STRUCTURAL EVALUATION FOR AIRPORT ASPHALT PAVEMENTS WITH EARTHQUAKE INDUCED CRACKS

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Two aspects were included in this paper: (1) evaluating the seriousness of earthquake induced cracks; (2) identifying the effectiveness of maintenance and rehabilitation (M&R). Firstly, through a theoretical analysis of elastic three-layer pavement model, pavement deflections D_{45} as well as D_{250} under FWD loading conditions at cracked and uncracked sections were recommended as indices to evaluate the seriousness of cracks. By means of statistical test, the structural evaluation procedure was proposed. Its validity was verified by coring tests. Then, by comparing the FWD deflections before and after M&R, the effectiveness of sealing, patching and overlay was identified.

Key Words: *structural evaluation, asphalt pavement, FWD, crack, M&R, airport, earthquake*

1. INTRODUCTION

(1) Background

The Hyogo-ken Nanbu earthquake of January 17, 1995 resulted in serious damage in runways of Osaka International Airport. The distribution of the earthquake induced cracks are shown as **Fig. 1**.

(2) Problem

Compared with road pavements, airport pavement cracks would result in higher risks for its transportation because of higher moving speed. Especially, earthquake induced cracks might be more serious and harmful because they often become wider and bring about severer faults. Therefore, urgent inspection, evaluation and effective repair will be needed when the pavements experienced an earthquake. In order to evaluate the seriousness of cracks and to assure the effectiveness of urgent repair, a simple and valid procedure should be developed.

(3) Literature review

Falling Weight Deflectometer (FWD) is an effective non-destructive means to inspect pavement structural condition. By using FWD deflections and corresponding criteria, pavement structural condition could be evaluated. Then, pavement maintenance and rehabilitation (M&R) alternatives could be recommended accordingly. For pavement structural evaluation, N. Abe et al., based on two years of continuous FWD measurement at more than 300 sites all over Japan, put forward a procedure with four FWD deflection indices D_0, D_{150}, D_0-D_{20} and D_0-D_{150} [1)]. At the same time, they proposed the relevant criteria to evaluate the strength of overall pavement structure, subgrade, asphalt layer as well as the overall pavement layers above subgrade, respectively. For response of cracked pavement under FWD loading condition, W. Uddin investigated the effects of pavement discontinuities under a standard FWD load by means of three dimensional finite element ABAQUES code, in which pavement crack was simulated as an uni-directional gap element GAPUNI [2)]. F. W. Jung et al., using the theory of Boussinesq and Odemark's method of equivalent layer thickness, investigated the degree of structural integrity of two layered pavements through the effective modulus calculated from measured surface deflection and the effective modulus from subgrade deflection [3)].

For structural evaluation of airport asphalt pavements with earthquake induced cracks, it

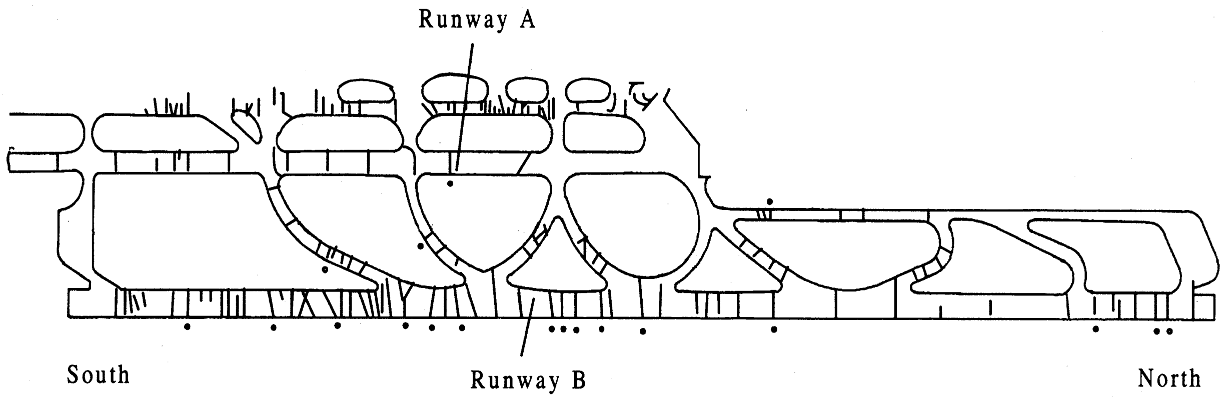


Fig. 1 Earthquake induced cracks in runways of Osaka International Airport

should take consideration of:

1) asphalt pavement structure,
2) FWD test condition,
3) the seriousness of cracks,
4) the effectiveness of M&R.

However, procedure in reference 1) mainly concerns with road asphalt pavement structure and road FWD test condition, which is weaker in pavement strength, lighter in FWD load and smaller in size of loading plate. The method in reference 2) has to make many assumptions such as moduli of pavement layers, friction coefficient at the interface of GAPUNI as well as the depth of cracks. The accuracy of these assumptions is difficult to verify. In reference 3), two layer system is far from reality of airport asphalt pavements.

Besides of all above, the main shortcoming of these procedures is that they rely heavily on absolutely true FWD deflection values. Actually, these values are difficult to obtain because many factors, e.g., temperature, FWD equipment, etc., influence the measured FWD deflections. Therefore, a new evaluation procedure is developed herein.

(4) Contents of the paper

Two aspects are included in this paper: evaluating the seriousness of earthquake induced cracks and identifying the effectiveness of M&R.

Firstly, through a theoretical analysis of elastic three layer pavement model, pavement deflections D_{45} as well as D_{250} under FWD loading conditions at cracked and uncracked sections were selected as indices to evaluate the seriousness of cracks. By means of statistical test, the structural evaluation procedure was proposed. Its validity was verified by coring tests conducted right after the earthquake.

Then, by comparing the FWD deflections before and after M&R, the effectiveness of sealing, patching and overlay was identified.

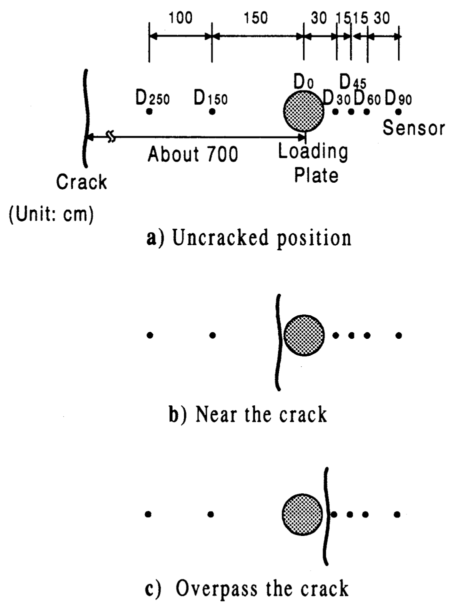


Fig. 2 Positions for conducting FWD tests

2. SERIOUSNESS OF CRACKS

(1) FWD measurement

Right after the earthquake, some wider cracks were selected for conducting FWD tests. For each crack selected, FWD tests were conducted at the positions shown in **Fig.2**. All FWD tests were carried out at night time, and the levels of impulse load were100kN, 150kN and 200kN.

(2) Theoretical analysis

a) Principle

Airport asphalt pavement is thicker in structure, heavier in load withstood and higher in functional requirements than that of road pavement. Hence, the

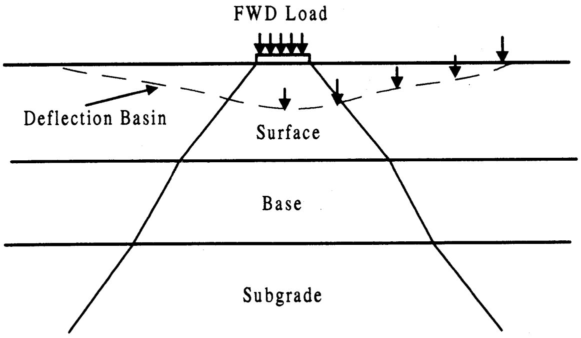


Fig. 3 Distribution of vertical strain under FWD loading

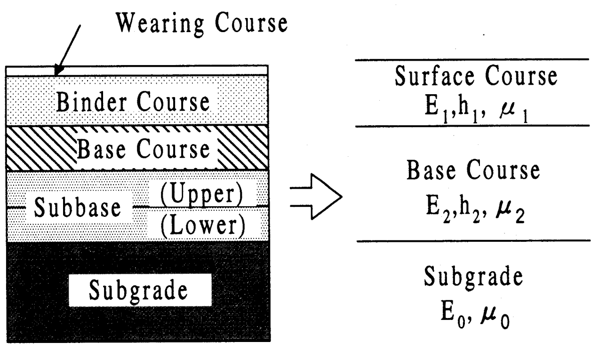


Fig. 4. Pavement structure model for theoretical analysis

FWD equipment was designed as a maximum impact loads of 200kN, 45cm of loading plate diameter, 250cm of maximum sensor distance and approximately 20-30msec of impulsive force duration. Under standard FWD loading condition, the distribution of vertical strain in pavement structure is shown as **Fig.** 3. The accumulated vertical displacements of pavement structure could be detected by FWD deflection sensors at different distances from the load center.

Existed researches reveal that the deflections far away from the load center are determined by the modulus of the bottom layer, those at intermediate distances from the load center are determined by the modulus of the middle layer, and those near the load center are determined by the modulus of the top layer [1), 4)]. Based on this principle, the theoretical analysis is carried out.

b) Investigation

During the theoretical analysis, airport asphalt pavement structure was modeled as an elastic three-layer system with asphalt surface course, base course and subgrade, as shown in **Fig. 4**.

Three kinds of asphalt pavements with thin, medium and thick structures were selected for analysis. The thickness, range of elastic modulus as well as Poisson's ratio of each layer were listed in **Table 1.** It represents the general scope of airport asphalt pavement structures currently used in Japan.

Utilizing BISAR program and modifying the elastic modulus of surface course, base course as well as subgrade respectively, the deflections at load center (D_0), 45cm (D_{45}) and 250cm away from the load center (D_{250}) were investigated under 200kN of FWD loading condition. It is well known that D_0 represents the overall pavement strength, whereas D_{250} mainly represents the influence of subgrade strength.

D_{45} was selected for two reasons:

1) D_{45} mainly represents the accumulated vertical displacements of pavement structures beneath the asphalt layer in case that the thickness of airport asphalt layers is generally less than 45cm.

2) D_{45} has larger deflection values and hence, has relatively higher precision than either D_{60} or D_{90} does.

Table 1 Parameters of airport pavement structures for theoretical analysis

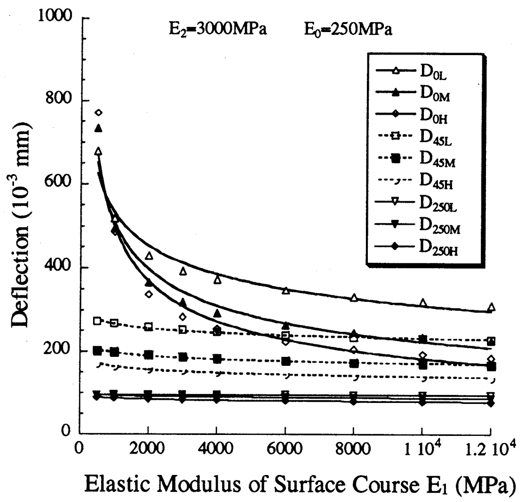
Item	Surface	Base	Subgrade
Thickness (cm)			
Thin	15	60	
Medium	23.5	90	
Thick	30	120	
Range of elastic modulus (MPa)			
	500 - 12000	250 - 3000	50 - 1000
Poisson's ratio			
	0.30	0.30	0.35

The results of theoretical analysis were demonstrated in **Fig. 5**, in which L, M and H represent pavement with thin, medium and thick structures, respectively.

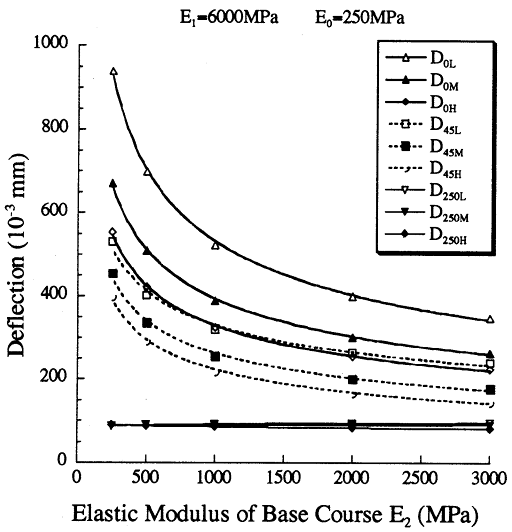
c) Analysis

From **Fig. 5**, the following relationships are found. As the elastic modulus of surface course decreases, D_0 increases, whereas D_{45} has relatively smaller increase and D_{250} almost keeps constant. To the contrary, as the elastic modulus of subgrade decreases, all deflections including D_{250} increase significantly. Moreover, as the elastic modulus of base course decreases, D_{250} almost keeps constant, whereas both D_0 and D_{45} increase significantly.

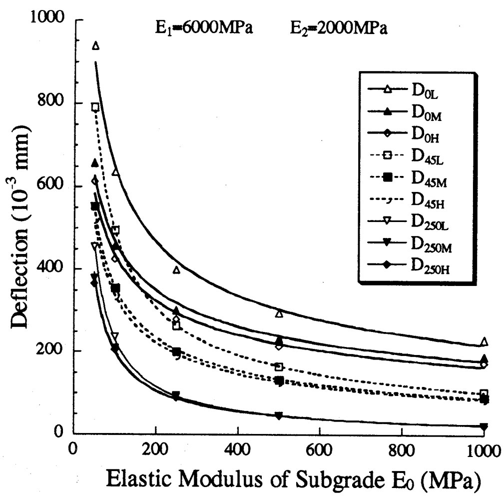
Generally, depending on a set of FWD deflections irrespective of the presence of cracks to backcalculate the elastic moduli of pavement layers, it may result in non-unique solutions. However, while comparing FWD deflections at cracked section with that of uncracked section, it is possible to identify the seriousness of cracks because crack



a) Surface course



b) Base course



c) Subgrade

Fig. 5. Relationship between pavement deflections with elastic modulus

is the only difference.

Compared with those of uncracked pavement layers, elastic moduli of the cracked pavement layers might be apparently lower. So, the difference in deflection values of D_{45} or D_{250} at cracked and uncracked sections is certainly resulted from the lower apparent elastic moduli in layers of cracked section. Thus, the seriousness of cracks could be identified qualitatively. As a result, the evaluation procedure was developed.

(3) Evaluation procedure

a) Procedure

For evaluating the seriousness of cracks, two FWD measurements must be conducted: far away from the crack and near the crack. The following procedure is recommended to make such an evaluation:

1) Comparing D_{250} of uncracked section with that of cracked section, if the latter is significantly larger than the former, there must be a lower elastic modulus in the subgrade of the cracked section. So, the crack may exist in the subgrade.

2) If no significant difference exists between the two D_{250} values, compare D_{45} of uncracked section with that of cracked section. Similarly, if the latter is significantly larger than the former, there must be a lower elastic modulus in the base course of the cracked section. So, the crack may exist in the base course.

3) Neither D_{250} nor D_{45} has significant difference, the crack may only exist in the surface course.

4) The deflections D_{45} and D_{250} of cracked section on FWD loading side were used for evaluation. That is to say, D_{45} is near the crack measurement, whereas D_{250} is overpass the crack measurement, as shown in **Fig. 2 b)** and **c)**, respectively.

The evaluation procedure was illustrated by a flow chart as shown in **Fig. 6**.

b) Statistical test

A t-statistics test was employed to check the significance of difference between the two deflection values. If the two deflection values, a_1 and a_2, meet Eq. (1), it means that they do not have significant difference under the statistical level α, and vice versa.

$$|a_1 - a_2| \le t_{\alpha/2} \cdot \sqrt{\frac{s_1^2}{n-1} + \frac{s_2^2}{m-1}} \qquad (1)$$

in which,

a_1, a_2 - average FWD deflections at cracked and uncracked section;

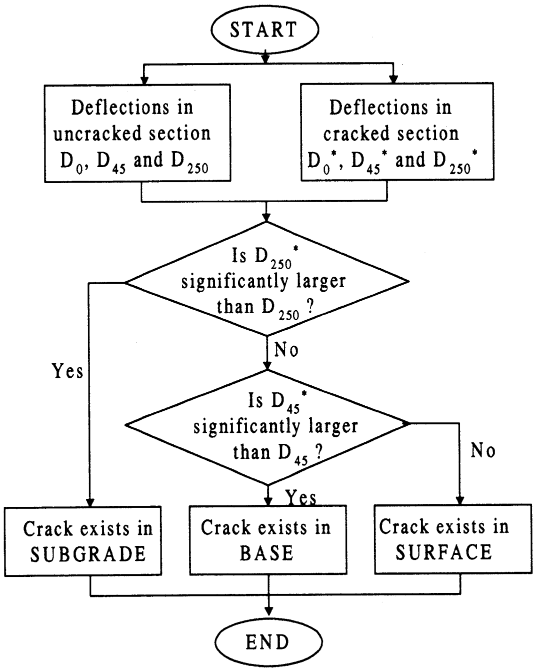


Fig. 6 Flow chart for evaluating the seriousness of crack

n, m - number of samples of FWD measurements at cracked and uncracked section;

s_1, s_2 - standard deviation of FWD deflections at cracked and uncracked section.

$t_{\alpha/2}$ - double side t - distribution value with freedom m+n-2 and statistical level α .

(4) Application

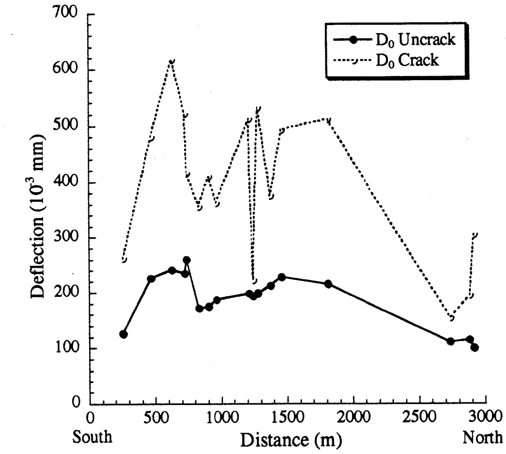
Right after the earthquake, FWD tests were conducted in runways of Osaka International Airport. Through the evaluation procedure proposed above, the seriousness of earthquake induced cracks was evaluated.

a) Deflections

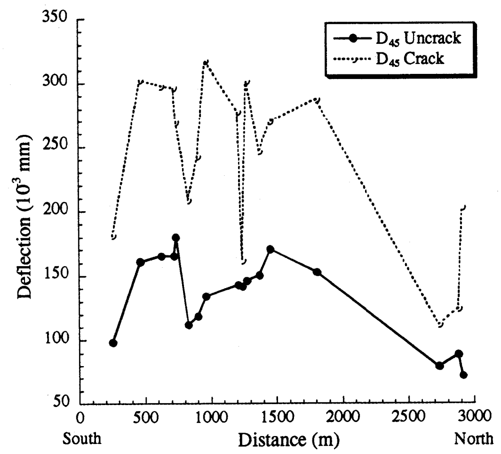
Fig. 7 demonstrates the distribution of FWD deflections D_0, D_{45} as well as D_{250} at cracked and uncracked sections in runway B. It shows that the deflection D_0 and D_{45} in cracked sections are obviously larger than that of uncracked sections, whereas D_{250} does not have such a phenomenon obviously.

b) Evaluation

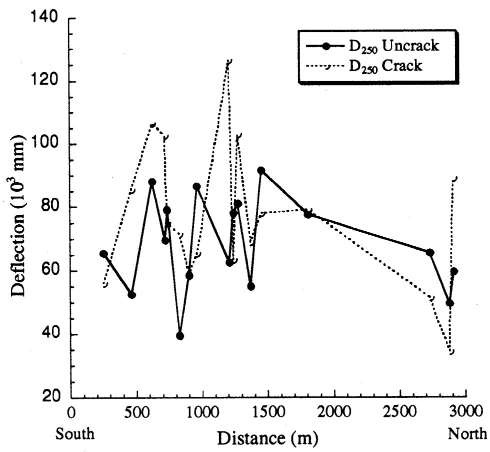
The FWD deflection was measured four times at some wider cracks. Omitting the first one, three sets of FWD deflection data were available. Thus, m=n=3. Statistical level α was taken as 5%. Therefore, $t_{\alpha/2}(m+n-2)$=2.7764. Consequently, the seriousness of earthquake induced cracks was evaluated, as shown in **Table 2.**



a) D_0



b) D_{45}



c) D_{250}

Fig. 7 Distribution of deflections

Table 2 Seriousness of earthquake induced cracks

Position	D_{250}	D_{45}	Estimated Crack Depth
B14	X	X	SUBGRADE
B19	X	X	SUBGRADE
B22	X	X	SUBGRADE
B23	O	X	BASE
B27	X	X	SUBGRADE
B28	O	X	BASE
B30	O	X	BASE
B35	X	X	SUBGRADE
B36	O	O	SURFACE
B37	X	X	SUBGRADE
B38	X	X	SUBGRADE
B40	O	X	BASE
B46	O	X	BASE

Note:

X— deflections at cracked section and uncracked section have significant difference;

O— deflections at cracked section and uncracked section do not have significant difference.

Table 3 FWD deflections of the example (FWD load level: 200kN; Unit: 10^{-3}mm)

Position	D_0	s_0	D_{45}	s_{45}	D_{250}	s_{250}
Uncracked section	101	5.3	65	4.0	51	3.6
Cracked section	234	6.6	158	5.6	65	4.5

Note: s_0, s_{45} and s_{250} represent the standard deviation of FWD deflection D_0, D_{45} and D_{250}, respectively.

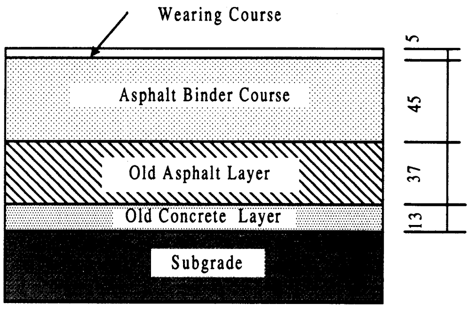


Fig. 8 Pavement structure of the example

c) Verification

Right after the earthquake, coring tests were conducted. By using the coring test results, validity of the evaluation procedure proposed in this paper was verified. One verification example was demonstrated here.

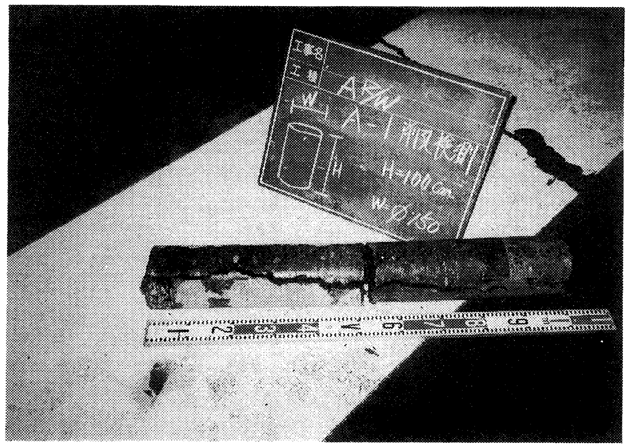


Fig. 9 Coring test result of the example

The pavement structure and coring test result of the example are shown in **Fig. 8** and **Fig. 9**. The FWD deflections are listed in **Table 3**.

By using Eq. (1), as its deflection D_{250} at cracked section is significantly larger than that of uncracked section, the crack is evaluated to be located in subgrade. Coring test confirms the evaluation result.

3. M&R EFFECTIVENESS

Three kinds of M&R were implemented in Osaka International Airport for repairing the earthquake induced cracks: namely, sealing, patching and overlay.

1) Sealing. Right after the earthquake, as an urgent repair, asphalt slurry sealing material was injected into cracks so as to prevent the pavements from further deterioration by water penetrating and traffic loads.

2) Patching. After the urgent repair, patching was implemented 2m wide at each side of the wider cracks. Such section was first cut in 10cm depth and then, paved by 5cm of coarse graded asphalt concrete lower layer and 5cm of dense graded asphalt concrete upper layer.

3) Overlay. Full length of the cracked section was overlaid by 4cm of coarse graded asphalt concrete lower layer and 5cm of dense graded asphalt concrete upper layer.

By comparing pavement deflections before and after M&R, the effectiveness of M&R was identified.

(1) Sealing

The ratios of deflections at the distance X from the load center in cracked sections with that of uncracked sections RD_X, before and after the sealing, were employed to measure the effectiveness of sealing.

From **Table 4**, it was revealed that for pavements

Table 4 Effectiveness of sealing

Seriousness	Before Sealing			After Sealing		
of Cracks	RD_0	RD_{45}	RD_{250}	RD_0	RD_{45}	RD_{250}
Subgrade	2.20	1.86	1.38	1.24	1.10	1.20
Base	1.60	1.50	0.95	1.31	1.18	0.85
Surface	1.15	1.15	0.81	1.16	1.03	0.94

Table 5 Effectiveness of patching

Seriousness	Before Patching			After Patching		
of Cracks	RD_0	RD_{45}	RD_{250}	RD_0	RD_{45}	RD_{250}
Subgrade	2.36	1.85	1.63	1.18	1.09	1.02
Base	1.94	2.37	0.76	1.20	1.15	1.06
Surface		N/A			N/A	

Note:
(1) N/A-- No sections existed for this kind of M&R action.
(2) Before patching, as an urgent repair, sealing was conducted.

Table 6 Effectiveness of overlay

Seriousness	Before Overlay			After Overlay		
of Cracks	RD_0	RD_{45}	RD_{250}	RD_0	RD_{45}	RD_{250}
Subgrade		N/A			N/A	
Base	2.24	2.00	1.18	1.02	0.96	1.02
Surface		N/A			N/A	

Note:
(1) N/A-- No sections existed for this kind of M&R action.
(2) Before overlay, as an urgent repair, sealing was conducted.

with earthquake induced cracks either in subgrade or in base, sealing can obviously decrease RD_0 and RD_{45}, whereas it shows no significant decrease in RD_{250}. However, for cracks in surface, from the viewpoint of structural condition, sealing seems has less effects on deflections.

(2) Patching

The same as above, the ratios RD_X , before and after the patching, were employed to measure the effectiveness of patching.

From **Table 5**, it was revealed that for pavements with severer cracks either in subgrade or in base, patching was effective. However, prior to patching, sealing seems to be necessary.

(3) Overlay

The ratios RD_X, before and after the overlay, were also employed to measure the effectiveness of overlay.

From **Table 6**, it was revealed that the structural condition of pavement sections with earthquake induced cracks in base, if properly sealed and then overlaid, can be as good as that of uncracked sections.

4. CONCLUSION

Two conclusions were obtained from this study:
1) The seriousness of earthquake induced cracks in airport asphalt pavements could be evaluated through the comparison of FWD deflections D_{45} as well as D_{250} at cracked sections with that of uncracked sections. The proposed evaluation procedure can be adopted to airport pavement asphalt structures under various FWD measurement conditions.
2) From the viewpoint of structural condition, sealing, patching and overlay are effective to repair earthquake induced cracks, but their application scopes are different. Sealing is effective for repairing lighter cracks in subgrade and base, patching is suitable for repairing severer cracks than sealing does, whereas overlay can totally rehabilitate the cracks. However, prior to patching and overlay, it is necessary to seal the cracks.

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地震によりひび割れが生じた空港アスファルト舗装の構造評価

段　建軍・八谷好高・中村　健

本論文では，(1)地震により生じたひび割れのひどさの評価，(2)ひび割れ部の維持補修方法の有効性の評価の2点について論じている．まず，前者については，舗装を3層弾性モデルとして理論解析した結果，ひび割れ部と非ひび割れ部で測定したFWDたわみ（D_{45}とD_{250}）に注目することにより実行可能であることがわかったので，統計的手法を採用したうえで，D_{45}とD_{250}に基づく方法を提案している．この方法の有効性は現地から採取されたコアによっても確認された．後者については，数種類の維持補修工法の実施前後で測定されたFWDたわみを比較することにより，シーリング，パッチング，オーバーレイといった補修方法の有効性について明らかにしている．