Construction of Prestressed Concrete Pavement Slabs in Osaka City

By

Yasuo KONDO and Kiyoshi OKADA*

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This paper describes the prestressed concrete pavement slabs, 60 m and 40 m in length which were constructed in Osaka City in January of 1958. Prestressing steel was laid in both longitudinally and transversely in the 60 m slab, and diagonally with angles of intersection of about 60 deg. in the 40 m slab.

The construction and testing of the pavement slabs are described in detail. The results prove the superior behavior of prestressed slabs, especially in their elastic recovery, and indicate that such construction could be advantageously utilized in future pavement construction when it becomes economically comparable with other forms of construction.

Introduction

The first prestressed concrete pavement on record appears to be a bridge approach at Luzancy (France), although prestressed pavement did not become firmly established until the construction of the well-known Orly runway in 1947. This runway was designed to meet the requirements of modern aviation.

Since then, many prestressed pavements have been constructed in Western Europe especially in Britain and France and recently in America[1].

In January of 1958 an experimental section of prestressed concrete slabs was built into a highway of the City Planning Project of Osaka City. The work was undertaken in order to investigate the use of prestressed concrete pavement which had previously received little attention in Japan. The various tests, including the loading tests, were carried out about 9 weeks after the completion of slabs.

Description of Test Slabs

Two slabs were built and placed about 100 m apart: one, called "slab A" hereafter,

* Department of Civil Engineering

was 60 m long and 5.47 m wide, and the other ("slab B") was 40.80 m long and 10.94 m wide, the latter part of which had a curvature with a radius of 500 m.

The depth of the slabs was fixed at 15 cm in order to assure sufficient cover above and beneath the sheathing of the tendons which crossed at different levels in the slab. Moreover, as shown in Figs. 1 and 2, haunches of 20 cm thickness were made near the sides and the ends of the slab in order to accommodate the curb stones and boundary curbs at the sides and in the adjacent standard concrete pavement slabs.

The prestressing in slab A was, as is indicated in Fig. 1, provided longitudinally by eleven Freyssinet cables, each consisting of twelve high-strength steel wires, 5 mm in dia. There seems to be no need for additional strength transversely in such a narrow width of slab as this, but a small amount of transverse prestressing was introduced for security by induction hardened high-strength bars, 18 mm in dia., since the problems of transverse prestressing are not yet solved.

The diamond pattern of tendons was adopted for slab B. The same kind of Freyssinet cables were used except near the ends and corners where hot rolled high-strength bars, 24 mm in dia., were used.

The general layout of the tendons is illustrated in Fig. 2, each tendon being at an angle of about 30 deg. with the line of the pavement at about 1.72 m. Near the ends and corners, the length of the tendons was so short that high-strength bars were used to avoid large prestress losses in anchoring the Freyssinet cables.

In this slab, all of the tendons were laid out in straight lines in order to avoid uncertain stress conditions at the extreme ends of the slab. In future work, however, with a series of such slabs, this procedure might not be desirable, and it may be preferable in the future to stress all cables from the sides of the slab by curving the cables, emerged from the end of the slab, rounded with an appropriate radius, say 2.5 m, as suggested by J. W. McIntosh[8].

The amounts of prestressing steel used were 4.95 kg per sq. m in slab A and 5.15 kg per sq. m in slab B. The total amounts of reinforcement were 6.0 kg per sq. m in slab A and 6.1 kg per sq. m in slab B, respectively.

Materials

Subbase:

The subbase, on which test slab A was placed, had been used formerly as a runway and maintained in fairly good condition, by frequently spreading gravel on it and compacting the layer, so that it required no additional deposits and that sufficient compaction was obtained by using a 10 ton roller over the full width of the pavement, the subgrade modulus (measured with a 75 cm dia. steel plate) reading as high as $k_{75}=19$ kg per cu. cm.

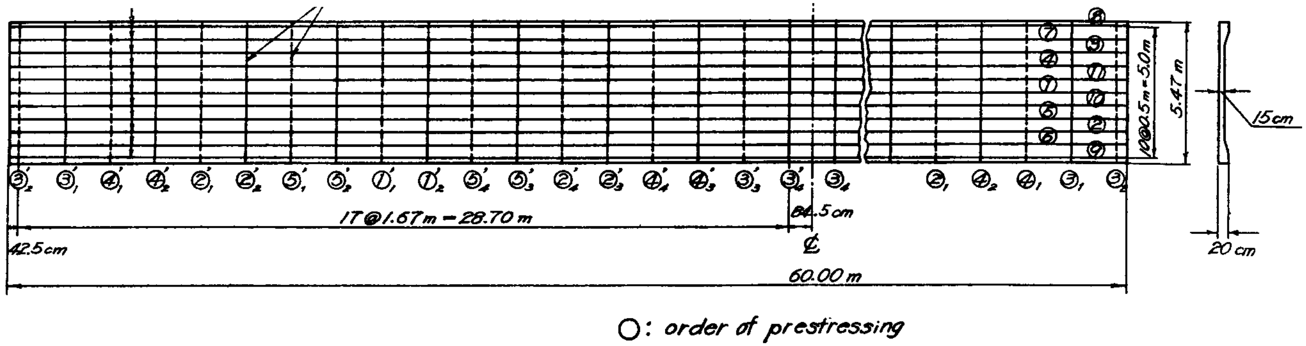

Fig. 1. Layout of prestressing steels in slab A.

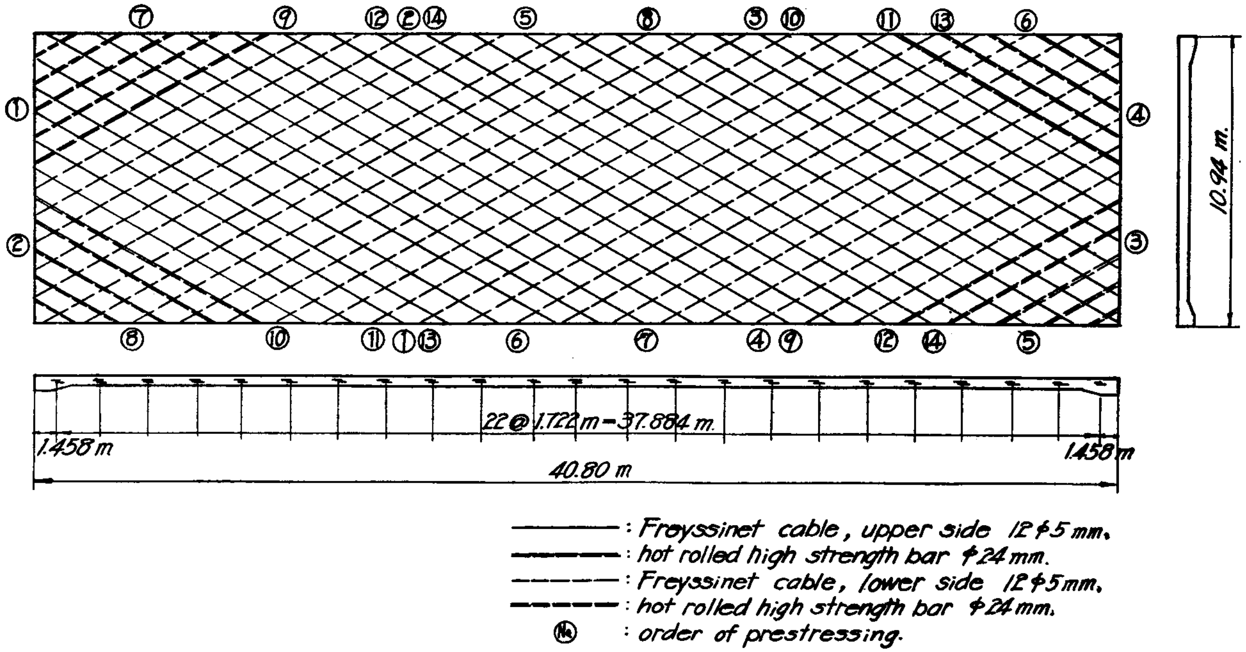

Fig. 2. Layout of prestressing steels in slab B.

On the other hand test slab B was placed on a comparatively poor foundation. A 20 cm layer of gravel with sand-clay directly under the slab was deposited on the subbase course, and was compacted by a 10 ton roller until a subgrade modulus of $k_{75}=7$ kg per cu. cm was obtained.

For both slabs a friction-reducing layer consisting of a 2 cm thickness of sand covered with kraft paper were placed immediately beneath the slabs.

Prestressing Tendons:

The prestressing wires, 5 mm in dia., which formed the Freyssinet cables used in slab A meet J. S. C. E. Specifications and were manufactured by the Shinko Wire and Cable Co. Ltd., and those in slab B, also meeting the same specifications, were made by the Sumitomo Electric Industry Co. Ltd.

The prestressing bars, 18 mm in dia., used as transverse tendons in slab A were made by induction-hardening of structural carbon steel S35C by the High Frequency Heat Treatment Co. Ltd., and those, 24 mm in dia., used for corner prestressing in slab B, were made by the Sumitomo E. I. Co. Ltd. The properties of those wires and bars are shown in Table 1.

Table 1. Properties of Prestressing Steels.

Prestressing steel	Normal dia. (mm)	Tensile strength (kg per sq. mm)	Yielding strength (kg per sq. mm)	Elongation (%)
Wire	5	65	145	4.5*
Bar (hot rolled)	24	90	65	8.0**
Bar (induction hardened)	18	110	95	5.0**

* Gage length 100 mm, ** Gage length 8×dia.

All cables and bars were sheathed in 35 mm dia. mild steel tubes, the tubes being provided in lengths of 2 m. The end of each tube was opened to form a socket and the end of the next tube forced into it, all joints being sealed with adhesive tape.

Concrete:

Table 2. Concrete Data.

Slab	Conc. temp. when casted (deg. C)	Age at tested (day)	Comp. strength* (kg per sq. cm.)	Modulus of * rupture (kg per sq. cm.)	Modulus of * elasticity (kg per sq. cm.)
A	11.0	5	332 (207)	—	—
	7.7	7	383 (252)	51.1 (40.2)	—
	8.4	10	420 (283)	—	—
	11.0	28	545 (388)	71.2 (51.1)	381,000
B	10.5	2	288 (145)	—	—
	10.0	7	396 (248)	—	—
	10.5	28	520 (372)	—	350,000

* Normal values obtained for standard-cured specimens, the values in parentheses being those obtained for specimens cured in a room at temperatures ranging from 4 to 15 deg.C.

Ready mixed concrete was purchased from the Asano Remicon Co. Ltd.. Specifications called for a min. flexural strength of 35 kg per sq. cm and a min. compressive strength of $\sigma_{28}=400$ kg per sq. cm at 28 days. The use of early high strength cement was also recommended because of the necessity for introducing prestress at ages as early as one week after placing the concrete, although in a cold climate of 4 to 10 deg. C.

The mixture used was 400 kg of cement, 160 kg of water, 670 kg of sand and 1200 kg of gravel per cu. m of concrete. Nakagawa River sand with a fineness modulus of 2.87 and Nakagawa River gravel with max. size of 25 mm were used. This design gave a mix with 6 to 8 cm. slump. Table 2 shows the results of tests of concrete specimens made in the laboratory and the field.

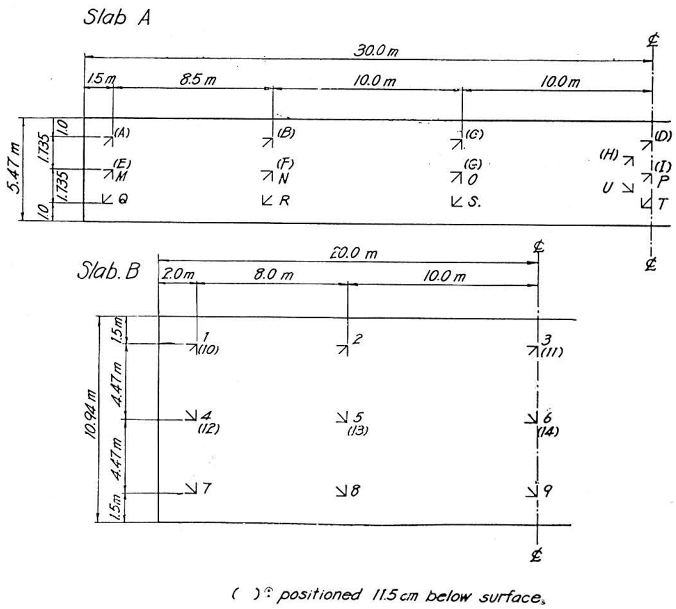

Fig. 3. Position of embedded Carlson strain meters.

Instrumentation

Carlson type strain meters were placed in the concrete as shown in Fig. 3 to determine the corresponding stresses in the concrete at depths of 3.5 cm and 11.5 cm. Longitudinal, transverse and diagonal strains were determined at each measuring point by three strain meters connected by spider arms as illustrated in Fig. 4.

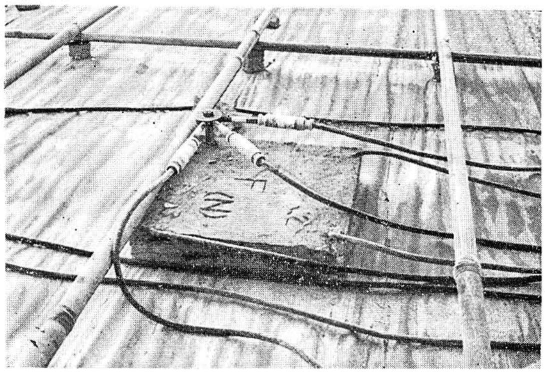

Fig. 4. Spider arm for holding strain meters.

The strain meters could also be used to determine the temperature in the concrete at any time after concreting. In each slab, the wires of the strain meters were assembled, for ease of handling, at two measuring boxes which were located in the green belt besides the slab. Strains in the surface of the slab were also measured in the gage length of 10 in. by a falcum type strain meter positioned on the slab surface corresponding to the location of the Carlson meter.

The load on the prestressing tendons was measured with gages on the stressing jack, that is, the Freyssinet hydraulic jack or the Simplex oil jack.

Dial gages were used for deflection measurements during the prestressing and loading tests.

Construction

Prior to placing the prestressing tendons, the fine sand layer and sheets of kraft paper thereon, were laid on the top of the prepared subbase courses. Owing to the rigid nature of the sheathed tendons, supports made of mortar were placed at the intersections of the tendons and at required intervals, but it was found necessary, especially in slab A, to adjust the cables as concreting proceeded because the placing of the concrete was liable to cause slight displacements.

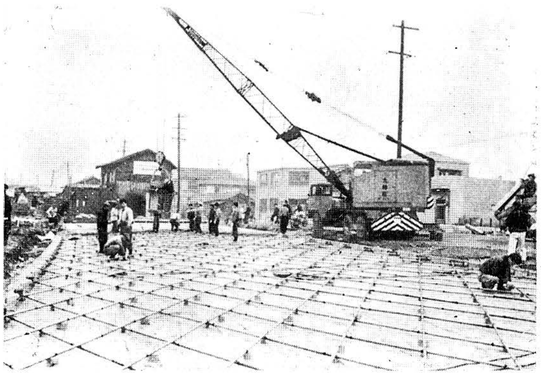

Fig. 5. Placing concrete by truck crane.

The concrete was transported by the Hilo-type mixing truck of a 3 cu. m capacity to the site every 15 to 20 minutes from the Central Batcher Plant about 30 minutes distance from the site, and was spread by hand and by a truck crane with an arm, 11 m long, (Fig. 5). The concreting of each slab was completed in about 9 hours.

Only internal vibratiors were used for compacting the concrete, since the floating vibrators usually used were found unfitted for this job due to the complicated structure of the prestressing tendons. The finished surface was inspected the day following the concreting, but no shrinkage cracks were found in either of the slabs.

The Stressing of the Slabs:

The stressing of the tendons was carried out 1 week after the completion of the concreting of each slab. The strength of the concrete was then estimated to be more than 200 kg per sq. cm. (ref. Table 2).

The order of stressing is shown in Fig. 1 or 2, and it will be seen that particular attention was paid, especially in slab B, to applying the stress as evenly as possible over the full length of the slab. In slab A the transverse prestressing was applied first by using two Simplex oil jacks, and two Freyssinet's jacks were used in prestressing longitudinally. In each prestressing, the tendons were stressed or jacked from both ends simultaneously.

In slab B one end of each cable was locked by hand and a jack was used at the other end of the cable.

In all cases the extensions were checked against the gage pressure on the pump, and sometimes, when the elongation was too small, the pressure on the pump was raised a little beyond the value calculated for obtaining the desired elongation.

The wobble effect λ per meter of Freyssinet cable was estimated as $(0.30$ to $0.43)\times 10^{-2}$ in slab A and as $(0.37$ to $0.63)\times 10^{-2}$ in slab B.

On completion of the stressing, clean water under pressure was injected into the cable ducts. The ducts were then grouted up. The proportions of the cement grout used were as follows: cement 960 kg, fly ash 320 kg, pozzolan 3.2 kg, aluminum powder 0.19 kg, per cu. m. of cement grout, and a water-cement ratio of about 50%.

Development of Prestressing in the Slab:

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

In the test slabs, the development of the prestressing along the slab length was investigated by the Carlson-type strain meters and a 10 in. Whittemore gage positioned as already shown in Fig. 3.

In general, losses in prestress due to base friction seem to be of greater importance and considerably more difficult to determine. There are various factors affecting the resistance to prestressing. However, by considering the many experiments conducted on the problem of friction-reducing devices, and also considering the cost, it was decided to build the slabs on 2 cm of sand, covered with kraft paper.

In analysing the losses in prestress due to base friction, the effects of the initial shrinkage, developed immediately following the casting of the slab, and the temperature conditions in the concrete must be very important, because the stresses in the concrete due to the shrinkage and to the decreasing temperature would cause a contraction in the slab and dissipate the friction resistance of the base, so that prestressing could be applied as a superimposed load virtually without loss. Actually one of the tests made in the United States on a 1500 ft long presstressed slab in February indicated no loss in the prestressing when the slab was stressed[3),4)].

Average temperatures in the slab, measured by the Carlson meters directly after completion of concreting, were, 8.8 deg. C in slab A and 9.1 deg. C in slab B, and they decreased to 5.9 deg. C and 5.5 deg. C, respectively, 7 days after the prestressings had been applied.

The contraction of the slabs before prestressing due to shrinkage and the decreasing temperatures are shown in Fig. 6. It may be seen that the base friction exerted an influence, to some degree, on the longitudinal contraction of the slab but did not affect the transverse one.

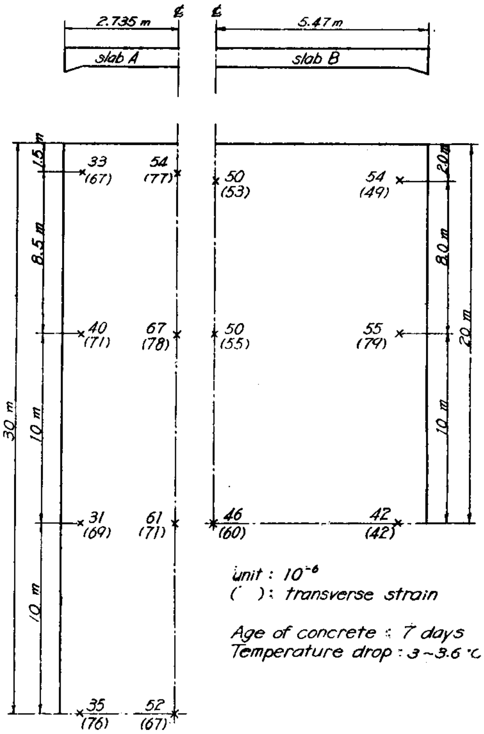

Fig. 6. Contraction of slab before prestressing.

Variations in longitudinal and transverse strain readings on the cross sections immediately after prestressing are shown in Fig. 7. It may be shown that a slight variations in prestress along the length of slab were found in each of the slabs, larger strains being developed in the middle parts than near the ends of the slabs probably because of the difference in the depth of the slab due to uneveness in the base course. In slab B the accumulation of the elastic shortenings which follow the successive prestressings might be another principal cause for the larger loss in prestress near the ends of the slab.

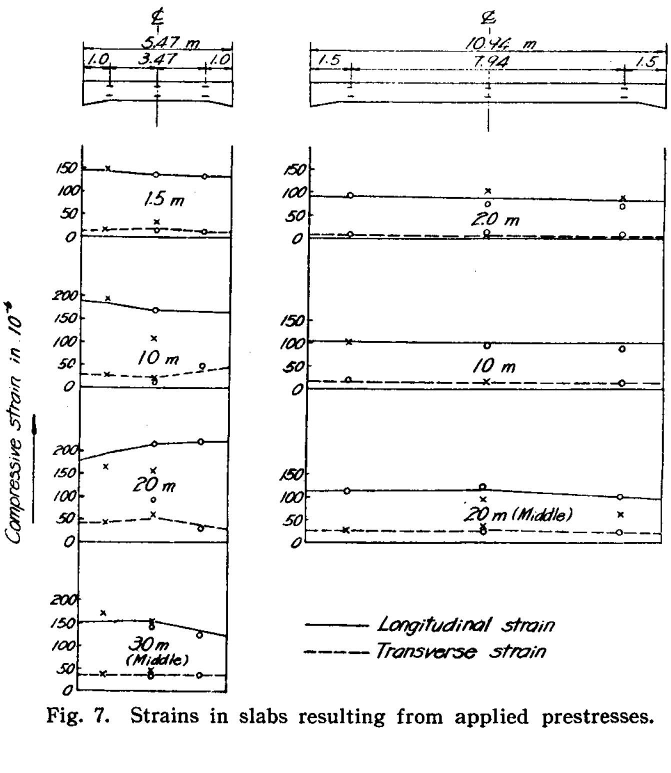

Fig. 7. Strains in slabs resulting from applied prestresses.

When assuming that the stresses introduced are calculated by the formula

$$\left.\begin{aligned}\sigma_x &= \frac{E_c}{1-\mu^2}(\varepsilon_x+\mu\varepsilon_y)\\ \sigma_y &= \frac{E_c}{1-\mu^2}(\varepsilon_y+\mu\varepsilon_x)\end{aligned}\right\} \qquad (1)$$

in which ε_x, ε_y = the measured longitudinal and transverse strains, respectively.
σ_x, σ_y = the longitudinal and transverse stresses, respectively.
E_c = the modulus of elasticity of the concrete.
μ = Poisson's ratio for the concrete.

and taking E_7=200,000 kg per sq. cm, and μ=0.15, slab A was prestressed, on the average, to 31.8 kg per sq. cm longitudinally and to 9.0 kg per sq. cm transversely, whereas slab B, in the middle part, to 24.0 kg per sq. cm and 10.2 kg per sq. cm, respectively.

The intended initial prestresses were σ_x=34.8 kg per sq. cm, σ_y=7.6 kg per sq. cm in slab A, and σ_x=30.0 kg per sq. cm, σ_y=11.1 kg per sq. cm in slab B. The residual prestresses, however, were intended to be larger than σ_x=25.0 kg per sq. cm, σ_y=6 kg per sq. cm in both slabs.

The eccentricities of the introduced prestresses, calculated from the differences between the strains in the upper and lower surfaces of the pavement and assuming the dimensions of the sections to be as designed, were, taking as positive above the neutral axis, e=(−0.34 cm to 0.218 cm) in slab A and e=(−0.41 cm to 0.54 cm) in slab B. This fact shows that a slight displacement of the prestressing tendons during the placing of the concrete occurred despite the great care taken and that it is inevitable so long as such a method of concreting is used.

Accordingly the results may indicate that the slight differences between the intended prestress and those actually introduced were primarily due to the variations in depth of the section caused by the uneveness of the subbase course rather than due to the base friction.

Generally speaking, however, it was noticed that the diagonal layout of the prestressing steel such as used in slab B could distribute stresses more evenly along the entire length of slab than the rectangular pattern for the prestressing steel.

Deflection of slab A when the prestresses were applied, was measured by the dial gages, but no appreciable deflection was observed at any point along the whole length of the slab.

Load Tests

Several load tests were made in May, 1958 on the test slabs using MINSEI Diesel trucks carrying 240 sacks of cement, the total weight being 19 tons as shown in Fig. 8. This rear wheel load nearly corresponds to the design load.

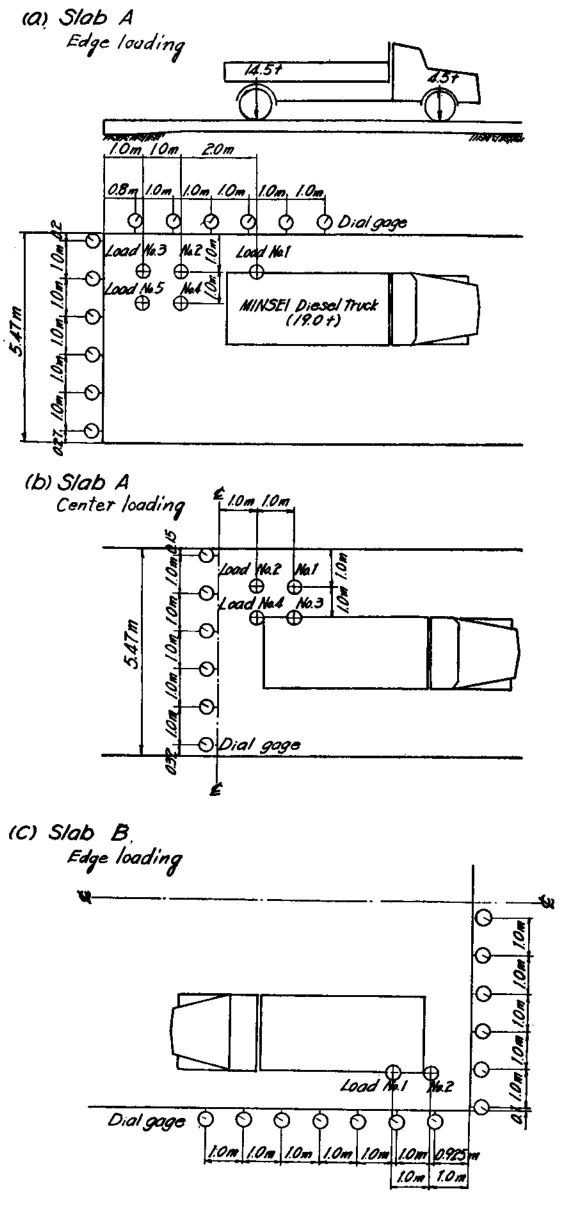

Fig. 8. Test Load and loading conditions.

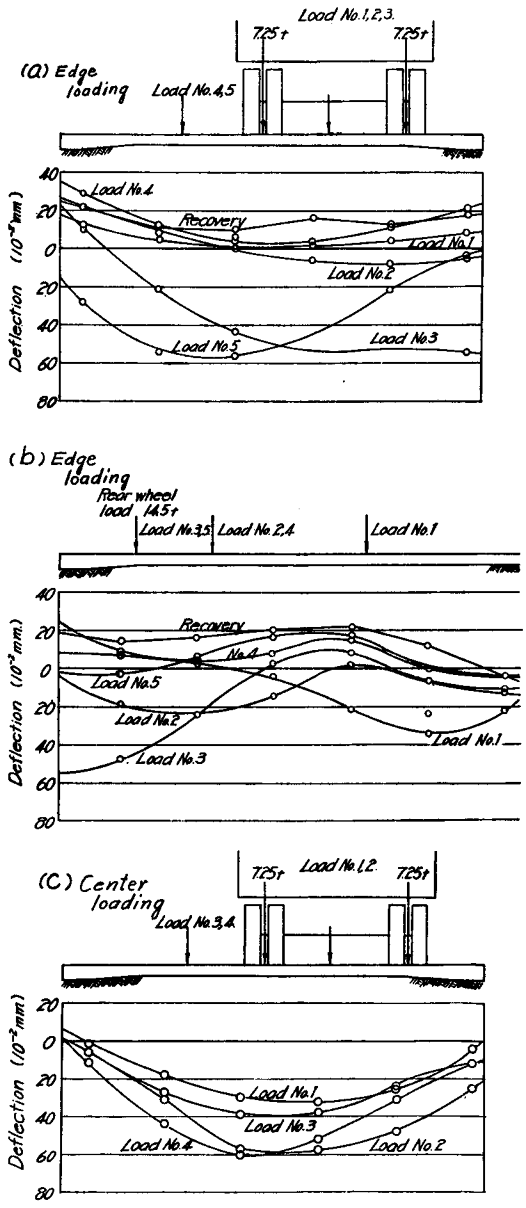

Fig. 9. Deflection of slab A due to load.

Statical load tests were made at the edges as well as in the middle of the slabs where strain meters to register concrete stresses had been placed. Deflections in the area of the load were also measured.

Dynamic strains in the concrete were measured in slab A when the truck passed over with speeds of 20 and 35 km per hour.

Deflection of Slabs:

In slab A deflections were measured for the edge and center loadings. The loading conditions and the location of the dial gages for measuring deflections are given in Fig. 8.

Deflection profiles for each load test are shown in Fig. 9.

It is seen from Fig. 9 (a) that for the edge-loading in slab A the maximum deflection was about 0.6 mm which was caused by the load at a distance of 0.8 m from the edge. Fig. 9 (b) indicates that when the load was at a distance of 2.0 m from the edge, the end of slab and the portion of the slab between the front and rear wheels of the truck were both raised up. The maximum rise of the slab was 0.35 mm. The slab rose up also after the release of the load, probably because a portion of the sand layer beneath the slab had been pushed a side following repeated loadings of the slab.

The test load used was considerably lower than the strength of the slab, so only small deflections resulted. Since the ends of the slab were not yet joined to the adjacent standard pavement, the edge loading conditions were limited as described above.

In slab B only edge-loading was performed. Deflections of the slab were considerably large compared with those of slab A, and a maximum deflection of about 2 mm was recorded for a load at about 0.93 m from the edge, as shown in Figs. 10 (a), (b). This indicates that the subbase of slab B was poorer than that of slab A, and that it does not necessarily prove the weaker strength of slab B, because slab B showed the same degree of elastic recovery as slab A did.

The high recovering ability as shown in the tests described above is considered to be one of the most remarkable characteristics of prestressed slab.

Stresses in Slabs Due to Statical Load:

A test truck load was applied at twenty-four places on slab A and at twenty-two places on slab B directly above or adjacent to the embedded strain meters.

Loading conditions were so limited as described before that the critical stresses in

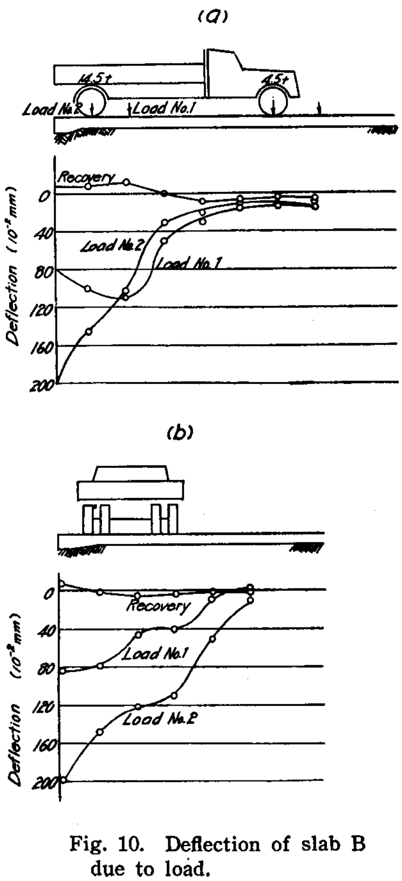

Fig. 10. Deflection of slab B due to load.

the corners of the slab were not measured.

In the other load tests the measured strains showed considerable deviations, but the general tendency was for the maximum strains to be observed in the longitudinal direction of the slab directly beneath the rear wheel, and for the compressive strains in the surface of slab to be larger than the tensile strains in the bottom of slab.

ACI Committee 325 recommends the following design formula for calculating the concrete tensile stresses at the bottom of an airport pavement slab for dual tire loading[5].

$$\left.\begin{matrix}\sigma_x\\ \sigma_y\end{matrix}\right\} = \frac{3P}{2\pi h^2}\Big[(1.15)(B+R)\pm(0.425)(C+S)\Big] \qquad (2)$$

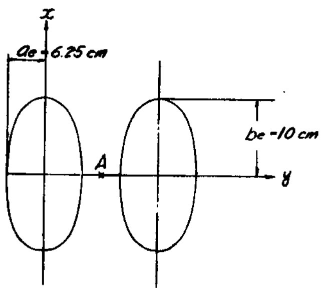

Fig. 11. Dual tire loading (stresses at point A are calculated).

The coefficient B and C are "place" and R and S are "area" coefficients, and Poisson's ratio for the concrete is assumed to be 0.15.

Table 3 shows the comparison of the tensile stresses calculated from the measured strains by using the previous eq. (1) with those computed from the above eq. (2) for dual tire lord as shown in Fig. 11.

Table 3. Tensile stresses in slabs due to load.

Slab	Stress	Measured at (kg per sq. cm)		Calculated by eq. (2)* (kg per sq. cm)
		10 m apart from slab end	Middle of slab length	
A	σ_x	23.1	25.3	28.5
	σ_y	15.2	9.8	10.1
		20 m apart from slab end	Middle of slab length	
B	σ_x	21.1	16.9	32.8
	σ_y	15.8	9.8	14.4

* With reference to ref. (5), $B=0.1159$, $C=0$, in eq. (2); R and S were calculated by using $E_c=323{,}000$ kg per sq. cm for slab A and $E_c=313{,}000$ kg per sq. cm for slab B. E_c was assumed to be $E_c=126000+(460\times1.1\sigma_{28})$ kg per sq. cm where σ_{28} was the strength of concrete specimens cured in a room for 28 days.

Judging from the above, the formula recommended for the larger load on airport pavement, neglecting the influence of base friction, seem to give rather conservative stress values for the design of highway pavement slab.

At any rate, the tests show that the prestressed slab could carry a load about three times as large as the design load without cracks even when the stresses due to shrinkage and temperature variation were critically large.

The strains in the slab due to the load decreased rapidly as the load moved away from the measuring point, and generally changed the signs from positive to negativ or vice-versa as shown by the theoretical analysis. And in cases where the load was 10 m apart, no strains were observed in the slab.

Stresses in the slab due to a moving load:

The dynamic strains in slab A along the length of slab where the strain meters were embedded as previously shown were recorded on the electromagnetic oscillograph when the test truck load passed over at the two speeds of 20 to 23 km per hour and 35 km per hour.

The maximum longitudinal strains occurred when the travelling load was just above the strain meter, and compressive strains of about 90 to 95×10^{-6} and tensile strains of about 50 to 80×10^{-6} were recorded at slab depths of 3.5 cm and 11.5 cm respectively.

The compressive strain in the surface was of about same magnitude as that obtained in the statical load test but the tensile strain in the bottom was somewhat larger than that statically obtained probably because the impact accompanying the moving load reduced the base friction to some degree.

So far as test speeds of the moving load are concerned, no appreciable differences in the strains were observed when the speed increased from 20 to 35 km per hour.

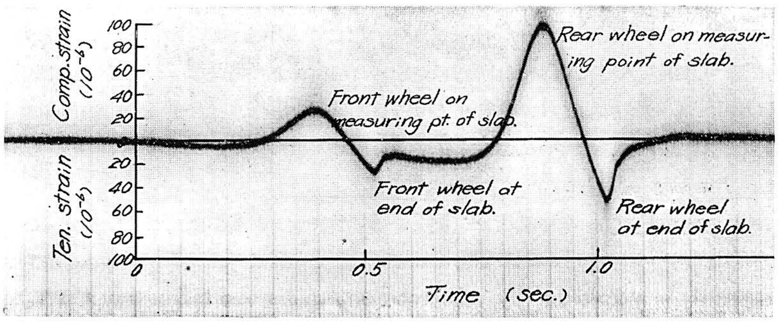

Fig. 12. Strains in slab due to moving load.

Typical strain results, shown in Fig. 12, were recorded in the strain meter placed in the slab at 1.5 m from the end of slab A. They indicate a maximum compressive strain of only 95×10^{-6} and a maximum tensile strain of 50×10^{-6}.

Summary

The first construction and testing of prestressed pavement in Japan has been described in full detail with the following conclusions.

1) For simplifying construction procedure, prestressing in only one direction is recommended for highway pavement, but the diamond pattern of prestressing steel seems to give a more even stress distribution in the slab.

2) Losses due to conduit friction of the prestressing steel can be kept to a minimum by providing proper support and using a suitable method for placing and spreading the concrete.

3) In placing the concrete, the friction-reducing layer should be protected from being damaged by the workers, and it is most desirable to place and to compact the concrete by machine only.

4) As for load-carrying capacity, the slab showed superior behavior though the test load used was rather small.

5) The impact of the moving load causes no appreciable increase in the stresses at speeds lower than 30 km per hour.

6) The compressive stress under load is usually larger than the tensile stress probably due to base friction.

7) Economy will probably be the deciding factor for the development of prestressed pavement as constructional techniques improve. In order to assess more fully the qualities of prestressed pavement more time is needed, since their durability is potentially greater.

Acknowledgement

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