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NONDESTRUCTIVE EVALUATION METHOD OF CONCRETE PAVEMENT BY FWD

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Nondestructive evaluation method of concrete pavement using deflections measured by a Falling Weight Deflectometer (FWD), has been developed. In this procedure, the mechanical properties of a concrete slab and foundation can be obtained by backcalculating from the FWD deflections measured at the slab center. Load transfer efficiency at a joint can be quantified from the FWD deflections measured at the joint. Furthermore, a void beneath the concrete slab can be detected and its size can be estimated. The time when the FWD measurement should be conducted is specified to minimize the influence of a vertical variation of temperature in a concrete slab.

Keywords : concrete pavement, structural evaluation, nondestructive test

1. INTRODUCTION

A destructive testing procedure has been adopted as a structural evaluation method for airport concrete pavement in Japan. This procedure is not only costly but time-consuming. Recently, however, the Falling Weight Deflectometer (FWD), one of the nondestructive testing instruments for pavements, has been introduced to solve these problems. After its deployment, various kinds of works[1),2)] have been carried out to verify the applicability of FWD for structural evaluation of airport concrete pavement and to establish a nondestructive evaluation method using it. This paper summarizes those results.

The thickness of concrete slab is determined on the basis of the maximum flexural stress at the bottom of a concrete slab. In the present design method of airport concrete pavement in Japan, the stress at the slab center calculated by Westergaard's equation, which considers the concrete pavement as an infinite slab supported by a Winkler foundation, is adopted. In this equation, the stress can be calculated when elastic properties of the concrete slab (E_c, ν_c : elastic modulus, Poisson's ratio, respectively) and a modulus of the foundation reaction (K) are given. Therefore, first, it is necessary to obtain E_c, ν_c and K in the nondestructive evaluation method of the concrete pavement.

In the current design method, a load transfer at a joint is assumed to be satisfactorily sufficient. However, all the joints cannot sustain the initial good load transfer function. Moreover, a void beneath the concrete slab may be caused by erosion of base course. As those situations bring the stress of the slab to a higher degree, they have to be quantified in the nondestructive evaluation method.

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After discussing these problems together with influence of a vertical variation of temperature in a concrete slab regarding the FWD deflections, the nondestructive evaluation method for concrete pavement is described briefly.

2. INSTRUMENT AND PAVEMENTS USED IN THIS STUDY

FWD can apply a load up to 49 kN to pavements through the loading plate which has a radius of 15 cm. The pavement deflections caused by this load are measured at three points of which distances from load center (r) are 0, 30 and 75 cm. The load is produced by dropping a mass of 150 kg from the given height. The FWD deflections used herein are those obtained in the case that the load is 49 ± 0.49 kN.

Concrete pavements at two airports and two kinds of full-scale test pavements were used in this study (Table 1). The actual airport pavements are plain, jointed concrete pavements of which thickness varies from 30 to 38 cm. The test pavements are also plain, jointed concrete pavements. Test pavement 1 was constructed to investigate mainly the load transfer efficiency at joints. In this pavement, several types of joints were installed. Test pavement 2 was used to study the influence of the void beneath the concrete slab on the pavement performance. In Test pavement 2, several voids were constructed along the joints[2].

The deflection measurement using FWD was conducted at night on the airport pavements, because aircraft use the pavements during the daytime. On the contrary, the FWD measurement was mainly conducted during the daytime on the test pavements. To investigate the influence of pavement temperature on the FWD deflections, 24-hr continuous deflection measurements were also carried out on Test pavement 1 in various seasons.

3. BACKCALCULATION OF MECHANICAL PROPERTIES OF CONCRTE SLAB AND FOUNDATION

First of all, E_c, ν_c and K have to be backcalculated from deflections obtained by FWD. Westergaard's equation for the pavement deflection in the case of interior-loading was used to do this because Westergaard's equation for the stress of the concrete slab is used in Airport pavement design manual.

In order to calculate a deflection of a pavement caused by an aircraft loading, a transformed Westergaard equation, which is developed by Pickett and Ray[3] to calculate the deflection caused by a uniformly distributed load, has to be adopted; for the original Westergaard equation for the pavement deflection can be applied only to a concentrated load. The deflection at the load center can be calculated easily using this equation. Different from this, the deflections apart from the load (r=30, 75 cm) have to be calculated by the time-consuming superimposing procedure in which a loading area is assumed to be split into many smaller parts and the desired deflection can be obtained as a sum of the deflections caused by the smaller parts[4]. To shorten a calculation time in the case of r=30, 75 cm, the applicability of the original Westergaard equation has been investigated. As a result, the original Westergaard equation is decided to be adopted because there seems no difference between deflections calculated by two methods.

In the Westergaard equations, a radius of relative stiffness ($l_r = [E_c h^3 / \{12(1-\nu_c^2)K\}]^{0.25}$; h : slab thickness) and K are used as the mechanical properties of the concrete pavement. This means that both E_c and ν_c will not be able to be obtained even if both K and l are obtained. Though E_c is likely to vary for some

Table 1 Test pavements.

	Test pavement 1	Test pavement 2
Length and width of slab (m)	5 - 7	3 - 5
Thickness of slab (cm)	30 - 45	25 - 38
Load transfer device	Keyed, Dowel bar	Keyed, Dowel bar, Horn
Base course	4cm asphalt stabilized layer on 11cm crushed stone layer	5cm crushed stone layer
Width of void along joint (cm)	None	0 - 80

reason or other and influence the deflections greatly, ν_c does not affect the performance of the pavement to any great extent in comparison with E_c. Therefore, ν_c is assumed constant in this study (=0.15, which is used in the design manual).

E_c and K can be backcalculated according to the following procedure, of which flow chart is shown in Fig. 1.

1) First, calculate the deflections according to various combinations of K and l assumed within the prearranged values.
2) Second, compute a difference between the calculated and measured deflections in each combination of K and l.
3) Then, find the solution (K and l) which shows the minimum difference between the deflections.
4) Finally, obtain E_c from the rearranged equation for the radius of relative thickness; $E_c=12\,(1-\nu_c^2)\,Kl^4/h^3$.

It is found that difference between the estimated and measured deflections is within 5 % for the most cases. The difference is defined by average absolute difference; namely, $1/3\sum_{i=1}^{3}|(d_{ic}-d_{im})/d_{im}|$ (d_{ic}: calculated deflection, d_{im}: measured deflection and i: sensor number).

4. INFLUENCE OF PAVEMENT TEMPERATURE ON FWD DEFLECTION

The concrete slab warps due to temperature variation in the vertical direction of the concrete slab. Fig. 2 shows K backcalculated from 24-hr continuous measurement at Test pavement 1 together with K measured by plate bearing tests on a crushed stone layer. They are recognized to coincide well with each other, based on the fact that estimated K is assumed on an asphalt stabilized layer. However, it is clear that backcalculated K varies with the time of day; that is, estimated K looks larger than measured K in the nighttime, and conversely, it seems smaller in the daytime. On the other hand, it is found that

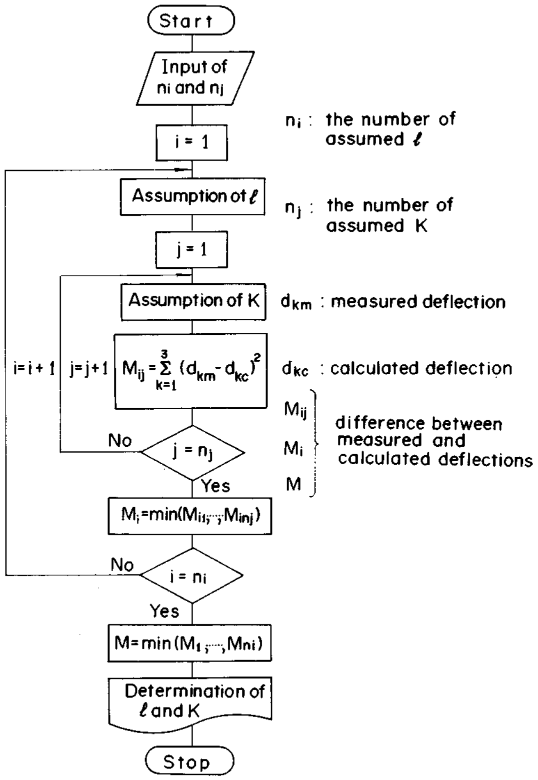

Fig. 1 Flow chart of backcalculation.

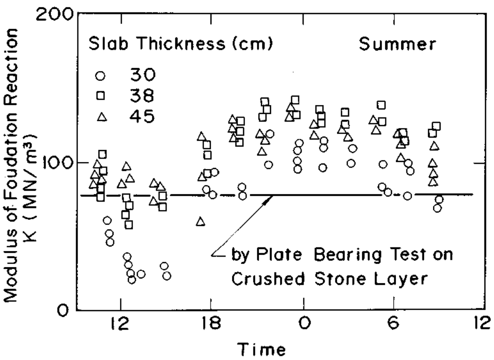

Fig. 2 Variation of K with time.

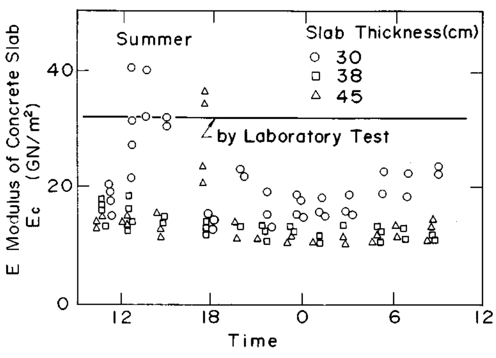

Fig. 3 Variation of E_c with time.

backcalculated E_c is constant regardless of time in a day different from K (Fig. 3). The backcalculated E_c seems to be smaller than that measured by laboratory compression test, but it may be explained by various factors such as the difference in the curing process of concrete.

When the concrete pavement needs to be treated as that composed of concrete slabs supported by an elastic foundation, an elastic modulus of foundation (E_s) has to be obtained. To do this, the procedure that is same as the above-mentioned method except that the finite element method (FEM) is used for calculating the deflection, has been developed[5]. Boussinesq's equation is used to simulate the elastic foundation in FEM. Fig. 4 shows E_s obtained by this procedure assuming that ν_c, Poisson's ratio of foundation (ν_s) is 0.15, 0.30, respectively, for simplification. E_s varies with the time of day as well as K shown in Fig. 2.

The mechanical property of the foundation looks like that it changes with the time of day regardless of considering the foundation as the Winkler foundation or the elastic foundation. In view of the result that K is smaller in the daytime than in the nighttime, the FWD deflections are surely affected by the warping of the concrete slab occurring from the vertical variation of temperature in it. As measurement of the amount of warping is difficult, its presence has not been confirmed in this study. However, experiment[6] will support the results obtained here. In this experiment, the warping, which is defined by a relative difference in vertical directional deformation of the concrete slab between the slab center and edge, was observed. The warping of 0.44 mm downwards in the early morning and 0.18 mm upwards in the daytime was shown.

5. QUANTIFICATION OF EFFICIENCY OF LOAD TRANSFER AT JOINT

The validity of the efficiency of load transfer at joint defined by Eq. (1) was verified[5,7].

$$E_{ff}=\frac{d_u}{(d_l+d_u)/2}\times 100 \qquad (1)$$

where, d_l, d_u is the deflection in the vicinity of a joint on a loaded slab and unloaded slab, respectively, which are obtained by plate loading test.

E_{ff} has to be determined in evaluating the airport concrete pavement structurally since the load transfer function is assumed to be sufficient in the design manual, and E_{ff} is necessary to determine the overlay thickness according to Airport pavement maintenance and rehabilitation manual. E_{ff} cannot be evaluated using FWD directly because the points where deflections are obtained by FWD are not the same as the points where deflections used in Eq. (1) are measured; that is, the distance from joint is 15 cm in case of FWD as shown in Fig. 5. Thus the efficiency of load transfer at joint has to be quantified by another way, and now E_{ff}', which is defined by the following equation, has been introduced.

$$E_{ff}'=\frac{d_{12}}{(d_{11}+d_{12})/2}\times 100 \qquad (2)$$

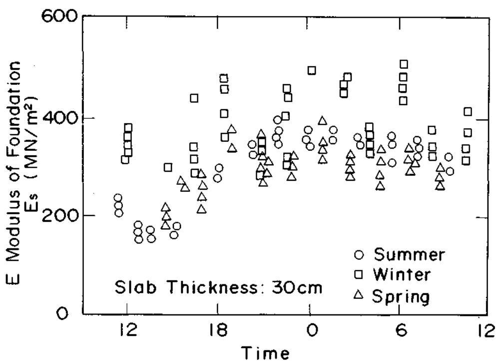

Fig. 4 Variation of E_s with time.

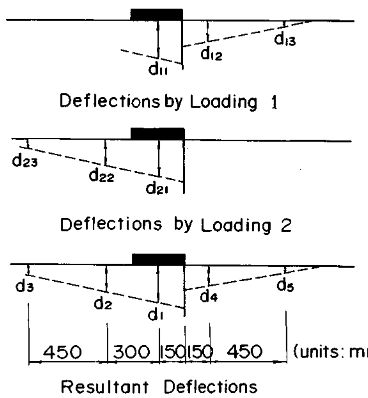

Fig. 5 Deflection measurement at joint.

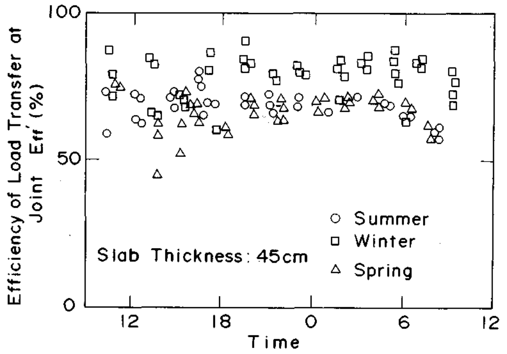

Fig. 6 Variation of E_{ff}' with time.

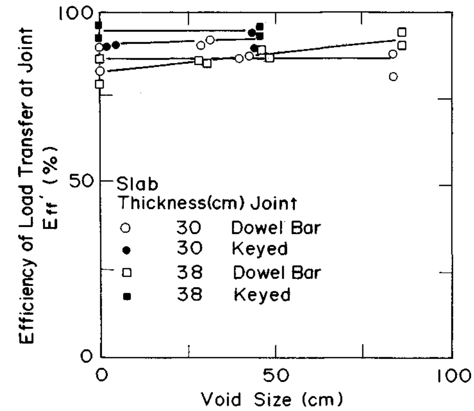

Fig. 7 Influence of a void on E_{ff}'.

where, d_{11}, d_{12} is the FWD deflection on the loaded and unloaded slab, respectively (shown as Loading 1 in Fig. 5).

To ascertain the validity of E_{ff}', the relationship between E_{ff}' and E_{ff} was investigated by numerical analysis ; that is, calculating the deflections required in Eq. (1) and Eq. (2) and comparing E_{ff}' with E_{ff} in various pavement structures using FEM. As a result, E_{ff}' can be recognized equal to E_{ff} practically because a coefficient of correlation between them is found to be 0.99.

Fig. 6 shows E_{ff}' measured at the various time of day on Test pavement 1. From this figure, E_{ff}' is found to be practically constant irrespective of the time of day. E_{ff}' measured in Winter seems to be slightly larger, but it is considered to be within the tolerable scattering range practically. This means that the void beneath the concrete slab, which is caused by the warping of the concrete slab, does not affect E_{ff}' greatly. It is supported by Fig. 7 showing the relationship between void size and E_{ff}' obtained at Test pavement 2.

6. ESTIMATION OF VOID BENEATH CONCRETE SLAB

As mentioned above, a void beneath a concrete slab seems to occur from the warping of the concrete slab. In addition to this, another type of void is possibly caused at the joint due to loss of base course material. The void does not affect E_{ff}' greatly but the FWD deflections themselves ; for instance, Fig. 8 shows the maximum FWD deflection at a joint measured at Test pavement 2. This may suggest that a void can be detected and its size can also be estimated by the FWD deflection. In order to determine void size, if present, from the FWD deflections measured at a joint, the special FWD measurement method shown in Fig. 5 was used ; FWD was placed in the vicinity of a joint to obtain deflections d_{11}, d_{12} and d_{13} (Loading 1), and then, FWD was turned to obtain the deflections d_{21}, d_{22} and d_{23} (Loading 2). As resultant deflections, five deflections were obtained shown in Fig. 5. The estimation will be able to be conducted more accurately by using these five deflections. It is possible to backcalculate E_c, K, E_{ff} and void size from these deflections by using the finite element method in which concrete pavement is considered as jointed slabs supported by Winkler foundation. However, this procedure is time-consuming ; for it needs a lot of computational time to determine four unknown quantities (E_c, K, E_{ff} and void size). Therefore, alternative method has been developed ; an apparent modulus of foundation reaction (K') has been introduced. K' is considered as the modulus of foundation reaction backcalculated from the deflections measured at the joint on the assumption that there is no void. It means that only K' has to be backcalculated. If the void exists, K' will be smaller than K, which is backcalculated from the deflections measured at the slab center according to the aforementioned procedure.

In this procedure, E_c and K obtained from the FWD deflections at the slab center are adopted, and E_{ff}' is calculated by Eq. (2) using the deflections obtained according to Loading 1 in Fig. 5. After obtaining K'

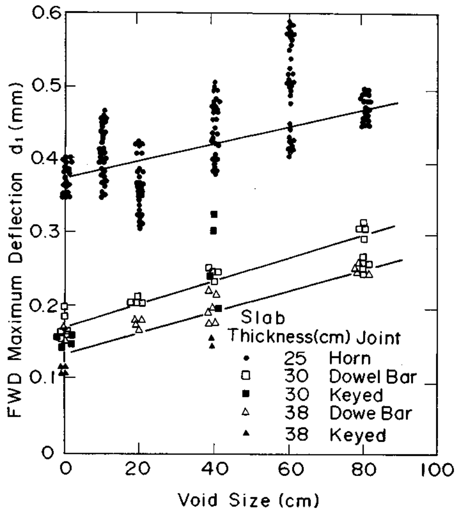

Fig. 8 Influence of a void on deflection.

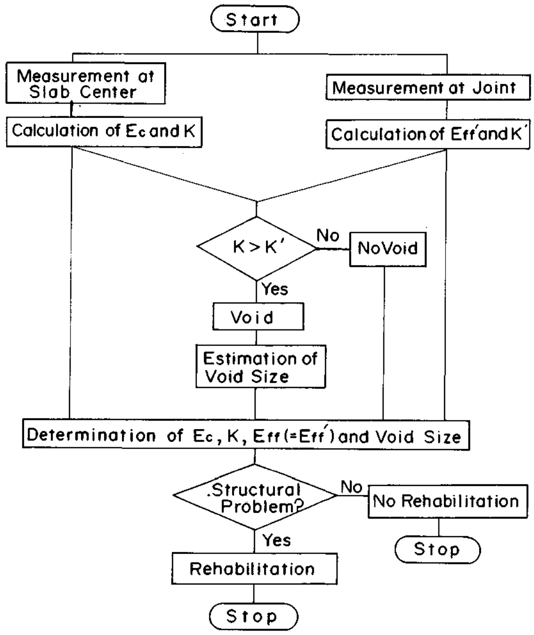

Fig. 10 Flow chart of nondestructive evaluation method.

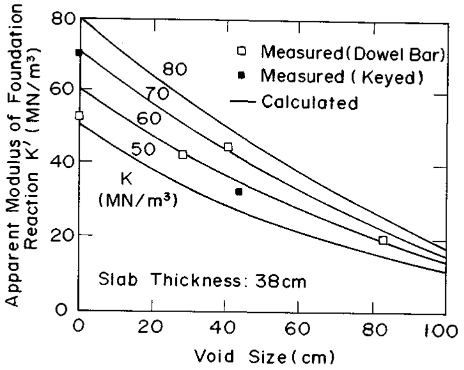

Fig. 9 Relationship of K' to a void.

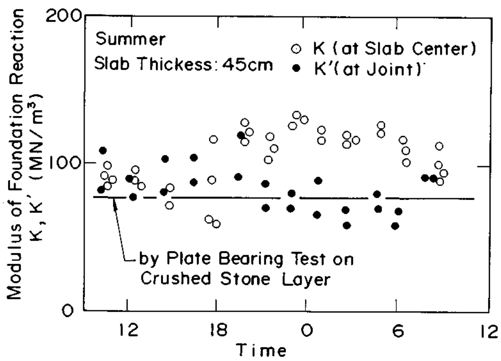

Fig. 11 Comparison of K' with K.

by backcalculating from those five deflections shown in Fig. 5 with reference to E_c and E_{ff}', the presence of void can be judged in comparison of K and K'. The void size can be estimated by the use of the theoretical relationship between K' and the void size such as shown in Fig. 9. This theoretical relationship is obtained by using FEM on the assumption that the void exists under the concrete slab. From this figure, the void size is estimated as 25 cm when K', K is 60, 80 MN/m^3, respectively. The validity of this method has been ascertained since the estimated values correspond with the theoretical line.

7. PROPOSAL OF NONDESTRUCTIVE EVALUATION METHOD

Summarizing the preceding discussion, the following nondestructive evaluation method of a airport concrete pavement is proposed. Fig. 10 is the flow chart. From the FWD deflections measured at the slab center, E_c and K are obtained. Using the deflections measured at the joint, E_{ff} $(=E_{ff}')$ is quantified first, and then, K' is obtained by backcalculation from the these deflections with reference to E_c and E_{ff}. If K' is smaller than K, there might be a void beneath the concrete slab of which size can be estimated using the relationship between K' and the void size such as shown in Fig. 9. In this way, E_c, K, E_{ff} and the void size, if present, can be decided and the structural condition of the pavement will be evaluated.

In addition to the above-mentioned method, E_c, K, E_{ff} and the void size, if present, can also be obtained from the deflections measured only at the joint. This method needs a great deal of computational time as four unknown quantities (E_c, K, E_{ff} and void size) have to be backcalculated. Therefore, it should be considered as a secondary method.

The warping of the concrete slab cannot be neglected for the structural evaluation of the concrete pavement as shown in Fig. 11 ; at the slab center, K measured in the daytime is smaller than K in the nighttime and, on the contrary, K' obtained at the joint is larger in the daytime than in the nighttime. Although it might be possible to estimate the amount of warping analytically, it has not been accomplished so far. Therefore, the procedure that the FWD measurement at the slab center, at the joint, should be made at night, in the daytime, respectively, has been adopted as a temporary rule for minimizing the influence. Both K and K' on the assumption that there is no void can be obtained in this way.

8. CONCLUSIONS

Structural condition of concrete pavements can be evaluated by the FWD deflections. Elastic modulus of the concrete slab and modulus of the foundation reaction (also elastic modulus of foundation if necessary) can be obtained from the FWD deflections measured at the center of a concrete slab. Also, the load transfer efficiency at the joint can be quantified using the deflections measured at a joint. Furthermore, a void beneath the concrete slab can be detected and its size can be estimated analytically.

The validity of the above-mentioned nondestructive evaluation method has been verified by the analysis of the FWD deflections measured on the pavements in two airports and two kinds of test pavements. It is also found from the collected FWD data that the warping of a concrete slab cannot be neglected. To minimize its influence regarding deflections, the FWD measurement at a slab center, at a joint, should be made during the nighttime and daytime, respectively.

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