SOME NEW CONSTRUCTION METHODS FOR PRESTRESSED CONCRETE AIRPORT PAVEMENTS

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Studies on the applicability of a class III prestressed concrete (PC) slab, in which cracking at the bottom of the slab is permitted, and the development of a new type of PC precast slab with a new jointing system (horn-joint) for airport pavements have been carried out. From the results of theoretical analysis and a series of full scale loading tests on class III PC pavements, it has become clear that a class III PC slab can be satisfactorily used for airport pavements. This type of pavement may be a more rationalized one for heavy aircraft. In addition, the results of a series of full scale loading tests on the PC precast slab pavement connected with horn-joints have shown that this new type of pavement has a sufficient load carrying capacity and can be applied even to pavements subjected to heavy aircraft. Since an allowance for the curing time on in-situ concrete is not necessary in this type of pavement, the construction time is so fast that it may be ideal for the rapid repairs of existing pavements.

The demand for air traffic has recently increased rapidly. The role of air traffic occupied a larger proportion of traffic system than ever before.

Under these circumstances, many serious problems with airport pavements have been encountered.

Since aircraft have become larger in recent years, pavements have had to be thicker than ever. The latest oil crisis and associated shortage of material have led to the study of more economical pavements in both energy and materials.

Large aircraft have also been the cause of more damage to existing pavements such as the rutting of asphalt pavements. At the same time, the maintenance period of runways and taxiways is considerably reduced, because the facilities cannot be closed during the day time. Maintenance work must be carried out during the night and facilities must be opened to traffic the next morning. Therefore, in-situ concrete pavements, which require a long curing time, cannot be used for maintenance. However, since concrete pavement is the only way to prevent rutting, a concrete pavement that needs no curing time must be developed.

As for the first problem, one approach is the use of prestressed concrete (PC) pavement. The thickness of PC slab can be thinner than that of plain concrete slab. In PC structures there has been an increasing interest in the class III PC members (1), in which cracking is permitted within certain limits. Since the amount of steel bars for prestressing in class III is considerably less in comparison with that in class I (full prestressing) or class II (partial prestressing), the class III PC members can be more economical.

The only solution to the second problem is the prefabrication of concrete pavements. This idea is not really new. However, since conventionally laid precast concrete block pavements and PC precast slab pavement tightened in the transverse direction with prestressing tendons have been used extensively, it is difficult to lay and keep the slabs exactly level. In the case of prestressing tendons, when a single slab is damaged, it is almost impossible to remove it without disturbing all the adjacent slabs connected with the corresponding prestressed tendons. To overcome these problems, PC precast slabs capable of being connected at their edges would obviously be useful.

This paper presents the results of studies on the applicability of class III PC slab in which cracking at the bottom of the slab is permitted and the development of a new type of PC precast slab with a new jointing system for airport pavements.

Class III PC slab pavement

Prestressed concrete is classified as follows, based on the probability of bending cracking occurring when concrete is under working load conditions.

1. Class I : prestressed concrete which has a very small probability of cracking (full prestressing)
2. Class II : prestressed concrete which has a relatively small probability of cracking (partial prestressing)
3. Class III : prestressed concrete in which cracking is permitted under working load conditions within certain limits

Conventional PC pavements have been designed for the condition wherein the probability of cracking at the bottom of the PC slab is relatively small.

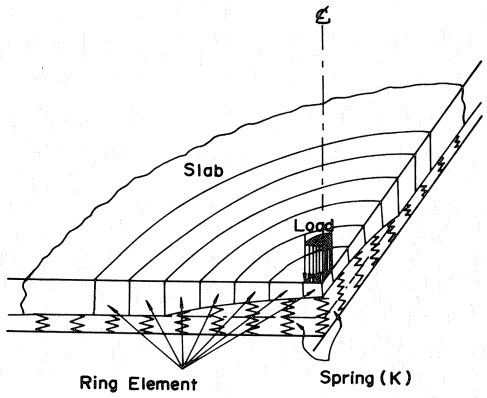
However, since these cracks will not prevent the functional performance of the pavement, a class III design method, which permits cracking only at the bottom of the PC slab under working load conditions, might be considered as a more reasonable method of designing PC slab.

Analysis of class III PC slab

In members such as pavement slabs, a redistribution of section forces occurs at the cracking phase.

In order to make clear the behavior of PC slabs after cracking occurs at the bottom of slabs, a model consisting of ring elements supported on Winkler foundation shown in Figure 1 was considered.

Figure 1. Model for analysis of class III PC slab.



In this model, as the load is increased and cracking occurs at the bottom of the ring elements, the effective thickness of each element is decreased in accordance with the depth of the cracks.

The following results were obtained from a mathematical analysis of this model by computer.

1. The positive bending moment at the loading point decreases slightly after cracking.
2. On the other hand, the negative bending moment, which relates to surface cracking, increases.
3. With increased loading, the position of the maximum negative bending moment comes closer to the loading point.

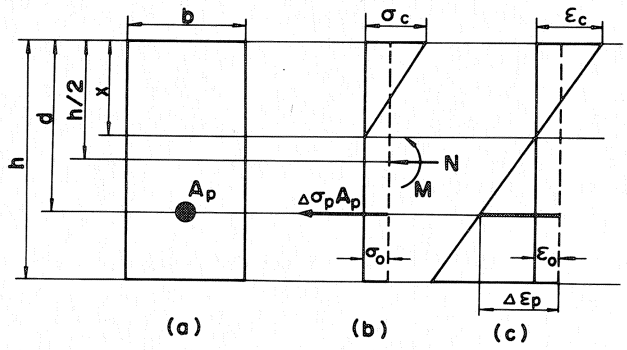
Design of class III PC slab

From the results described in the former section, the design of class III PC slabs in pavements can be made as follows.

1. The value of bending moment, which is obtained assuming that all the section is valid, is adopted to check the section where cracks occur at the bottom of a slab. This assumption is in the safety side for the design.
2. Since the assumption made in 1 is in the danger side for the check of the occurrence of surface cracking, the redistribution of the moment is taken into consideration.

Check of the section where cracks occur at the bottom of a slab. When the bending moment M on a section is greater than the cracking moment Mc, the

Figure 2. Distributions of stresses and strains on the cracked section.



following method is used to calculate the increased stresses of prestressing tendons and the compressive stresses at the top of the concrete. Assuming the section of the slab to be shown in Figure 2(a) and the distributions of stresses and strains on the section as those in Figure 2(b) and (c), the following equations can be obtained from Hooke's low, equilibrium of axial forces, and equilibrium of moments.

$$\frac{\sigma_c}{\Delta\sigma_p/n - \sigma_o} = \frac{x}{d - x} \tag{1}$$

$$N = \frac{\sigma_c bx}{2} - \Delta\sigma_p A_p = \sigma_o bh \tag{2}$$

$$M = \frac{\sigma_c bx}{2}\left(\frac{h}{2} - \frac{x}{3}\right) + \Delta\sigma_p A_p \left(d - \frac{h}{2}\right) \tag{3}$$

where

N : axial force of PC slab (prestressing load)
M : bending moment
ε_o, σ_o : strain and stress caused by N
ε_c, σ_c : strain and stress at the compressive fiber of concrete
$\Delta\varepsilon_p, \Delta\sigma_p$: increased strain and stress of prestressing tendon
h : slab thickness
d : distance from upper fiber to prestressing tendon
x : distance from upper fiber to neutral axis
b : width of section
A_p : area of prestressing tendon
n : modular ratio (E_s/E_c)

By solving the equations from 1 to 3, the following formulas can be obtained.

$$A_1x^3 + A_2x^2 + A_3x + A_4 = 0 \tag{4}$$

$$\Delta\sigma_p = \frac{x^2 - 2hx + 2hd}{bx^2 + 2nxA_p - 2ndA_p} nb\sigma_o \tag{5}$$

$$\sigma_c = x(\sigma_o - \Delta\sigma_p/n) \,/\, (x - d) \tag{6}$$

where

$$A_1 = -2\sigma_o b(bh + nAp)$$

$$A_2 = 3b\{\sigma_o(bh^2 + 2ndA_p) - 2M\} \quad (7)$$

$$A_3 = 6nA_p\{\sigma_o bh(h - 2d) - 2M\}$$

$$A_4 = -dA_3$$

The position of the neutral axis, the increased stress of prestressing tendon and the compressive stress of concrete can all be obtained from these equations.

Check to prevent the occurrence of surface cracking. The load P_c, which causes surface cracking, is calculated from an analysis of the previously-mentioned model or the following equation proposed by Meyerhof (2).

$$P_c = \left\{\frac{4\pi}{1-4a/(3b')} + \frac{1.8(S+S_T)}{\ell-a/2}\right\} \times (M_r+M_r') \quad (8)$$

where

S : dual wheel spacing
S_T : tandem spacing
a : contact radius of load
ℓ : radius of relative stiffness of slab

$$\left(\sqrt[4]{\frac{Eh^3}{12(1-\mu^2)K_{75}}}\right)$$

b' : 3.9 ℓ
M_r : positive moment of resistance of slab
M_r' : negative moment of resistance of slab

$M_r(=M_r')$ can be obtained by the sum of the flexual strength and prestress and then multiplying by the section modulus.

Construction of test pavement

The lay-out of the test pavement is shown in Figure 3.

Three types of base courses, of which structures and moduli of reaction (K value) are shown in Figure 4, were constructed to investigate the influence of K value on the performance of PC slab.

The test PC slabs were designed on the basis of class III theory. The input data for the design is tabulsted in Table 1. From checking the stresses of the concrete and prestressing tendons in the sections where cracks occurred, the effective amount of prestressing was determined to be about 2450 kPa both longitudinally and transversally. The prestressing tendons were 17.8 mm diameter strands spaced at 40 cm. The longitudinal and transversal tendons were respectively provided at 13.5 cm and 10.5 cm below the surface of the slabs. Since the PC slabs had two longitudinal construction joints, the three areas of concrete were cast separately. The longitudinal strands in each lane were tensioned to 73 kN for the first phase one day after the concrete was placed. The final stressing, in which all strands in both longitudinal and transverse directions were tensioned to 270 kN, was conducted when the strength of the concrete had reached its specified compressive strength (29.4 MPa). And then grouting was carried out.

To measure the performance of the test pavement, instruments such as settlement gages, pressure gages, strain gages, joint meters, and thermometers were installed in the test pavement during the construction. Their locations are shown in Figure 3. Since it would be difficult to measure the strains in the actual prestressing tendons, some steel bars were cast into the concrete near them so that the equivalent tensile values could be measured.

Figure 3. Class III PC slab test pavement.

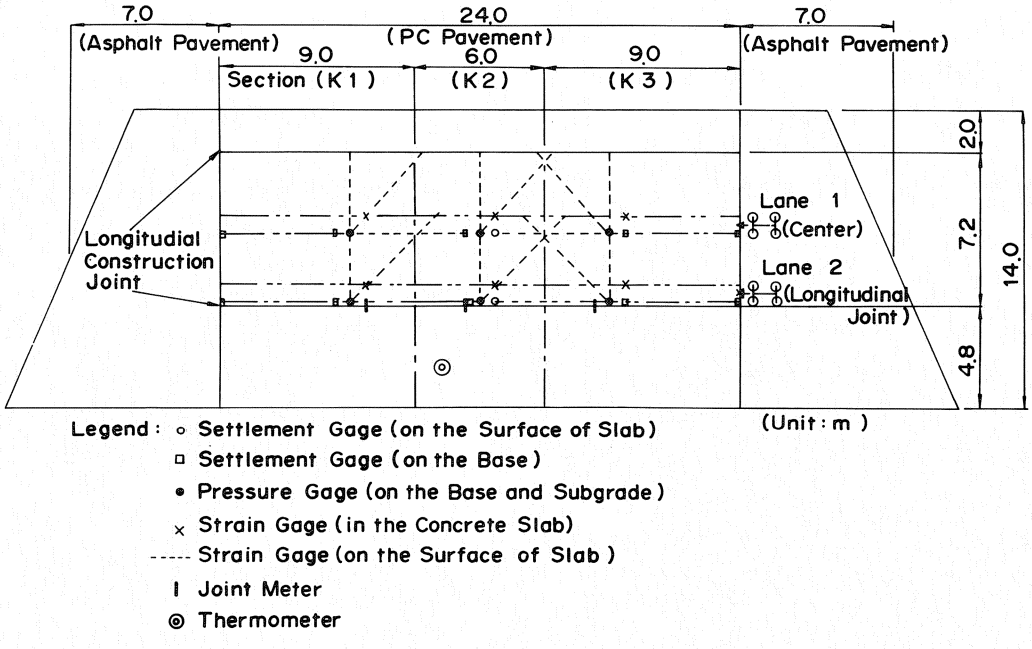


Figure 4. Sections in test pavement

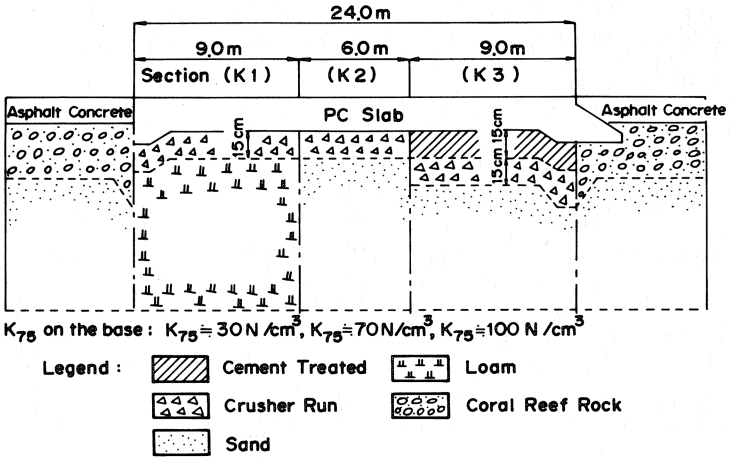
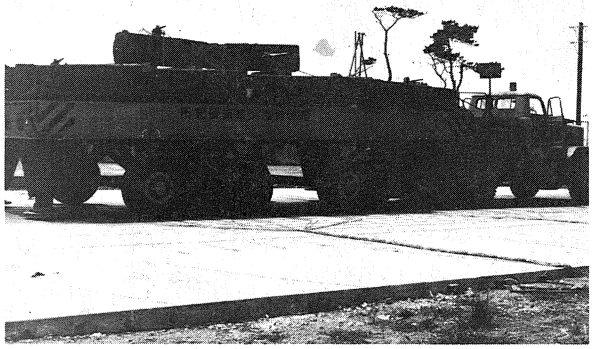


Table 1. Design conditions of PC slab.

Slab thickness, h (cm)		18
Design load DC-8-63	Dual wheel spacing, S (cm)	80
	Tandem spacing, S_T (cm)	140
	Gear load, P (kN)	722
	Radius of tire contact area, a (cm)	20
Design K_{75} (N/cm^3)		49
Concrete	Compressive strength (MPa)	34.3
	Flexural strength (MPa)	4.4
	Modulus of elasticity (MPa)	31900
Prestressing tendon (17.8 mm strand)	Tensile force (kN)	387
	Allowable increased stress (MPa)	98

Figure 5. Loading cart.



Loading Tests

The loading tests on the test pavement were carried out by the use of a loading cart with a dual tandem wheel arrangement similar to that of DC-8-63 aircraft (dual wheel spacing:80 cm, tandem spacing: 140 cm). Figure 5 shows the loading cart. Tests consisted of static loading tests and traffic tests. After the static loading tests (loading test 1) in which the load was increased step by step (maximum gear load:722 kN) were finished, the traffic tests (gear load:722 kN) on the two lanes shown in Figure 3 were conducted. The number of gear load repetitions was 10000 for lane 1 (at the center of the slab) and 5000 for lane 2 (at the longitudinal joint of the slabs). The static loading tests (loading test 2) were made after a measured number of gear load repetitions of 10, 500, 1000, 3000, 5000, 7000, 10000 had been conducted.

The relationships of strains of concrete and prestressing tendon to load in the loading test 1 are given in Figure 6 for the slab in section K1. During the small load phase the increases in strains are almost linear with the increasing load, but after the load reached a certain level, the strains of both concrete and prestressing tendons can be seen to increase rapidly out of proportion to the load. This load level is regarded to be the minimum load which causes cracking at the bottom of the slab. A similar tendency was observed in the measurements of strains for the other sections (K2 and K3). It was considered that cracking at the bottom of the slab occurred in all the sections. The cracking loads are given in Table 2. A good agreement can be recognized between the actual and theoretical values in case of the center portion of the slab. The cracks at the bottom of the slab were observed and confirmed by the specimens cut from the slab, after all the loading tests had been finished (Figure 7).

Figure 8 is the distribution of strains of concrete and prestressing tendon in the center portion of the slab under a gear load of 722 kN. There is a good agreement between the measured values and the theoretical ones for the cracked sections. Similar results were also obtained for the longitudinal joint portions. Therefore, the joints may have acted as a kind of crack in the case of class III PC slab.

Even though the behavior of the class III PC slab pavement was observed and it has been shown that they could be analyzed theoretically by the use of the previously-mentioned formulas, they are not considered sufficient to evaluate the applicability of class III PC slab for airport pavements. Almost all airport pavements are exposed to repeated loadings. It is extremely important therefore to

Figure 6. Relationships of strains of concrete and prestressing tendon to load.

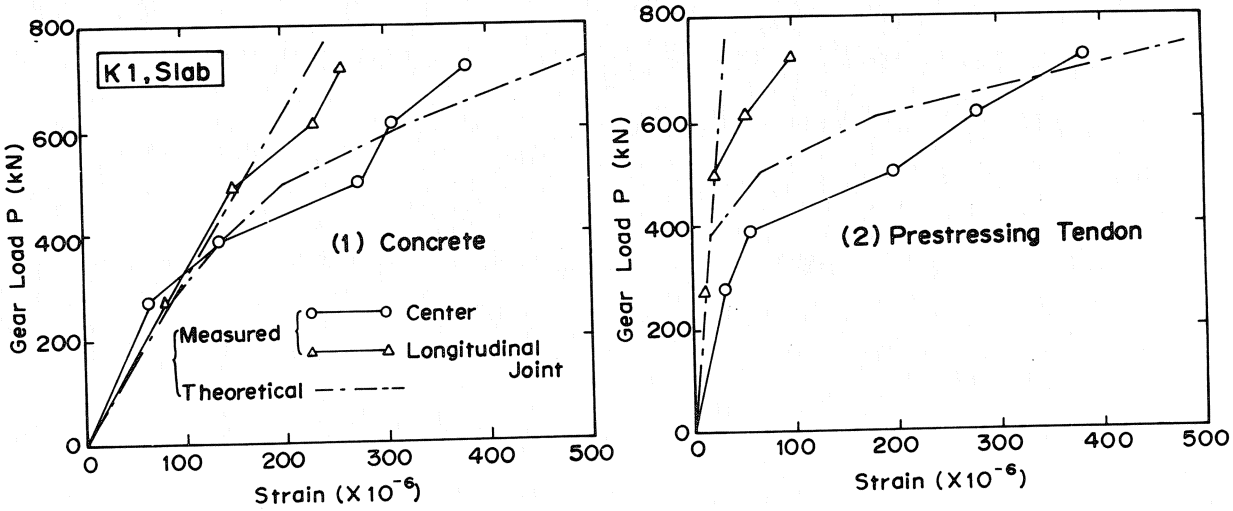


Table 2. Comparison of cracking loads between in measurement and in theory.

	Section	K1	K2	K3
Measured	Center loading	392～490	490～588	588～686
	Longitudinal joint loading	490～588	722～	722～
Theoretical	Ascending temperature	509	653	727
	Descending temperature	732	939	1044

(Unit : kN)

Figure 7. Cracks at the bottom of the slab (K2 section).

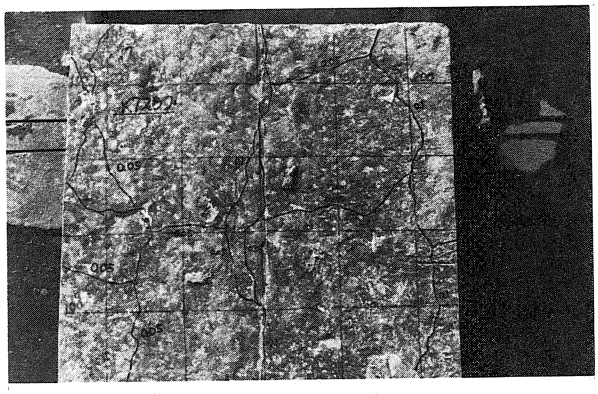
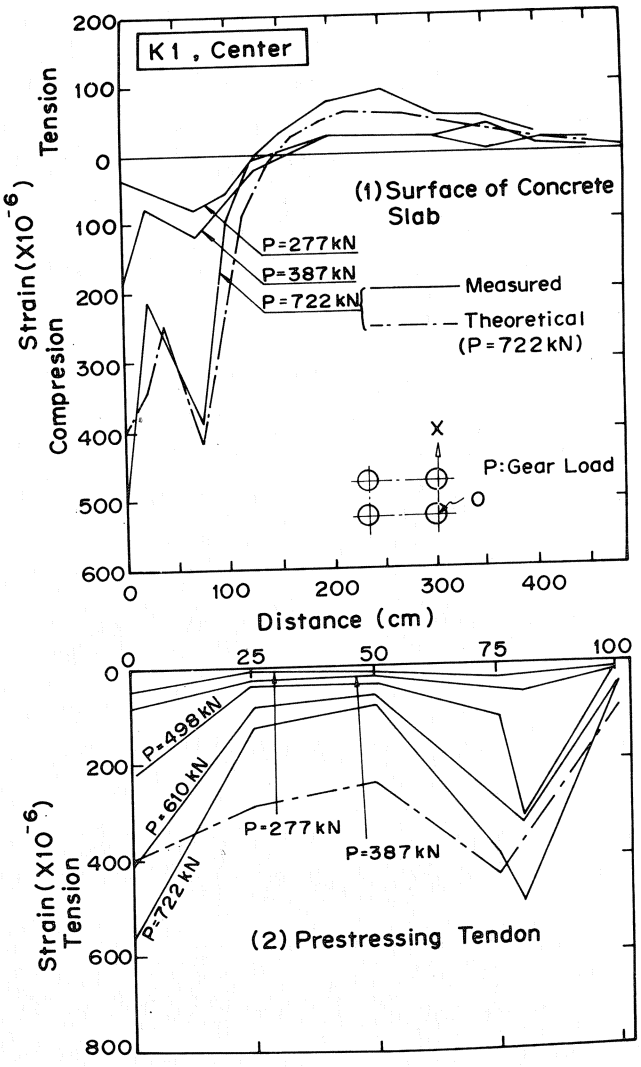


Figure 8. Distributions of strains of concrete and prestressing tendon.



investigate the bahavior of class III PC slab pavement when subjected to repetitive loads and evaluate them from the structural and functional points of view.

Figure 9 shows how the strains at the surface of the concrete slab are influenced as repeated loadings occur. The changes in position of the neutral axis of the slab during both the loading test 1 and the traffic test are given in Figure 10. Figure 11 shows how the permanent deformations of the base and slab change for each section according to the repeated loadings. In addition, the changes in the opening width of the longitudinal joints are shown in Figure 12.

From these results, the following characteristics regarding the durability of class III PC slab pavement were demonstrated.

1. The compressive strains at the surface of the concrete slab and the tensile strains of the prestressing tendons were increased slightly, as repeated loadings were carried out, but they did not reach a level to cause cracking at the surface of the concrete slab.
2. The positions of the neutral axis of the slab for all the sections scarcely changed during the repeated loadings. It is assumed that the depths of crack at the bottom of the slab remained almost constant.
3. The permanent deformations on the base and the surface of the slab gradually increased, and some voids might occur between the concrete slab and the base course.
4. The logitudinal joint opening widths under working load conditions increased, but by less than 0.2 mm. As for the recovery at the time of load removal, it was quite excellent due to the transverse prestressing.

Figure 9. Changes of strain distribution under repeated loadings.

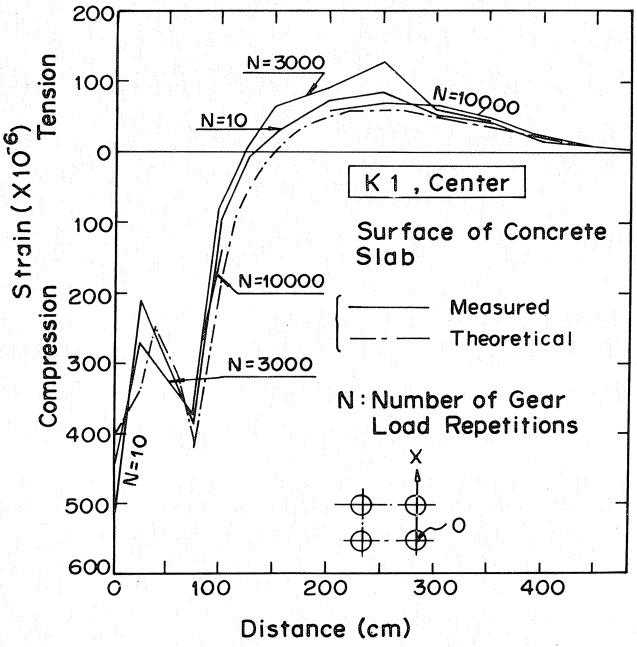


Figure 10. Positions of neutral axis during loading tests.

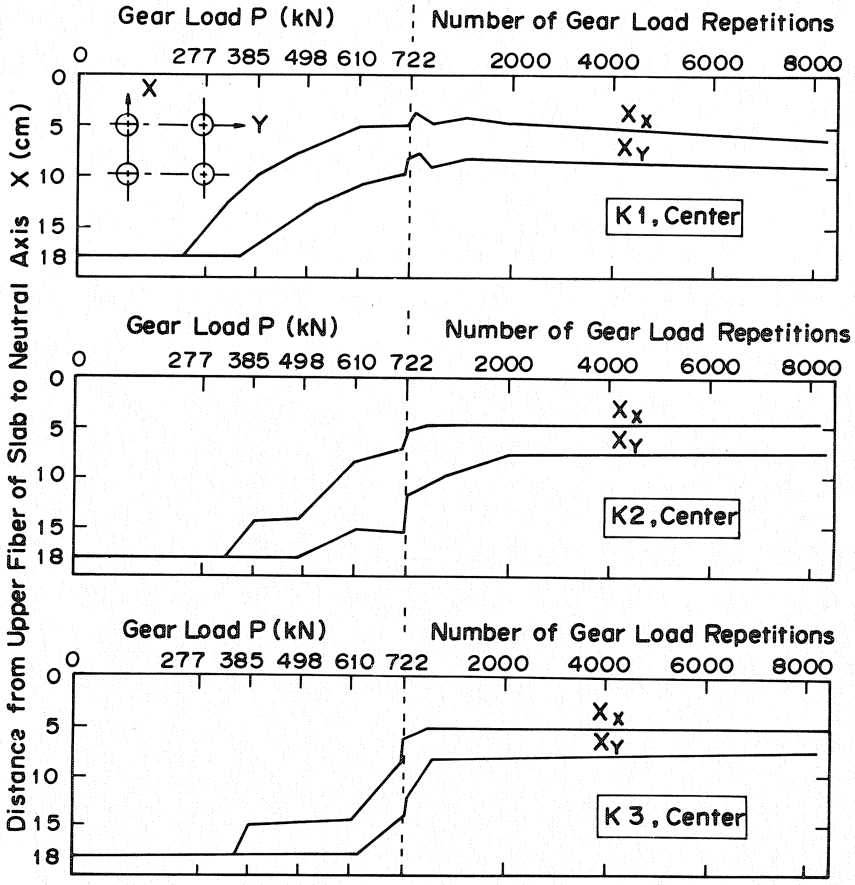


Figure 11. Permanent deformations under repeated loadings.

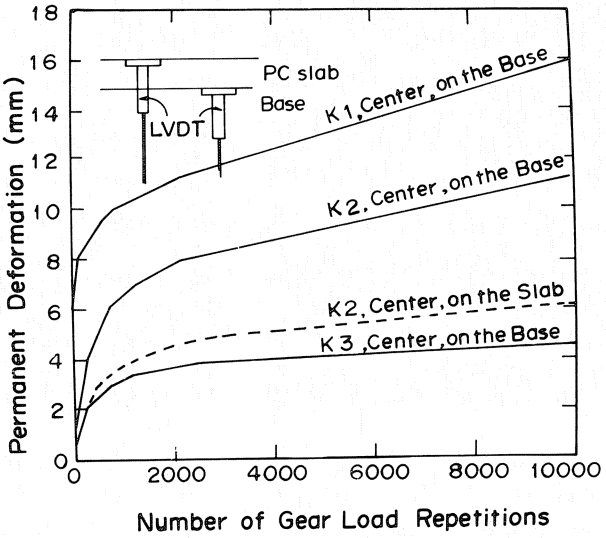
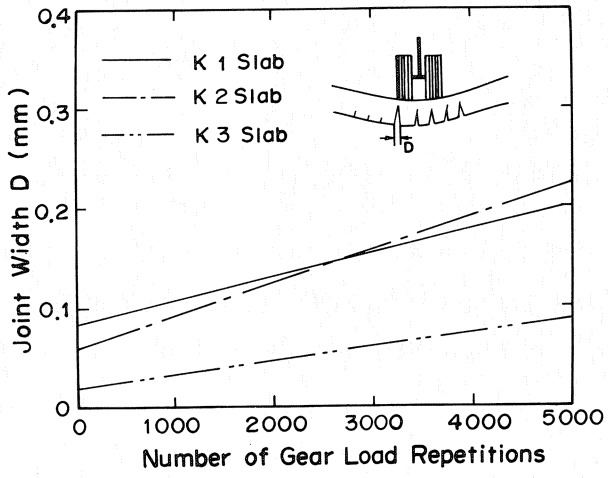


Figure 12. Joint widths under repeated loadings.



Discussion

In actual airports, since various types of aircraft travel and their movements possess some lateral wander, the pavements are under much less severe loading conditions compared with those of the test pavement over which the loading cart travelled in exactly the same direction and location. Nevertheless the test pavement even under such severe conditions did not show any problems in either structural or functional performance. Therefore, it may be safely assumed that a class III PC slab can be satisfactorily used for airport pavements.

It was confirmed that the longitudinal joints in PC slabs are efficient for the load transfer by the effect of transverse prestresses. The longitudinal joints in class III PC slabs may not be different from the center portion of the slab where cracks occur at the bottom of the slab. Accordingly, no special consideration should be necessary for longitudinal joints in airport pavements.

New type of PC precast slab pavement

Development of new connecting device

In concrete pavements, instead of placing concrete slabs in-situ which requires a long curing time, pavement using PC precast slabs which are manufactured in a factory has long been considered.

But since the conventional method of connecting laid PC precast slabs is by prestressing tendons or screws (3), it has always been subject to problems such as being inefficient, difficult to lay exactly level and impossible to remove and reset portions when a single slab has been damaged.

To overcome these problems, a horn-joint as shown in Figure 13 has been developed.

This technique is designed to connect the slabs by inserting arc-shaped steel bars from the surface of the slabs into arc-shaped plastic tubes cast into the concrete and grouting the gap between the tube and bar. This joint also makes it possible to replace and rejoin slabs simply by cutting the reinforcing bars and knocking the old bars and grout out of the tubes. This is possible as each tube is lined with grease.

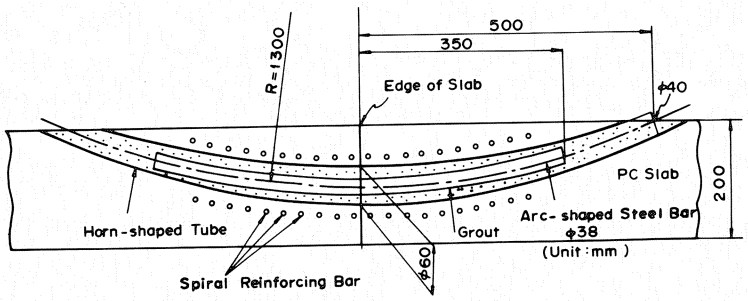
Laboratory tests were conducted to evaluate the function of this horn-joint and to decide the optimum material and radius of tube and the quality of fulling grout.

As a result, it was confirmed that this has almost the same load-transference properties as those of the conventional straight slip bar. It was also made clear from the tests that the bars and grout in tubes could be easily knocked out thanks to their tapered design giving them a "horn-like" shape.

Design and construction of test pavement

A new type of PC precast slab pavement, in which slabs are capable of being connected at their adjacent edges by the use of horn-joints, was made and

Figure 13. Horn-joint.



various tests were conducted to investigate their constructional properties and structural strength.

The PC precast slabs in the test pavement were designed for DC-8-63 aircraft. The slab thickness was 20 cm. The amount of prestressing was 2840 kPa. The length of each slab was 10 m and the width 2.3 m in consideration of ease of transportation and handling on site. Each slab was 11.5 t.

In the test pavement, six precast slabs were arranged on a levelling course of fine aggregate (sand 7: cement 1 by volume, 2 cm thick in average) over the base course of crushed stone. The measured $_3K_{75}$ values on the base course are 100 $\sim$ 150 N/cm^3.

The methods of connecting the slabs were mainly the previously-mentioned horn-joints. The diameter and spacing of the arc-shaped steel bars were determined by using the same procedure as for straight slip bar joints. The diameter of the steel bars was 38 mm and they were positioned at 40 cm centers. Further ordinary tests on the PC precast slabs tightened with prestressing tendons, which had been evaluated to be almost complete in load transfer effect, were also conducted for the purpose of comparison between the two methods.

After placing the slabs inposition by crane, the slabs were carefully levelled by the use of special tools (Figure 15), and the gab between the slab and the base course was grouted. The bottom of each slab was wrapped with vinyl sheet (Figure 15) to prevent the grout spreading unevenly. Superhigh early strength cement slurry was used as the grouting material and hydraulically pumped through four or five holes on the surface of slabs from a height of 1.2 m. One of the test slabs was turned over after the loading tests had been completed and it was observed that the gab was completely filled with the grout.

After conducting the loading tests on the grouted slabs in their disconnected condition, the slabs were interconnected. This was carried out by the insertion of the arc-shaped steel bars through the holes from the surface of the slabs and by grouting the gap between the tube and the steel bar. This process proved easy and quick to carry out.

Loading Tests

The static loading tests in which the load was increased step by step (in four stages up to the maximum gear load of 722 kN) were conducted before and after the connection of the precast slabs. The traffic tests (gear load: 722 kN) on the lane shown in Figure 14 were also conducted repeatedly for over 5000 times after the static loading tests. The previously-mentioned loading cart (Figure 5) was also used for these tests.

Figure 16 shows the measured strains at the edge of a slab under a 498 kN gear load placed at the

Figure 14. PC precast slab test pavement.

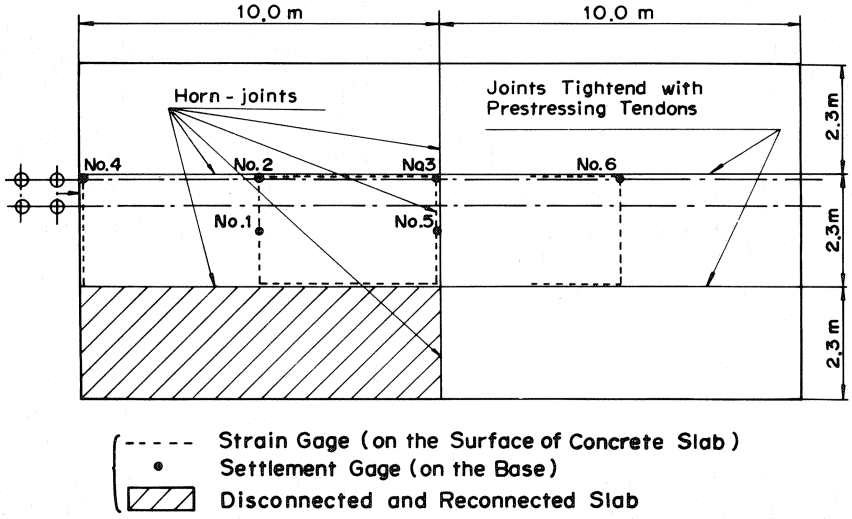


Figure 15. Section of PC precast slab pavement.

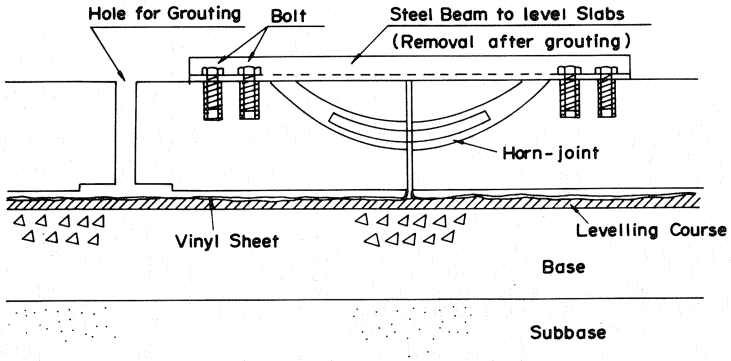


Figure 16. Comparison of slab edge strains between in a single slab and in single slab and in connected slab.

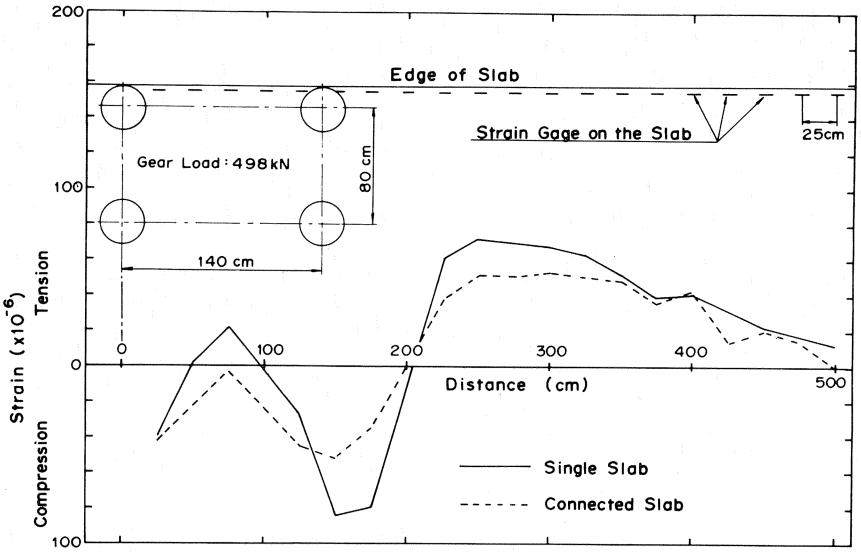
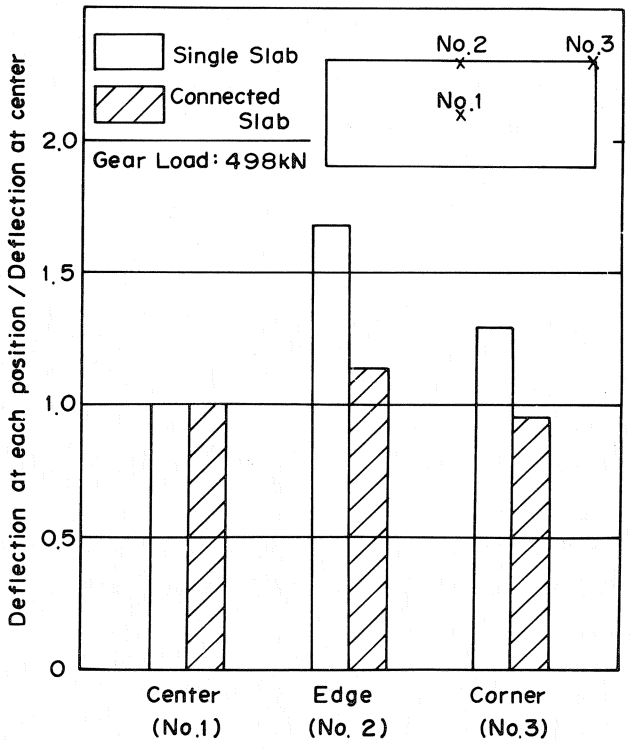


Figure 17. Comparison of deflections at various loading positions.



edge of the slab. The measurements were carried out both before and after the connection of the slabs. The former is called "a single slab" and the latter "connected slabs". From the comparison of these results, the strains of connected slabs seem to be considerably less than those of a single slab. Also, the strains of connected slabs are similar to, but slightly less than, those in the FEM analysis. Figure 17 shows the comparison of deflections at various loading positions in both a single slab and connected slabs. In the case of a single slab, the deflections at the edge and corner of a slab are fairly large compared with those at the center of a slab. On the other hand, after the slabs were connected, the deflections at each position of the slabs were almost the same.

From these results, it is clear that the horn-joint shown in Figure 13 has sufficient load transfer capabilities.

Figure 18 shows the change of the measured strains at the longitudinal joint of the connected slabs in the traffic tests. The maximum strain increases slightly with the repetitive loadings. However, since the measured strain after 5000 repetitions (number of wheel passes:10000) is not over that at the center of a slab in the FEM analysis and the cracking strain of a slab is considered to be about 300×10^{-6} based on the results of laboratory bending tests on concrete samples, the possibility of cracking in the connected slabs is negligible and the durability of the slabs connected with horn-joints will be sufficient for normal traffic.

This is also ascertained from the results shown in Figure 19. Figure 19 is a comparison of deflections at the longitudinal joint of connected slabs between with horn-joints and with prestressing tendons. Since they are almost the same and the latter has complete load transfer effect and large durability to repetitive loadings as explained in the chapter "class III PC slab pavement", the former has also similar characteristics.

Figure 18. Change of joint edge strain distribution under repeated loadings.

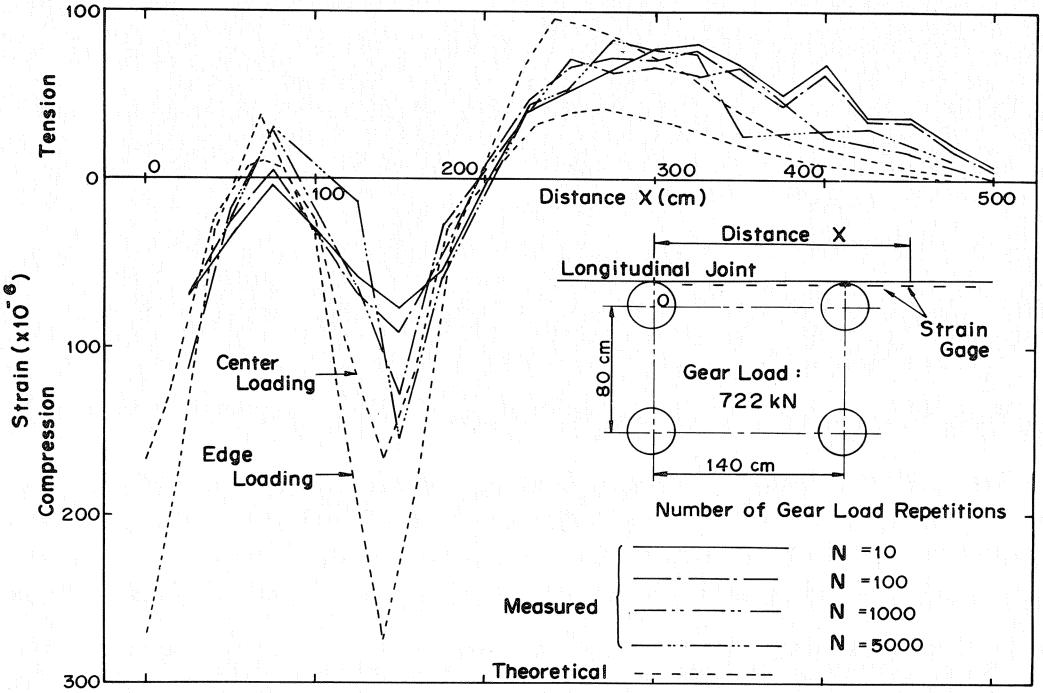
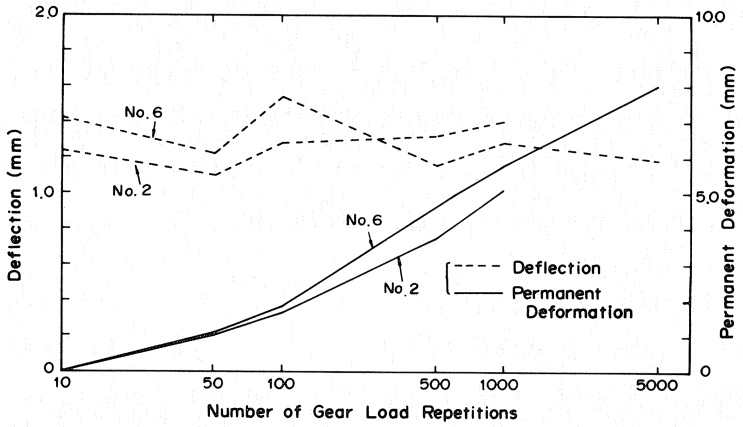


Figure 19. Comparison of joint deflections between in horn-joint slabs and in prestressing tendon slabs.



Methods for exchange of damaged slabs

After the completion of the loading tests on the connected slabs, a slab shown in Figure 14 was disconnected and reconnected to check the ease of maintenance in this new type of precast pavement.

The procedure for disconnection was as follows.

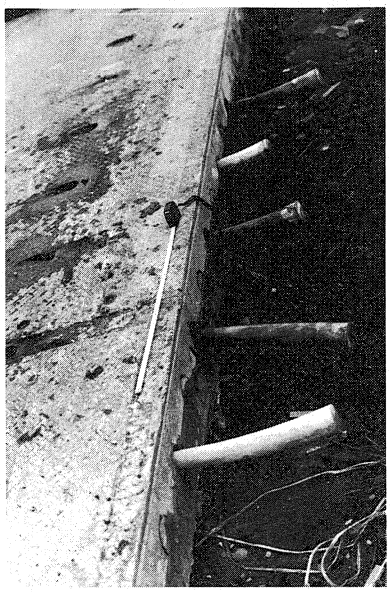
1. Cutting of curved iron bars.
2. Removal of disconnected slab.

The procedure for reconnection was as follows.

1. Adjustment of base course
3. Removal of bars and grout from tubes in exposed edges of disconnected slab (Figure 20)
3. Relaying of the slab
4. Levelling of each slab
5. Insertion of new bars
6. Grouting
7. Reconnection

Both disconnecting and reconnecting sequences were carried out rapidly and without any problems.

Figure 20. Removal of bars and grout from tubes.



Discussion

Since the PC precast slab pavement interconnected with horn-joints was confirmed by testing to have sufficiently smooth surface and good structural performance, and to be the easy facility in the exchange of damaged slabs, this new type of pavement can seem to be suitable for airport pavements application.

In this new type of PC precast slab pavement, the interconnection of each slab is very easy and it is possible to do the connecting work in parallel with the placement of slabs. This enables a construction speed to be faster than ever. Thus this new type of pavement will be widely suited not only to airport pavements but also to the other pavements areas where ease and speed of maintenance work are critical factors.

Conclusion

It is clear that the two developments described in this paper will prove themselves as highly practical solutions to the two major problems increasingly encountered in the construction and maintenance of airfields. The need to conserve energy and materials has become increasingly important recently and the increased air traffic at major airports has made fast and simple replacement of damaged pavement section a paramount consideration. The use of PC precast slab pavement connected with horn-joints promises to become widely used and familiar construction methods in the future.

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