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Effect of Distresses on Deflection Basins and Backcalculation Modulus of Asphalt Pavement with Cement-Treated Base

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Abstract: The Falling Weight Deflectometer (FWD) is widely used to evaluate the asphalt pavement structural conditions through the deflection basin and the backcalculation modulus. The FWD test has sometimes been performed on asphalt pavement with distresses. It is necessary to investigate the effect of the distresses on the deflection basin and the backcalculation modulus. In this study, the finite element method (FEM) was used to simulate the asphalt pavement with and without the distresses and the FWD load, and thus produce the defection data. The modulus of the structural layers and subgrade was backcalculated from the FWD data using the MODULUS 6.0 program. Then the effect of the distresses was investigated on the deflection basin and the backcalculation modulus. The results indicate that the cracking and cement-treated base crushing in the asphalt pavement may result in an abnormal deflection basin and make the backcalculated modulus incorrect; therefore, it may be necessary to remove the unusual deflection basin before the backcalculation to obtain accepted backcalculation results, or decrease the number of structural layers to reduce the unreasonable backcalculation results.

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Key words: *Backcalculation moduli; Deflection basin; Distresses; Dynamic FEM; FWD.*

Introduction

The Falling Weight Deflectometer (FWD) is widely used to evaluate the structural capacity of pavements in service for rehabilitation designs [1-3]. The backcalculation programs (i.e., Modulus, WESDEF, and ILL-BACK) and deflection basin parameter (DBP) method are typically used to gain the modulus of pavement layers [4, 5]. Most backcalculation analyses assume pavements to be continuous, homogeneous and intact. However, the FWD test has sometimes been performed on asphalt pavement with distresses such as cracking. It is necessary to investigate the effect of the distresses on the deflection basin and the backcalculation modulus.

Many efforts have been conducted on the influence of the distresses on the FWD deflection basins. The shape of deflection basin may exhibit unusually as the severe discontinuous distresses (i.e., cracking and stripping in the asphalt layer) exist in the asphalt pavement with granular base layer [1-3, 6]. Qiu reported that the deflection basin displayed a tremendous difference between intact and cracked pavements with the cement-treated base layer [7].

Most of the asphalt pavements in China employed the cement-treated base layer to effectively reduce the vertical compressive strain on the subgrade. The cracking and cement-treated base crushing were common on this asphalt pavement because of the shrinkage properties and load sensitivity of the cement-treated material as well as the overloading. It is still unclear whether the distresses may significantly affect the backcaluculation results and result in an incorrect evaluation on the pavement conditions when FWD was utilized.

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Based on the above considerations, the objective of the study is to explore the effect of the typical distresses in the asphalt pavement with the cement-treated base on the FWD deflections and backcalculation modulus.

Distressed Pavement Model and Model Parameters

In the study, two common distresses in cement-treated base asphalt pavement, transverse crack and base crushing, were selected. For transverse crack, the top-down crack (TDC) and the reflection crack (RC) were analyzed. The top-down crack was assumed to only go through the asphalt layer while cement-treated base was intact; the reflection crack was supposed to go through both the asphalt concrete and cement-treated base layers. During the analysis, the transverse crack was placed between two sensors. The top-down crack was assigned to distances of 250 or 450 mm from the loading center and labeled as TDC250 and TDC450, respectively (Fig. 1). The reflection crack was located at distance of 250, 750, 1050, 1350, 1650, and 1950 mm from the loading center, labeled as RC250, RC750, RC1050, RC1350, RC1650 and RC1950, respectively (Fig. 1). The crack width was assumed as 10 mm which represented the high severity level and crack surfaces remain separate throughout the finite element analysis.

Cement-treated base crushing was assumed to break to small block and equivalent to granular base. A low modulus value of 500 MPa was assigned to the crushed region base on the references [9, 10]. The severities of the crushing conditions were represented by the radius of crushing area: the larger the broken area of the cement-treated base was, the severer the crushing. Five damage levels of base crushing were considered with the radius of 250, 450, 750, 1050, and 1350 mm (named as Crush250 Crush450, Crush750, Crush1050 and Crush1350, respectively) (Fig. 1).

Finite element method (FEM) was used to simulate the asphalt pavements with and without the distresses. The 2-D axi-symmetric and 3-D FEM models were developed using ANSYS. 2-D

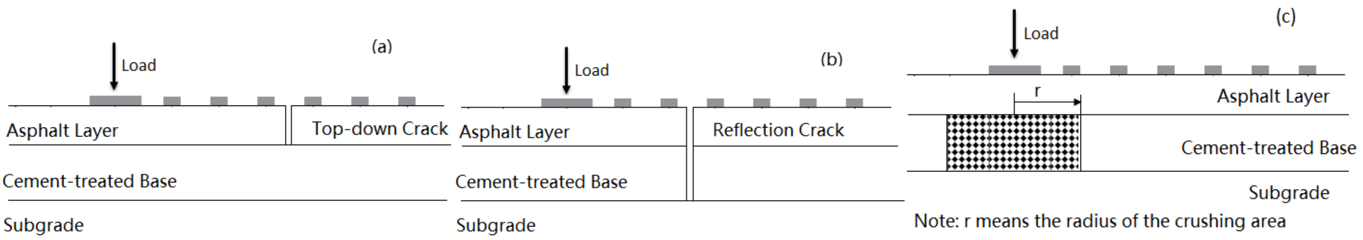


Fig. 1. Distresses Type Considered in This Study: (a) Top-down Crack; (b) Reflection Crack; (c) Base Crushing.

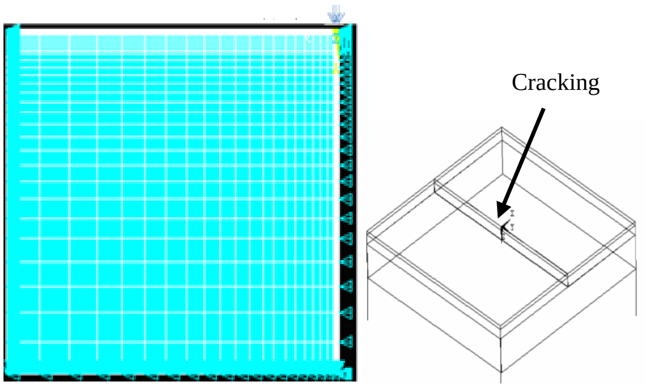


Fig. 2. 2-D axis-symmetric and 3-D FEM Model.

axi-symmetric FEM model was used to save the calculation time. The 2-D FEM model was employed for the pavement with intact and base crushed conditions (Fig. 2). The 3-D FEM model was used to model pavement with transverse cracks because the transverse cracks were linear not circle. The lengths of the 2-D axi-symmetric FEM model were set to 8 m. The 3-D FEM model was considered as a cube with 8-m length. The nodal points at the bottom boundary were fixed whereas those on the vertical boundary were constrained from moving in the horizontal direction. The FEM mesh was designed finer at the loading area. At locations father from the load, the mesh became coarser to reduce the computation burden. To verify the 2-D axi-symmetric and 3-D FEM models used, the data from AASHTO Sherrard test section was used to produce the deflection basin, and then the calculated deflection basin was compared to the measured deflection basin as shown in Fig. 3. To compare the difference between dynamic model and static model, the static analysis software- BISAR was also used to calculate the

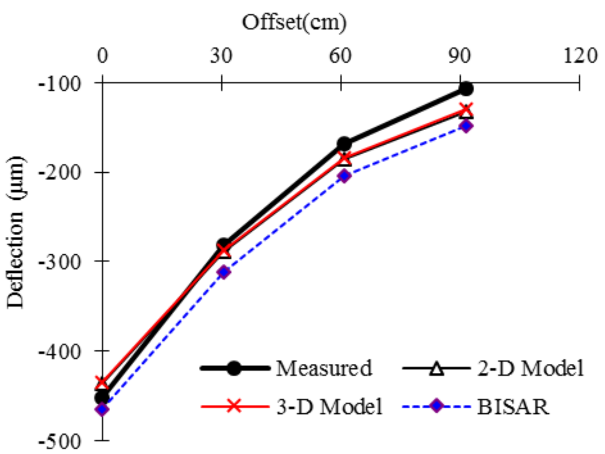


Fig. 3. FEM Model Verification.

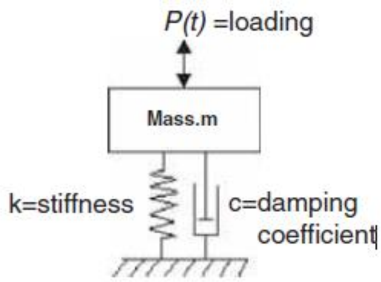


Fig. 4. Dynamic Model [11].

Table. 1. Parameters for Semi-Rigid Base Asphalt Pavement.

	Asphalt Layer	Base Layer	Subgrade
Modulus (MPa)	2000	4000	200
Thickness (mm)	120	400	7480
Density (kg/m^3)	2400	2200	1800
Poisson's Ratio*	0.35	0.20	0.40
Damping (%)*	5	5	5

Note: Poisson's Ratio and Damping are selected based on the references [3, 8].

deflection basin of AASHTO Sherrard test section [3]. Fig. 3 shows that the defections from dynamic models were closer to the measured data than ones from the static model because the dynamic model considered the inertia and damping (Fig. 4). Additionally, it was observed that the deflections from the 2-D and 3-D models were similar.

In this study, the asphalt pavement was considered as a three-layer system, and the pavement layer properties are given in Table 1. The linear elastic material model was utilized for all layer material in this study. A half-sine load with 50KN peak load and duration of 0.03 s that simulates a typical FWD load was used for dynamic analysis. The deflection sensors were placed at distances of 0, 305, 610, 914, 1219, 1524, and 1829 mm from the loading center. Peak deflections obtained from transient data were used in this study.

Influence of Pavement Distresses on FWD Deflection Basin

Fig. 5 shows the effect of the top-down crack on FWD deflection basin. Fig. 5 shows that the top-down crack had slight effect on FWD defection since the top-down crack was close to the loading plate, and the effect of top-down crack on deflections was negligible as top-down crack was farther than 450 mm away from the load.

Fig. 6 shows the effect of the reflection crack on FWD deflection basin. As shown in Fig. 6, the load center deflection increased

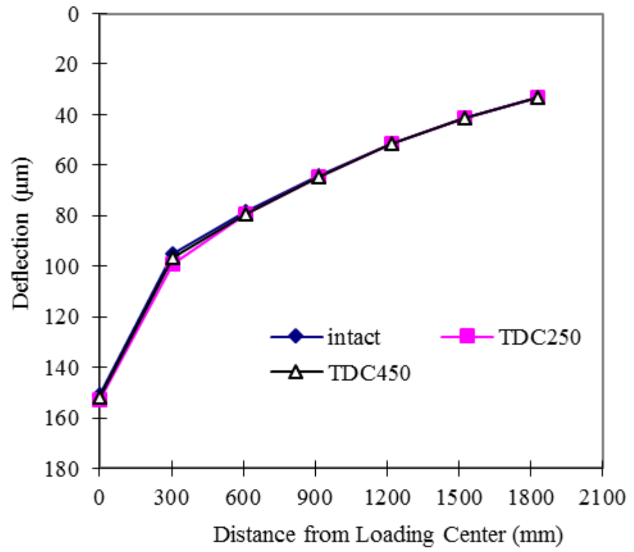


Fig. 5. Effect of Top-down Crack on Deflection Basins.

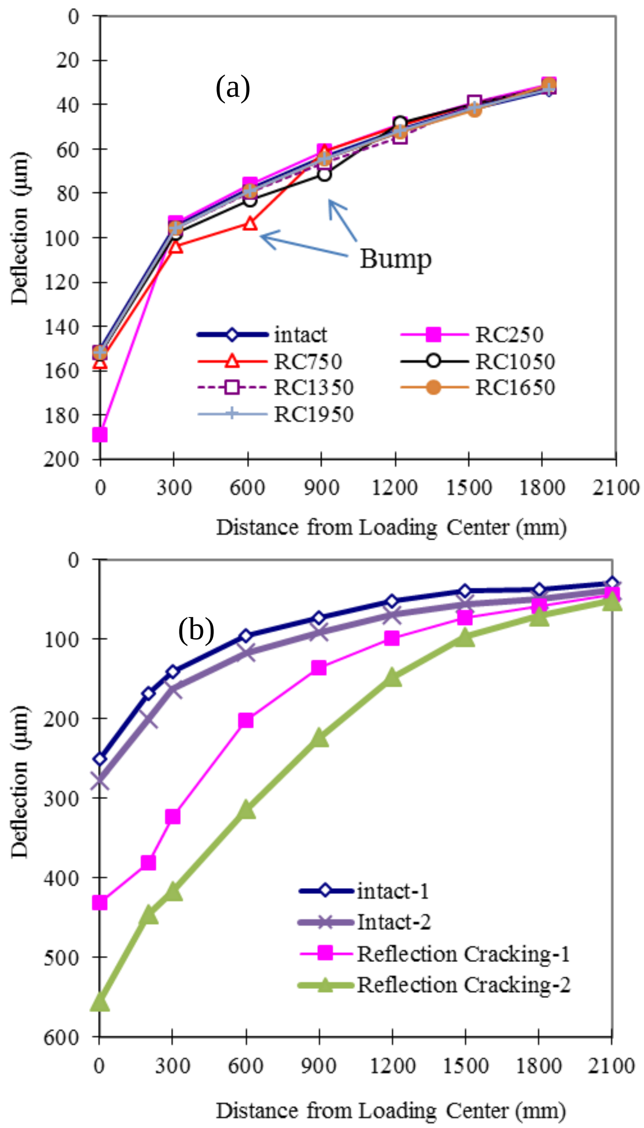


Fig. 6. Effect of Reflection Crack on Deflection Basins: (a) Calculation Data, (b) Measured Data.

significantly as the reflection crack was near the loading plate (i.e., RC250). The FWD deflection basin showed an unusual shape and a significant "bump" in deflection basin occurred when the reflection crack was 750 mm or 1,050 mm away from the load center (i.e., RC750 and RC1050). When the distance of the reflection crack from the loading center was farther than 1,050 mm, the effect of the reflection crack on the deflection basin significantly reduced. The effect of the refection cracking on the deflection basin was verified by the measured FWD deflection date (Fig. 6(b)).

It is well known that the pavement surface deflection is a result of deformation of the various materials in the applied stress zone (Fig. 7). When the reflection crack existed, the reflection crack may have prevented the distribution of stress in the pavement structure and make the stress zone decrease (Fig. 7), resulting in the increase of the load center deflection and the abnormal shape of deflection basin. Furthermore, the effect of the reflection crack on the deflection basin significantly decreased when the reflection crack occurred beyond the stress zone (i.e. RC1050 in Fig. 7).

Fig. 8 shows the deflection basins for the pavement with base crushing. It can be seen that the deflections near the loading plate increased significantly and the slope of the deflection basins became steeper. When the distance from the load was larger than 900 mm, the effect of base layer crushing on the deflections became less. Furthermore, it can be shown the rate of increase of the deflections near the loading plate decreased as the radius of base crushed zone increased.

It is known that the deflections near the loading are the direct result of the deformation of asphalt layer, base layer, and subgrade. The decrease of base modulus due to base crushing may significantly result in the increase of the deflections near the load. In addition, the effect of base crushing on the outermost deflection was very little since the outermost deflection mainly comes from the deformation of the subgrade soil.

Influence of Pavement Distresses on Backcalculation Moduli

The MODULUS 6.0 program was used to backcalculate the

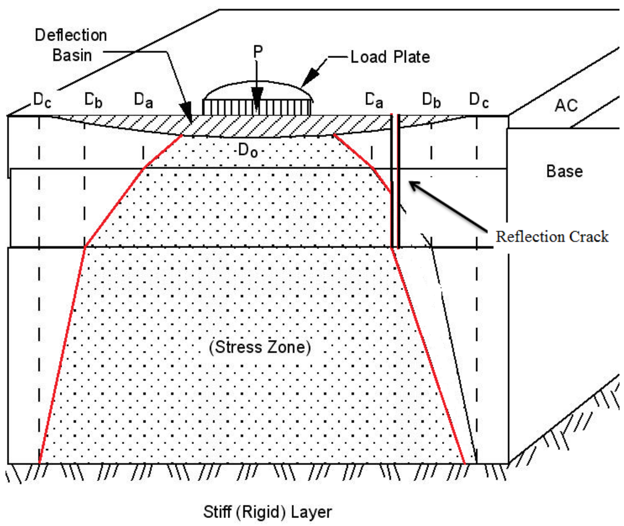


Fig. 7. Effect of Reflection Crack on Stress Zone [12].

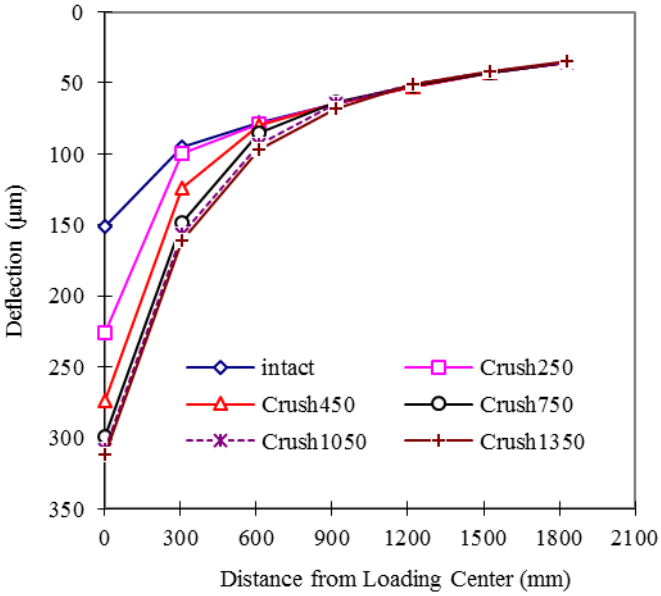


Fig. 8. Effect of Base Layer Crushing on Deflection Basin.

modulus for each pavement layer and investigate the effect of the distresses on backcalculation results. The depth to bedrock was fixed to be infinity when backcalculating layer moduli. The MODULUS 6.0 program, based on static linear theory, uses deflection databases generated from the forward program BISAR and then a Hook-Jeeves pattern search algorithm within a three-point Lagrange interpolation technique to backcalculate a set of layer moduli.

To eliminate the effect of the static backcalculation from the program, the backcalculated layer moduli of intact pavement were selected for reference values. The deviations between the reference and backcalculation modulus of distressed pavement were caluculated according the following equation.

$$\text{Deviation} = \frac{E_{distress} - E_{intact}}{E_{intact}} \times 100\% \qquad (1)$$

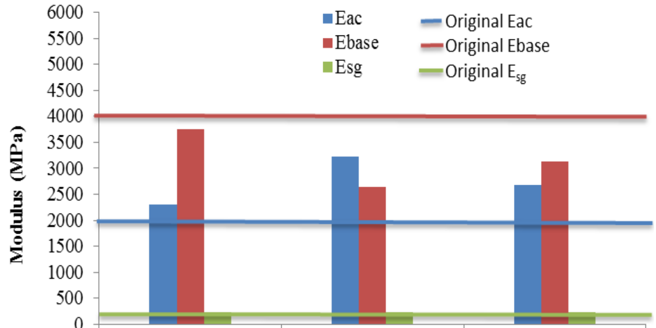
where

$E_{distress}$ = the backcalculated moduli of pavement layer with distressed conditions.

E_{intact} = the backcalculated moduli of pavement layer with intact condition.

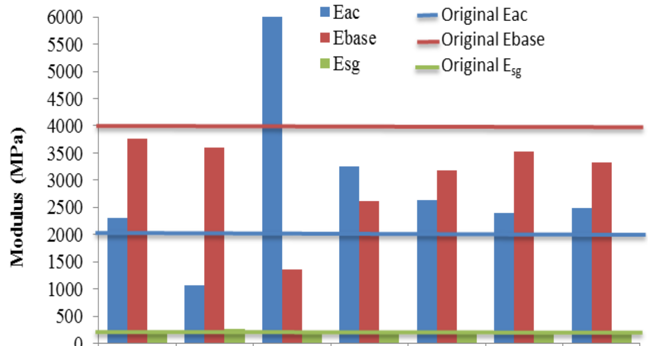
Figs. 9 and 10 show the backcalculated modulus and modulus deviations of each layer for intact and cracked conditions. For the intact pavement, the backcalculation values of asphalt layer modulus (E_{ac}) and subgrade (E_{sg}) were 15.2% and 15.5% more than original values, while the backcalculation value of cement-treated base modulus (E_{base}) was 6.1% less than original values (see Table 1). This may be attributed to the static analysis and the convergence error in MODULUS 6.0 program.

In general, the backcalculated E_{ac} in cracked conditions is higher than those with intact condition except for RC250 (Fig. 9). These results do not agree with the fact that cracking can decrease the layer modulus [13, 14]. In addition, it is interesting that the backcalculated E_{ac} is so much higher than original values when the reflection crack is 750 mm from the load center.



	Intact	TDC250	TDC450
Eac	2304	3224	2678
Ebase	3756	2649	3124
Esg	231	233	233

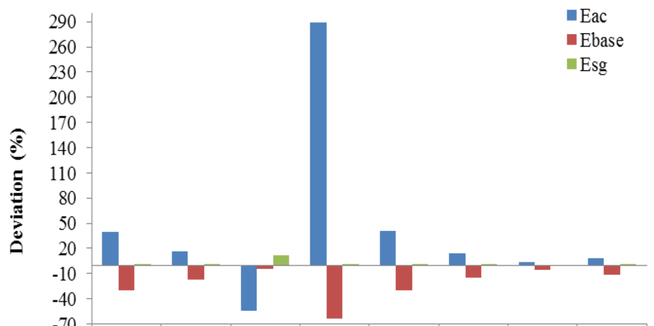
(a)



	Intact	RC250	RC750	RC1050	RC1350	RC1650	RC1950
Eac	2304	1061	8955	3254	2627	2397	2494
Ebase	3756	3596	1354	2608	3177	3526	3320
Esg	231	258	232	232	233	231	235

(b)

Fig. 9. Backcalculation Moduli for Pavement with Intact and Cracked Conditions.



	TDC250	TDC450	RC250	RC750	RC1050	RC1350	RC1650	RC1950
Eac	39.9	16.2	-53.9	288.7	41.2	14	4	8.2
Ebase	-29.5	-16.8	-4.3	-64	-30.6	-15.4	-6.1	-11.6
Esg	0.9	0.9	11.7	0.4	0.4	0.9	0	1.7

Fig. 10. Moduli Deviation between Intact and Cracked Pavements.

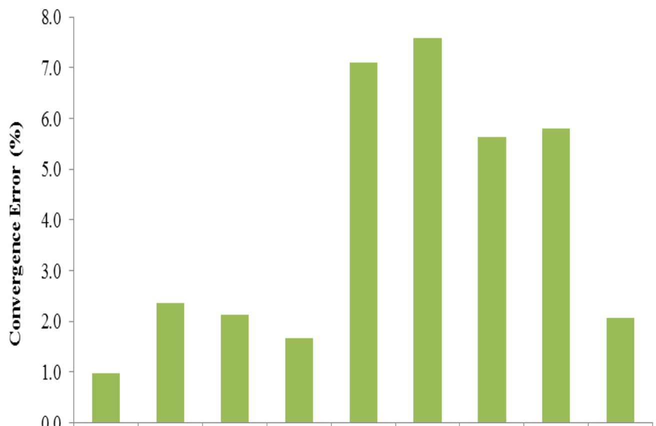
The above analysis shows a significant "bump" in deflection basin exists in RC750 and RC1050 conditions. The abnormal shape of FWD deflection basin may result in higher convergence error for MODULUS 6.0 program. In order to analyze the effect of distresses on the convergence error for MODULUS 6.0 program, the Root Mean Square (RMS) of deflection basin, generally referred to as the convergence error, is calculated (Fig. 11). It can be seen that the deflection basin with the reflection crack have higher convergence error than that with top-down crack. In addition, the deflection basins with RC750 and RC1050 have higher convergence error when compared to other deflection basins (Fig. 11(a)).

Figs. 12 and 13 show the backcalculated modulus and modulus deviations of the pavement with crushing base. Generally, most backcalculated E_{ac} with crushing base is lower than that with intact condition when cement-treated base layer is crushed. The results do not agree with the fact that AC layer is intact in the study. Furthermore, backcalculated E_{ac} is significantly lower than original value, as the radial of base crushing zone is smaller (i.e., 250 mm and 450 mm), while backcalculated E_{ac} is close to the original value, as the radius of base crushing zone is larger (i.e., 1050 mm and 1350 mm). In other words, the effect of crushing base on backcalculated E_{ac} decreases, as the radius of base crushing zone increases.

A fundamental assumption for static linear theory is that the material of each layer is homogeneous and isotropic. However, the base material becomes nonhomogeneous when part of the area of base layer is broken to small blocks while other area is intact, as assumed in this study. In this case, the deflection basin may appear irregular and different than that of the homogeneous pavement, which may produce higher convergence error and incorrect backcalculated modulus when using the MODULUS 6.0 program (Fig. 11(b)).

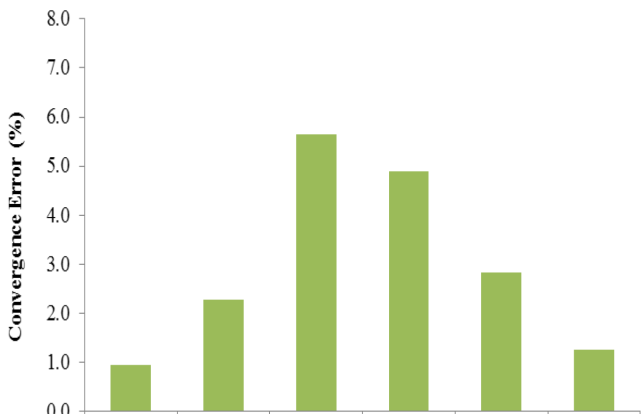
With the increase of the radius of base crushing zone, the base material under the stress zone of FWD loading becomes more uniform, agreeing with the assumption of static linear theory. In this case, the convergence error of backcalculation modulus may decrease so that the backcalculated E_{ac} is close to the original value and the backcalculated E_{base} is close to the assigned value (500 MPa) (Fig. 11(b)).

Additionally, for subgrade modulus, the difference between the intact and distressed pavements is less than 10%, regardless of cracks or base crushing. This may be because subgrade modulus may be backcalculated based on the outermost deflections, which are less affected by the conditions of upper layers.



	Intact	TDC250	TDC450	RC250	RC750	RC1050	RC1350	RC1650	RC1950
RMS	1.0	2.4	2.1	1.7	7.1	7.6	5.6	5.8	2.1

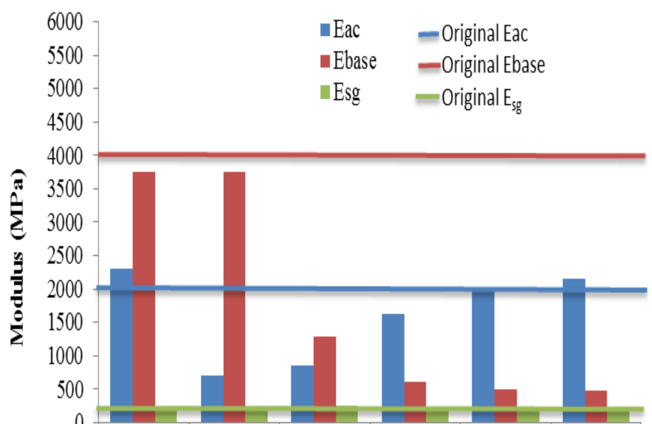
(a)



	Intact	Crush250	Crush450	Crush750	Crush1050	Crush1350
RMS	0.9	2.3	5.6	4.9	2.8	1.2

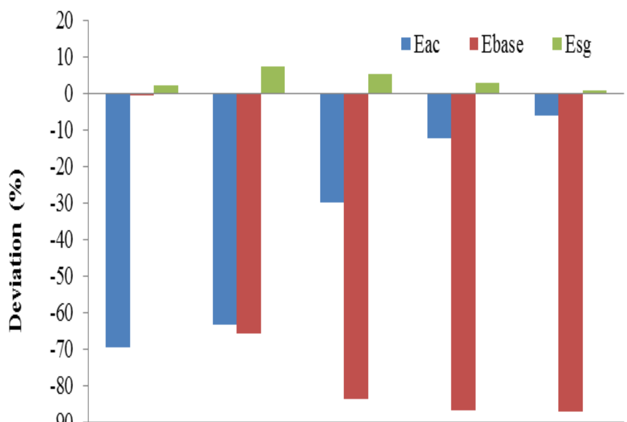
(b)

Fig. 11. Convergence Error of Deflection Basin: (a) Crack; (b) Base Crushing.



	Intact	Crush250	Crush450	Crush750	Crush1050	Crush1350
Eac	2304	702	847	1618	2019	2161
Ebase	3756	3754	1292	607	505	479
Esg	231	236	248	243	238	233

Fig. 12. Backcalculation Moduli for Pavement with Crushed Base.



	Crush250	Crush450	Crush750	Crush1050	Crush1350
Eac	-69.5	-63.2	-29.8	-12.4	-6.2
Ebase	-0.1	-65.6	-83.8	-86.6	-87.2
Esg	2.2	7.4	5.2	3	0.9

Fig. 13. Moduli Deviation for Pavement with Crushed Base

Overall, the severe distresses made the pavement significantly different from the ideal elastic multi-layer system used by backcalculation programs such as MODULUS 6.0, which significantly increased the convergence error and led to false backcalculated modulus. Therefore, it may be necessary to remove the deflection basin before backcalculation in order to obtain acceptable backcalculation results. Another possible solution to avoid the incorrect backcalculation modulus may be to reduce the number of structural layers. For example, the ASSHTO two-layer backcalculation method may be used on the asphalt pavement with the distresses to decease the unreasonable backcalculation results.

Conclusions

The effect of structural distresses on deflection basins and backcalculation results was investigated. The following conclusions can be stated:

1. The cracking in the asphalt pavement may result in a significant "bump" in FWD deflection basin and make the shape of deflection basin unusual. Base crushing may increase the deflection values near the loading plate significantly and produce the steeper deflection basins. The increase rate of the deflections near the loading plate decreases as the radius of base crushed zone increases.
2. A significant "bump" in deflection basin and the nonhomogeneity of pavement material (such as base crushing) may increase significantly the convergence error of the backcalculation program and produce incorrect backcalculated modulus.
3. Since the distresses may result in the incorrect evaluation of the pavement conditions, it may be necessary to screen the unusual deflection basin before the backcalculation to obtain accepted backcalculation results, or reduce the number of structural layers to decrease the unreasonable backcalculation results.

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