater advantages than those obtained by jacks.

External prestressing represents only an additional compressive and flexural strength in the concrete section, which once exceeded by either loads or stresses created by restrained volumetric changes, would be completely lost and would lead to the failure of the slab. On the other hand, the presence of internal elements represent a tension field in the concrete section, which, coupled with the resistance of the concrete in compression, will be capable of resisting higher loads. When such loads are applied the section will behave as a reinforced concrete section and will be capable of carrying additional loads until ultimate conditions are reached either in the concrete or steel.

Volumetric changes which develop mainly as the result of temperature variations have little effect on the prestressing forces if they are created by internal steel elements because the thermal expansion coefficient of steel and concrete differ only slightly. The preservation of constant prestressing forces, as applied by hydraulic jacks, would become problematic in view of the continuous volumetric changes, which will take place in the concrete. Assuming a modulus of elasticity of 4 million and a thermal expansion coefficient of 6 millionths and no friction under the slab, a prestressing of 300 psi could be offset by a temperature drop of 12.5 deg F.

It is felt that prestressing provided by hydraulic jacks should be applied only as an auxiliary means in addition to internal steel elements.

No preference can be given to wires or strands, because from the theoretical point of view both satisfy equally the requirements of efficient prestressing. The selection of one or the other must be made with regard to the over-all economy in their respective application. In addition to material cost, expenses in connection with their handling, placing, stressing and anchoring should be considered. It is, of course, assumed that wire if used, would be grouped into units of several wires and protected so by adequate tubing.

The elements should be placed prior to placing of the concrete if post-tensioning is used. Conduits provided in the concrete and pulling the prestressing elements through them after the concrete has hardened seems to be an unnecessary complication. The tests indicated that with sufficiently stiff tubing around them and after careful placing,

the conduit resistance in these prestressing elements will be negligible.

It seems to be unlikely that pretensioning of pavements will be adopted. More consideration should be given, however, to the possibility of whether the post-tensioned elements should be left free in their conduits, or should be grouted after stressing.

The primary concern is, of course, corrosion which may necessitate the grouting of these elements to secure long life to prestressed concrete pavements. It is also evident that for ultimate stress conditions grouted prestressed concrete sections offer a higher safety limit than comparable sections which have ungrouted tendons. This matter of safety, however, is of lesser importance because as is evident there is no need for such extra safety margin. UngROUTED prestressing elements furthermore will offer an over-all spring effect to pavement sections and will secure over-all continuity of the slab more likely than grouted elements.

The grouting of conduits several hundred feet long will, of course, increase the cost also. Therefore, it is felt that finding lasting lubricants with corrosion resisting properties would offer the best solution for future applications.

The cardinal problem in designing future prestressed concrete pavements will be the complex problem of determining the amount of prestressing and the thickness of the pavement. There are no theories available for prestressed slabs supported by an elastic foundation. Even if the various available theories would be further developed to include the effect of prestressing on deflections and stresses, they could not give sufficient indication as to the behavior of the slab after initial cracking took place and certain sections of the slab lost their homogeneous characteristics. Empirical solutions will, therefore, be the only ones at hand and should be accepted until better means are found.

As emphasized in the preceding paragraphs, the main advantage of prestressing pavements is that they become continuous and by virtue of their inherent compressive energy they remain so, even if accidental reasons such as overloads or excessive restrained stresses create temporary discontinuity.

Therefore, the minimum of prestressing applied should be sufficient to maintain and restore continuity in the pavement. It is felt that for such purpose 100-150 psi prestressing is adequate in addition to the prestressing which may be lost due to base friction. The over-stressing of the slab does not seem to be justified for several reasons.

Considering conventional pavements of 6 to 8 in. in thickness, the actual saving in concrete when prestressing would be used could not affect the additional expense of providing the prestressing element with present prices and construction techniques in view. This is mainly true because of limitations set for reducing pavement thickness. With conduits to be used of approximately one inch in diameter and providing sufficient clearances for possible transverse reinforcement and adequate cover for protection, the practical limitation for pavement thickness would be 5 rather than 4 in. Pavements with less thickness would require high prestressing in the order of 500-600 psi to offer sufficient resistance to loads. With such higher prestressing the anchorage of the prestressing elements would become problematic because of the high concentration of loads. High prestressing would also increase the number of tendons to be used and would thereby create increased difficulties for placing concrete.

Pavements, if highly prestressed, would carry loads on average subbases with considerable deflections without detriment to the concrete slab but definitely causing permanent deformations in the supporting material.

The amount of prestressing necessary to overcome friction of the base is a function of length of the slab and of the unknown friction coefficient. This coefficient should be in the order of 0.5. To secure the proper development of prestressing, it should be applied with temperatures showing a decreasing tendency and in repetition (i.e., the prestressing elements should be released and restressed once but preferably twice after the first stressing).

It was assumed in the preceding paragraphs that prestressing is to be applied only in one direction. This is recommended for highway pavements. There seems to be no need for additional strength transversely except for some light transverse reinforcement. This reinforcement should be placed above the longitudinal prestressing elements.

The prestressing elements should be placed directly under the neutral axis of the slab.

The preferred position of these elements cannot be precisely defined. The test performed at Patuxent did not lead to the clarification of this problem. Unfortunately, with the limited capacity of the loading equipment, it was impossible to produce limit conditions which would have shed some light on the effect of strands placed at various levels.

The term continuity used in connection with prestressed concrete pavement should by no means indicate that such pavements could be built practically without any limitations in length. Also, not all joints will be eliminated. It is more reasonable to speak about continuous panels, with special joints provided between them which will permit the free movements of the ends of such panels.

Prestressed concrete pavements are undoubtedly superior in general behavior to conventional concrete pavements. They seem to provide not only more strength, but also reduce problems which are connected or created by pavement thicknesses, joints, cracking and some other phenomena to be dealt with. As a matter of fact, they seem to offer answers to a good many problems for which highway engineers seek solutions.

It would be unwise, however, to overlook important problems of rigid pavements for which even prestressed concrete cannot offer a satisfactory solution.

First of all, it must be emphasized that it would be a fallacy to believe that the adoption of prestressed concrete pavements would lead to the acceptance of poorer sub-base than those presently used. Economical prestressed concrete pavements must be thin and thereby more flexible. Such flexibility itself will result in greater deflections. In this case, attention must be directed to the permissible limits of base deflections in determining the quality of material underlying prestressed concrete pavements.

Pumping, which is one of the paramount problems of rigid pavements is not going to be solved by prestressed concrete pavements either. As a matter of fact, decreased pavement thicknesses and increased deflections resulting therefrom could add to this problem.

There are a good many other problems which must be closely investigated and solved before the adoption of this novel pavement.

Joints, as mentioned previously, cannot be eliminated completely. Their number can be reduced, but by doing so, the anticipated magnitude of movement at such joints may be in the order of 2-3 in. Therefore, special expansion joints will have to be devised, which by itself will require some ingenuity. In addition, such joints will represent free edges in the pavement right there, where most likely heavy concentrations of applied prestressing forces are present.

The construction of such pavements will also create problems not experienced before. Irregular pavement sections to be formed at intersections, pavement widenings, etc., together with horizontal and vertical curves will present design and construction details which will not always be solved easily.

Damage to such pavements, especially to their prestressing elements will be more detrimental and will call for more elaborate repair procedures.

Economy above all will probably be the deciding factor. Prestressed concrete pavements should be considered economical only if the savings in reduced concrete thicknesses will not be offset by the cost of prestressing elements and the cost of related new construction methods. In such comparison, the probable increased life-time of prestressed concrete pavements should also be taken into consideration.

The few attempts made, mainly in France and England, point to the future possibilities of such pavements. It should be noted that most of the experimental work in the field of prestressed concrete pavement was aimed at the improvement of airfield pavements. There loads and resulting pavement thicknesses increased to such an extent that the advantages of prestressed concrete, both theoretically and economically, could be utilized in satisfactory manner. The elimination of joints, furthermore, would solve maintenance problems of pavements where jet planes are in great use.

Therefore, it is believed that highway engineers should follow with great anticipation and interest the various experimental projects which are planned or conducted by various agencies to investigate the adoptability of prestressed concrete to airfield pavements.

There is need, of course, for more research and development to solve problems of

this novel pavement related directly to highway applications. Whether prestressed concrete will be used in the future for the improvement of concrete highway pavements can be decided only after such extensive investigations.

REFERENCE

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