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**USE OF FALLING WEIGHT DEFLECTOMETER TESTING TO
DETERMINE RELATIVE DAMAGE IN ASHALT PAVEMENT
UNBOUND AGGREGATE LAYERS**

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Use of Falling Weight Deflectometer Testing to Determine Relative Damage in Asphalt Pavement Unbound Aggregate Layers

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ABSTRACT

Falling weight deflectometer (FWD) testing is a nondestructive pavement structural evaluation technique routinely performed on highway and airfield pavements to estimate pavement layer properties from measured deflection basins. This paper presents a methodology based on analyzing FWD test data between the trafficked and non-trafficked lanes to determine degradation and rutting potential of asphalt pavement unbound aggregate layers in comparison to the subgrade damage. The validity of the approach is demonstrated by analyzing the heavy weight deflectometer (HWD) data obtained from the Federal Aviation Administration's National Airport Pavement Test Facility (NAPTF) flexible airport pavement test sections built with substantially thick unbound aggregate base/subbase courses. The modified Base Damage Index and Base Curvature Index defined from HWD pavement deflection basins were used to determine relative base to subgrade damage, which clearly showed evidence of the increased base damage induced in the NAPTF airport pavement layers during trafficking partly due to the applied gear load wander. This was in accordance with both the individual pavement layer recovered and unrecovered (inelastic or residual) deformation trends identified from analyzing the multi-depth deflectometer data collected during trafficking and the post traffic forensic analysis results, which indicated that a majority of the permanent deformation occurred in the unbound aggregate layers and not in the subgrade. The methodology presented for the detailed analyses of the FWD (or HWD) test data between trafficked and non-trafficked lanes can be effectively used in asphalt pavements to detect unbound aggregate layer deterioration and its pavement damage potential.

Key Words: Falling or heavy weight deflectometer testing, deflection basin, unbound aggregate base/subbase, flexible pavements, rutting damage, load wander

INTRODUCTION

Evaluating structural condition of existing, in-service pavements constitutes a major part of the maintenance and rehabilitation activities of state highway agencies and airport authorities. Falling weight deflectometer (FWD) tests, routinely conducted in the field to measure pavement deflection basins, provide a sound nondestructive approach to estimate pavement layer properties and evaluate structural condition. Any detailed information gathered from field FWD test data on how individual pavement layers react to traffic and how that behavior affects the pavement system can help identify important damage mechanisms that cause pavement deterioration. A better understanding of the individual pavement layer response and performance will result in economic pavement construction decisions, more efficient and reliable pavement designs, and longer lasting pavement repairs.

For unbound aggregate layers in highway and airport flexible pavements, rutting is the only failure mechanism of relevance as no bound layers are involved for a fatigue failure to occur. With the recent Federal Aviation Administration (FAA) and AASHTO moves towards a mechanistic-empirical pavement design procedure, the validation and field calibration of proper unbound aggregate rutting damage models has gained attention. Using the data from the FAA's National Airport Pavement Test Facility (NAPTF) flexible pavement test sections, Kim and Tutumluer (1) successfully developed unbound aggregate base/subbase permanent deformation models that consider layer stress states and the effects of dynamic loading by a moving wheel in addition to the number of load applications. Their findings indicate that to accurately predict both recoverable and unrecoverable (residual) deformations per pass of the aircraft gear the effects of gear wander locations and wander patterns are critical, and have to be considered in the modeling of rut development.

Pavement unbound aggregate layers are said to shakedown under channelized traffic applications which means they consolidate and gain strength with time. This process is seen in the field as well as with repeated load triaxial testing in the laboratory. The recent successful research efforts on the aggregate shakedown concept by Werkmeister et al. (2) identified three zones of shakedown as: A – plastic shakedown, B – plastic creep, and C – incremental collapse. It is likely that for all shakedown ranges, any particle rearrangement that occurs due to load wander, such as in the case of NAPTF pavement test sections, will no doubt relieve some of the residual compressive stresses locked in the granular layer due to shakedown; which in turn will cause additional rutting. Such a mechanism was recently observed by Hayhoe and Garg (3) in the NAPTF pavement test sections. Their post traffic forensic analyses indicated that a majority of the permanent deformation occurred in the unbound aggregate layers and not in the subgrade.

As part of the ongoing research efforts at the FAA's Center of Excellence for Airport Technology (CEAT) at the University of Illinois, individual pavement layer dynamic response data from the NAPTF pavement test sections were analyzed due to passing of aircraft gear for various combinations of applied load magnitudes and loading sequences (application order and stress history effects), traffic directions, gear spacings, wander positions, and wander sequences. Nondestructive heavy weight deflectometer (HWD) tests, similar to FWD tests with higher dropped weights, were also used to collect pavement deflections and evaluate pavement profiles due to trafficking. There was significant movement of the unbound aggregate particles in the base and subbase layers during trafficking due to transverse load wander. The permanent deformation during a complete wander cycle was negated due to aircraft wander, indicating recurring particle movements and rearrangements in the unbound pavement layers (4,5). As a

result, the NAPTF pavement test section unbound aggregate base/subbase layers accumulated considerable amounts of damage during trafficking.

The objective of this paper is to present a methodology for the detailed analysis of FWD (or HWD) test data in an effort to determine the relative location of the pavement damage; whether it is in the unbound aggregate layers or in the subgrade. FWD/HWD pavement deflection basin measurements taken from both trafficked and non-trafficked pavement surfaces are essential for individual pavement layer damage evaluation. The research scope has been to correlate the damage observed in the unbound aggregate layers of the NAPTF test sections to HWD deflection basin parameters. The findings will demonstrate how the commonly performed nondestructive FWD/HWD testing can be used with conventional flexible pavements to detect individual layer deterioration and its pavement damage potential.

NAPTF TESTING

The FAA's NAPTF, located at the William J. Hughes Technical Center close to the Atlantic City International Airport was built to analyze the effects of New Generation Aircraft (NGA) on pavements. The NAPTF is an indoor facility designed to limit environmental effects, but it is not climate controlled. Tests are conducted using a specially designed 1.2-million-pound (5.34 MN) test vehicle, which can apply loads of up to 75,000 lbs (34,020 kg) per wheel on two landing gears with up to six wheels per gear; a total capacity of 12 wheels and an applied load capacity of 900,000 lbs (408,230 kg). The test vehicle is supported by rails on either side, which allow the load to be varied according to the testing protocols. The vehicle can be configured to handle single, dual, dual-tandem, and dual-tridem loading configurations with variable gear and wheel spacing. The maximum tire diameter is 56 in. (142 cm) and maximum tire width is 24 in. (61 cm). Vehicle control can be automatic or manual. Traffic tests were run in a fully automatic control mode at a travel speed of 5 mph (8 km/h). Wheel loads are programmable along the travel lanes and the transverse positions of the landing gears are variable up to ± 60 in. (1524 mm) from the nominal travel lanes to simulate aircraft wander.

The first round of NAPTF pavement test sections were built with the objective to compare the damage done by the 6-wheel Boeing 777 (B777) type dual-tridem landing gear to those of dual and dual-tandem type gears of older aircraft (6). The first full-scale tests were designed and conducted on a pavement test strip 900 ft. (274 m) long, 60 ft. (18.3 m) wide, and 9 ft. (2.7 m) to 12 ft. (3.7 m) deep. The width of 60 ft. (18.3 m) was necessary to investigate load wander interaction effects, and the depth of up to 12 ft. (3.7 m) was necessary to minimize the influence of the finite depth of imported subgrade materials. The pavement sections were built on three subgrade materials with California Bearing Ratio (CBR) values in the range of 3 to 20 percent. Six asphalt and three concrete surfaced test sections were built on top of the subgrades according to standard FAA airport pavement construction and thickness design specifications.

NAPTF Instrumentation

A comprehensive instrumentation system was installed in the pavements to measure structural response to wheel loading. In all, 1,050 sensors were installed in the test pavements for measuring moisture and temperatures, and wheel/gear load related strains, deflections, and pressures. Rutting was measured manually throughout the test program using a transverse surface profile (TSP) device, a rolling inclinometer, and straightedge rut depth measurements. Pavement degradation was recorded using a Heavy Weight Deflectometer (HWD).

Multi-depth deflectometers (MDDs) were installed in the test sections at various depths to record the important deformation trends in individual layers to wheel/gear loads. The MDD data can be separated into the recoverable response (also called the elastic or rebound deformation) and the unrecoverable response (also called the inelastic, plastic, or residual deformation). The MDDs were placed at the layer interfaces in each test section to record critical pavement response values. With the measured movements of the layer interfaces, individual layer response can be calculated.

Test Series

The first series of tests conducted are referred to as Construction Cycle 1 (CC1) tests and the first NGA aircraft to be analyzed was the B777 with a six-wheel dual-tridem gear configuration in the North test lane. Loads from a Boeing 747 (B747) dual tandem gear configuration were tested at the same time in the South test lane so that comparisons between the pavement responses from each aircraft could be made. The wheel loads were set to 45,000 lbs (200.2 kN) and the tire pressure was 189 psi (1,303 kPa). Trafficking speed was applied at 5 mph (8 km/h). This speed represents aircraft taxiing from the gate to the takeoff position. It is during this maneuver that maximum damage occurs to the pavement because of the low speed and the aircraft is fully loaded with fuel and payload.

Pavement cross section details and important MDD locations are shown in Figure 1. The letter designations indicate the subgrade strength (L – Low, M – Medium), the type of pavement (F – Flexible) and the type of base course (C – Conventional unbound aggregate, S – Stabilized [P401 asphalt]).

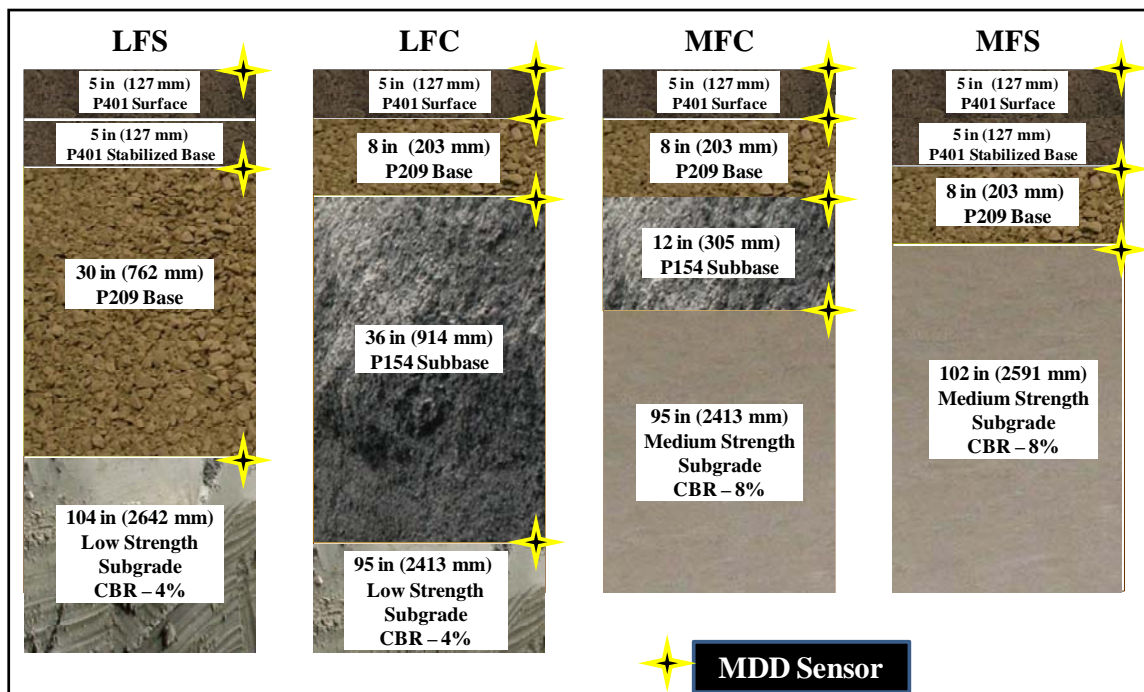


FIGURE 1 Cross section details of the CC1 NAPTF pavement test sections

Induced Aircraft Wander

To account for aircraft gear wander on the pavement test sections, the test passes were divided into nine wander positions spaced at intervals of 9.843 in. (250 mm) for a total center to center

wander width of 78.75 in. (2 m). Each position was traveled a different number of times based on a normal distribution with a standard deviation that is typical of multiple gear passes on airport taxiways, 30.5 in. (775 mm). The nine wander positions covered 87% of all traffic (approximately 1.5 standard deviations). One complete wander cycle consisted of 66 vehicle passes (33 East and 33 West). Figure 2 shows the application patterns of wander position, pass number, and wander sequence.

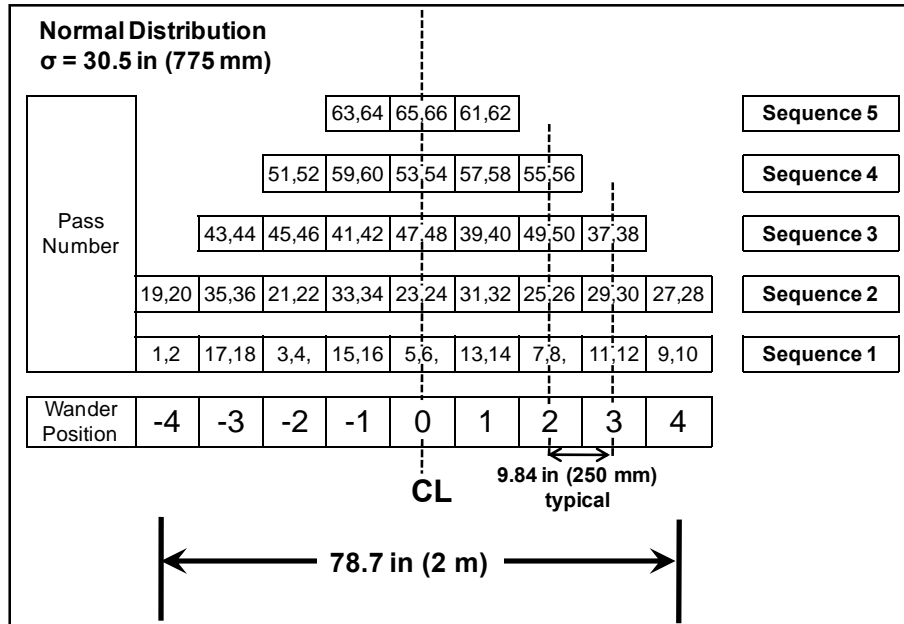


FIGURE 2 Correlation of wander position, pass number, and sequence

Hayhoe et al. (7) found that the relative magnitude of the NAPTF unrecovered displacements depended on the transverse position of the load relative to the transverse position of the measurement. The net accumulated unrecovered deformation in the pavement structure over a complete wander cycle was a small fraction of the unrecovered deformation occurring during a single back and forth load application. More recently, analysis of the NAPTF MDD data by Donovan and Tutumluer (4) also found that the downward unrecovered deformation caused by one pass of heavily loaded landing gear was canceled by the upward unrecovered deformation resulting from the pass of the same gear transversely offset by wander. This interaction indicated a shuffling or rearrangement of the particles in the unbound aggregate base/subbase layers of the pavement system. The particle rearrangement in turn reduced the strength of the unbound layer causing future load applications to cause more residual deformation, what Donovan and Tutumluer (4) referred to as the “anti-shakedown” effect.

MDD Test Data and Post Traffic Testing Results

Post traffic trench studies of the NAPTF CC1 test sections indicated that a majority of the residual deformation was in the unbound aggregate layers (3). Analyses of the MDD data showed how the damage was accumulating in the granular layers and that the majority of the residual response after each pass of the gear was in the P209 and P154 layers in the MFC section (5). Figures 3 and 4 present the percentages of residual responses accumulated during each pass in the various layers in the B747 and B777 lanes of the MFC section, respectively. In each case, the residual response in the unbound aggregate layers continues to dominate throughout the

testing indicating that damage is accumulating in these layers instead of in the subgrade. This finding from the MDD data was quite useful for establishing correlations between the HWD deflection basins and the individual layer damage.

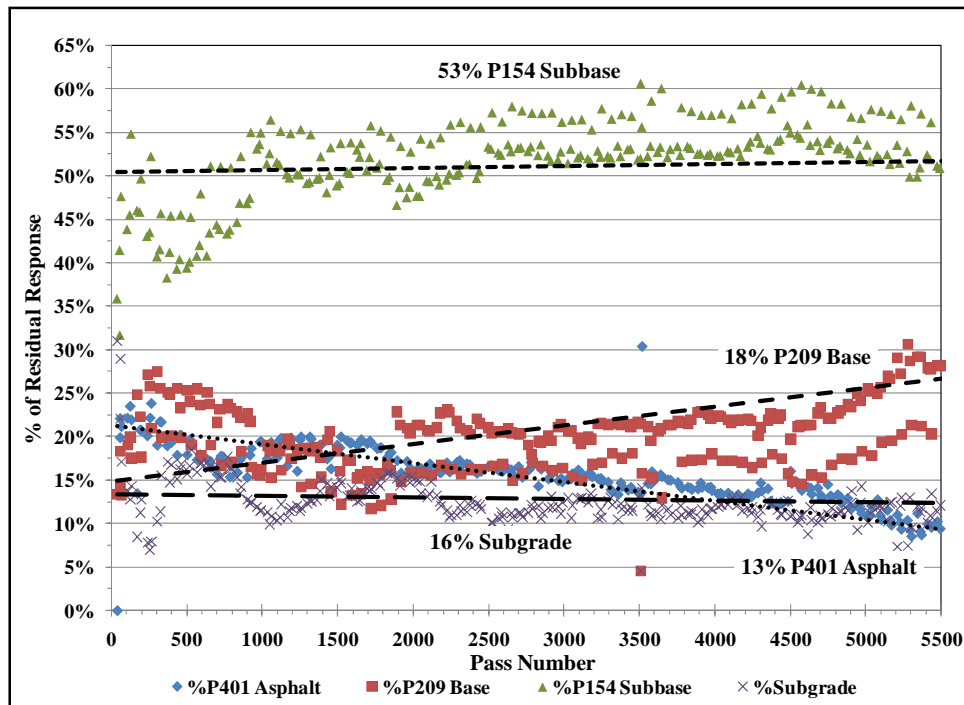


FIGURE 3 Percentage of total residual response in each layer, MFC section B747 lane

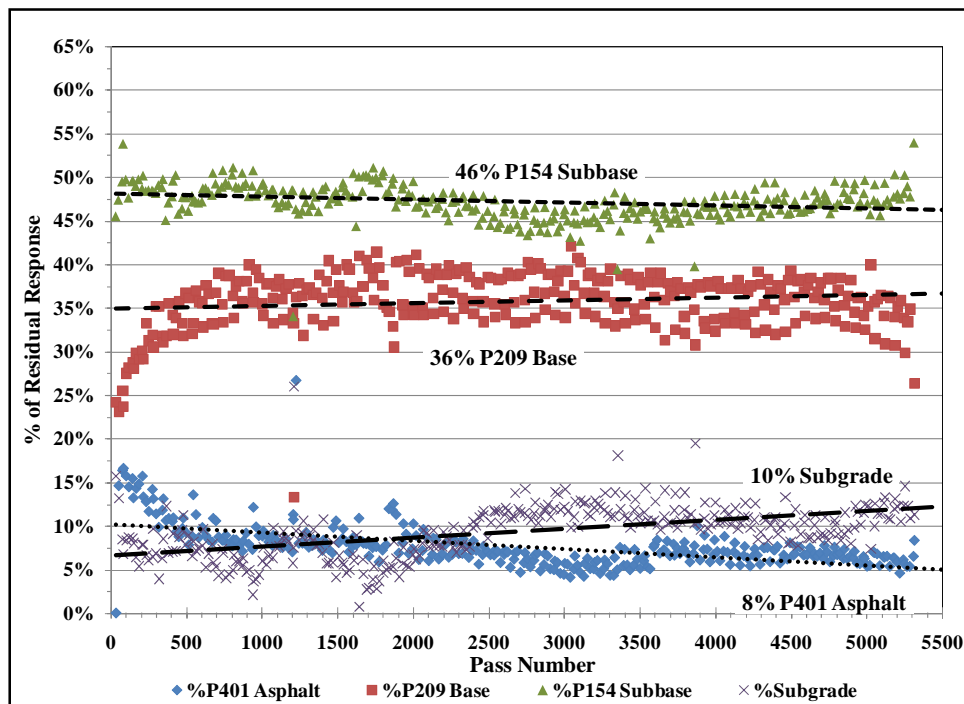


FIGURE 4 Percentage of total residual response in each layer, MFC section B777 lane

FALLING WEIGHT DEFLECTOMETER TESTING

The Falling Weight Deflectometer (FWD) test is commonly used in the field by highway agencies for the nondestructive evaluation of pavement structural condition. Airport agencies use the same device but with heavier loads due to thicker airport pavements. The testing machine used to drop the heavier weights is called a heavy weight deflectometer (HWD). In the FWD/HWD test, a weight is dropped from set heights and the deflection values at specific radial locations from the center of the dropped load are recorded to form a deflection basin, as shown in Figure 5. The designations for the set points used to describe the deflection basin are often D_0 , D_1 , D_2 , D_3 , D_4 , and D_5 . The maximum deflection is recorded directly under the load at position D_0 and the other sensors are placed radially out from the load center generally at 12 in. (305 mm) intervals; that is, D_1 is at 12 in. (305 mm) and D_5 is at 60 in. (1524 mm) from the center of the load. The measured deflections are an indicator of the quality of the pavement system; larger deflections indicate a weaker pavement system or a higher impact load. Figure 5 shows four FWD tests conducted at the same pavement location but with different impact loads. As expected, larger deflections are recorded by the higher loads.

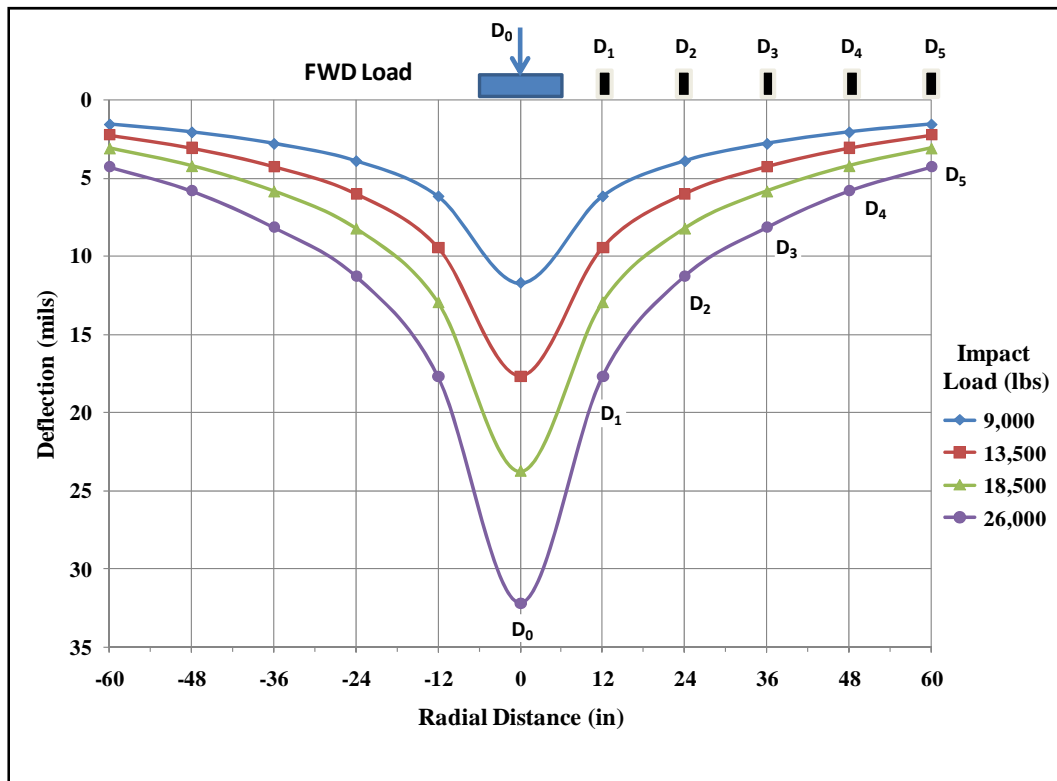


FIGURE 5 Typical FWD deflection basins for different applied load levels

The shape of the deflection basin also provides insight into the qualities of the specific layers of the pavement system because the deflections recorded by the various sensors are influenced by the pavement layer properties. Figure 6 depicts the concept of the zone of stress applied by the impact load. The zone of stress spreads out as the impact load is transmitted through the pavement system layers; therefore, the deflection recorded farther from the load is controlled by the properties of a deeper layer.

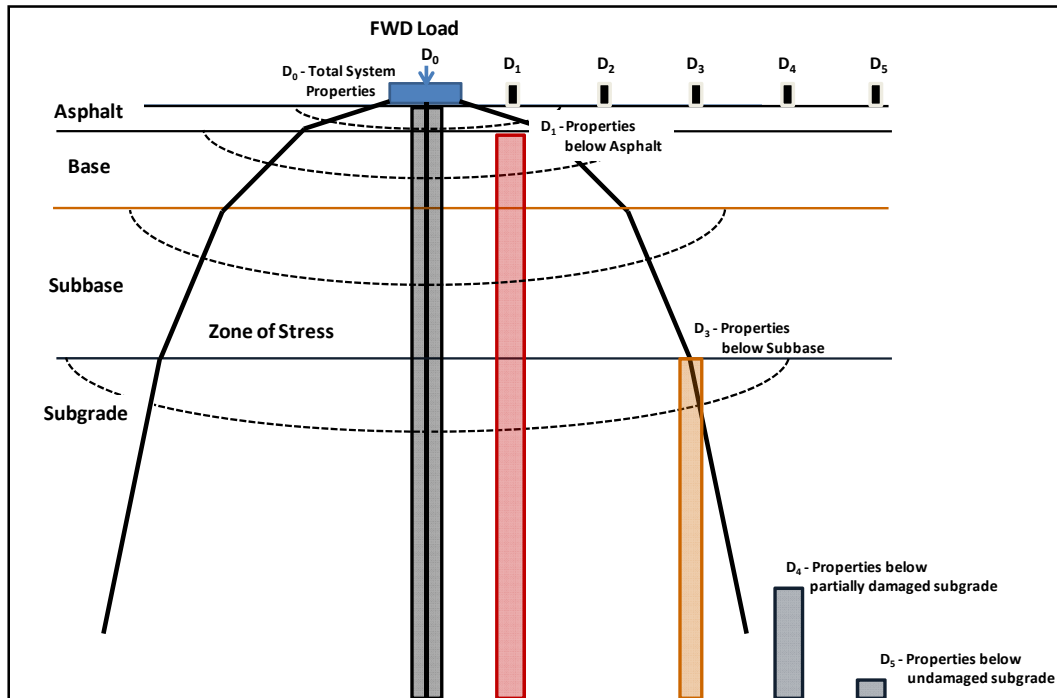


FIGURE 6 Stress zone and principle of correlating deflection values to layer properties

FWD/HWD DEFLECTION BASIN PARAMETERS

FWD/HWD data from nondestructive pavement evaluation in the field and the associated deflection basin parameters can be used to determine the degradation of the layers in a pavement system (8,9,10). The deflection basin parameters are commonly utilized in South Africa to provide guidance on individual layer strengths and help in “pinpointing rehabilitation needs” (10). Horak and Emery (10) report on the use of FWD test data on granular pavements with surfacing layers of thin asphalt (less than 4 in. or 100 mm) or a waterproofing membrane for evaluating pavement degradation. The lighter weight FWD test is ideal for this purpose as the pavement system is relatively weak and the degradation of the unbound aggregate base and subbase can easily be distinguished in this case with lighter impact loads.

Use of HWD Data to Describe Layer Degradation

The deflection basin parameters used to evaluate the pavement condition can be classified into three categories: basin curvature parameters, area parameters, and basin slope parameters. The basin curvature parameters seek to correlate the radius of a circle that is centered at some point above the center of the load with two points on the circumference of the circle defined by two deflection points. The principle is that as the radius of curvature goes down, the deflection basin is becoming deeper and thus the pavement is weakening. Area parameters calculate an “area” of the deflection basin and use this area to indicate the strength of the pavement system

The basin slope parameters calculate the relative changes to the slope of the deflection basin between deflection points. A steeper slope often defines a weaker pavement layer described by the deflection points used. The basin slope parameters will be used as the basis for HWD test data analysis in the rest of this paper.

According to Xu et al. (8), the Base Damage Index (BDI) is the parameter that is most sensitive to the strength or stiffness of the unbound aggregate base/subbase layers. Figure 7 illustrates the physical meaning of the BDI, which is calculated as the difference between the second and third sensor readings (D_0 is the first sensor):

$$\text{BDI} = D_1 - D_2 \quad (1)$$

Xu et al. (8) found that the Fourth Area Index (AI_4), given by Equation 2, was the most sensitive to the strength/stiffness changes in the subgrade.

$$\text{AI}_4 = \frac{D_3 + D_4}{2D_0} \quad (2)$$

By definition, the AI_4 value cannot be easily compared with the BDI calculation because they represent different parameters. The BDI is directly the slope of the deflection basin between the two points of interest, whereas the AI_4 value is the average of the D_3 and D_4 deflections normalized by the centerline D_0 deflection. The assumption with the AI_4 calculation is that the normalized average of the D_3 and D_4 deflections provides an indication of the strength at some point in the subgrade (see Figure 6), yet, it does not capture the change in strength of that layer.

The Base Curvature Index (BCI) is another parameter suggested to evaluate the subgrade condition (8). Like the BDI definition, BCI represents a slope between two deflection basin points and captures the damage in a layer of the pavement system. The Base Curvature Index is given as the difference between the third and fourth sensor readings:

$$\text{BCI} = D_2 - D_3 \quad (3)$$

The BCI indicates damage in a deeper layer than the BDI because the calculation uses sensor deflections farther away from the impact load. Accordingly, the BDI and BCI can be used together to assess relative damage between pavement layers through a direct comparison of the changes to the slope of the deflection basin.

In relation to the NAPTF flexible airport pavement test sections, Figure 7 shows the deflection basin of the same impact load of approximately 35,000 lbs (156 kN) at different levels of pavement distress over 12,000 passes in the MFC section B777 lane. Note that the D_0 to D_3 deflections appreciably increase as the pavement weakens, while the D_5 deflection stays relatively constant. Considering the MDD data indicated quite small residual deformation in the subgrade when compared the granular base and subbase layers (see Figures 3 and 4), the damage indicated by the BCI definition in Equation 3 is unlikely to be due to subgrade damage only.

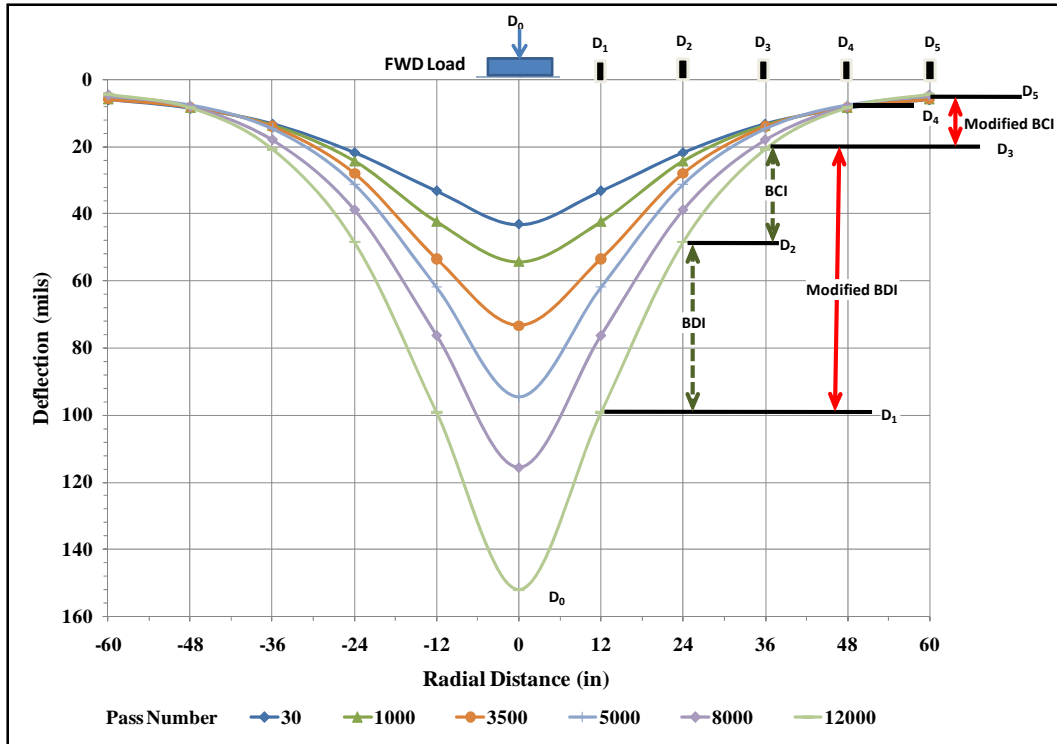


Figure 7 Layer degradation recorded by HWD and deflection basin parameters in the MFC section B777 lane

Gopalakrishnan (9) investigated the traditional BDI and BCI values for the NAPTF test sections and found that the BDI was 10-20% higher than the BCI when traffic lane values were directly compared. However, the traditional definitions do not account for the thicker pavements of the NAPTF tests. Accordingly, D_2 and D_3 may not indicate the base and subgrade behavior, respectively. More likely, the traditional BDI and BCI calculations are both analyzing the base and subbase layers because they are substantially thicker in airport pavements. To account for the thicker layers in the NAPTF CC1 test sections, modified BDI and BCI definitions are proposed herein to identify the degradation in the unbound aggregate layers and the subgrade, respectively. The modified BDI calculation simply extends the farthest deflection value used from D_2 to D_3 as follows:

$$\text{Modified BDI} = D_1 - D_3 \quad (4)$$

Though D_4 does seem to indicate a stable response in Figure 7 there may be situations where D_4 does not indicate stable subgrade behavior. Therefore the BCI calculation is also modified by changing the first deflection value used from D_2 to D_3 and the last deflection value from D_3 to D_5 :

$$\text{Modified BCI} = D_3 - D_5 \quad (5)$$

FWD/HWD sensor readings are sensitive to the level of the impact load, the pavement temperature, moisture in the pavement system, and the overall pavement condition. Because non-traffic lane HWD tests were conducted on the NAPTF CC1 test sections at the same time as

the traffic lane tests, these variables can be accounted for by comparing the deflection basin parameters of the traffic lane and the non-traffic lane. Compensation for the applied impact load magnitude is completed by dividing the recorded deflection measurements by the associated D_0 measurement. The other FWD/HWD sensitivity factors are accounted for by dividing the traffic lane deflection basin parameters by the non-traffic lane deflection basin parameters. By comparing the traffic lane readings (t) to the non-traffic (nt) lane readings, the relative damage in a specific layer is computed as follows:

D_{*t} – traffic lane HWD deflection readings;

D_{*nt} – non-traffic lane HWD deflection readings.

Normalized BDI values for load level – traffic (t) and non-traffic (nt) lanes – are calculated as,

$$BDI_t = \frac{(D_{1t}-D_{3t})}{D_{0t}} \quad ; \quad BDI_{nt} = \frac{(D_{1nt}-D_{3nt})}{D_{0nt}} \quad (6)$$

which gives the relative base and subbase damage:

$$\text{Relative Base and Subbase Damage} = BDI_{\frac{t}{nt}} \text{ ratio} = \frac{BDI_t}{BDI_{nt}} = \frac{\left(\frac{(D_{1t}-D_{3t})}{D_{0t}}\right)}{\left(\frac{(D_{1nt}-D_{3nt})}{D_{0nt}}\right)} = \frac{(D_{1t}-D_{3t})D_{0nt}}{(D_{1nt}-D_{3nt})D_{0t}} \quad (7)$$

Normalized BCI values for load level – traffic (t) and non-traffic (nt) lanes – are calculated as,

$$BCI_t = \frac{(D_{3t}-D_{5t})}{D_{0t}} \quad ; \quad BCI_{nt} = \frac{(D_{3nt}-D_{5nt})}{D_{0nt}} \quad (8)$$

which gives the relative subgrade damage:

$$\text{Relative Subgrade Damage} = BCI_{\frac{t}{nt}} \text{ ratio} = \frac{BCI_t}{BCI_{nt}} = \frac{\left(\frac{(D_{3t}-D_{5t})}{D_{0t}}\right)}{\left(\frac{(D_{3nt}-D_{5nt})}{D_{0nt}}\right)} = \frac{(D_{3t}-D_{5t})D_{0nt}}{(D_{3nt}-D_{5nt})D_{0t}} \quad (9)$$

To calculate the relative damage between the base/subbase (referred to as base hereafter) and the subgrade, one should simply divide Equation 7 by Equation 9.

$$\text{Relative Base to Subgrade Damage} = \frac{BDI_{\frac{t}{nt}} \text{ ratio}}{BCI_{\frac{t}{nt}} \text{ ratio}} = \frac{\left(\frac{BDI_t}{BDI_{nt}}\right)}{\left(\frac{BCI_t}{BCI_{nt}}\right)} = \frac{\left(\frac{(D_{1t}-D_{3t})D_{0nt}}{(D_{1nt}-D_{3nt})D_{0t}}\right)}{\left(\frac{(D_{3t}-D_{5t})D_{0nt}}{(D_{3nt}-D_{5nt})D_{0t}}\right)} \quad (10)$$

which simplifies to:

$$\text{Relative Base to Subgrade Damage} = \frac{BDI_{\frac{t}{nt}} \text{ ratio}}{BCI_{\frac{t}{nt}} \text{ ratio}} = \frac{(D_{1t}-D_{3t})(D_{3nt}-D_{5nt})}{(D_{1nt}-D_{3nt})(D_{3t}-D_{5t})} \quad (11)$$

Notice that when comparing traffic lane and non-traffic lane deflection basin parameters, the normalization for load level (dividing by D_0) is absent. In fact, this makes perfect sense

considering that the approach is truly measuring relative damage between the trafficked and non-trafficked pavement lanes. In other words, as long as the impact load is large enough to stress the deeper layers and kept the same between the HWD tests on trafficked and non-trafficked lanes, the load level becomes irrelevant in determining the relative damage in individual layers.

If the unbound aggregate layers do sustain more damage than the subgrade, the relative base to subgrade damage formulated in Equation 11 should then be larger than 100%. If the damage in both layers is somewhat similar, then this value should be approximately 100%. Otherwise, if the damage in the unbound aggregate layers is less than in the subgrade, then the ratio should be less than 100%.

HWD DATA ANALYSES OF NAPTF CC1 TEST SECTIONS

Figures 8 through 12 indicate the relative base to subgrade damage computed by Equation 11 for the four different NAPTF pavement sections tested in the CC1 test series (see Figure 1). Previous MDD data analyses have shown that the P209 base and P154 subbase unbound aggregate layers accumulated considerably higher residual deformations, as shown in Figures 3 and 4. The main intent of the NAPTF HWD data analyses is therefore to validate the previous research findings and provide a field validated method of determining individual layer damage to be used during trafficking of pavement sections when no MDD instrumentation is available.

Figure 8 shows that the base is initially sustaining a significant amount of damage in both the B777 and B747 lanes, with more damage in the B747 lane than in the B777 lane. Note that the relative base to subgrade damage decreases after approximately 5,000 passes. This is due to layer material property degradation in the unbound aggregate layers resulting in an increase in the magnitude of stresses applied to the subgrade. This in turn causes the subgrade to degrade while the damage in the base layers levels off, thus the base to subgrade damage ratio decreases. This is in accordance with the trench study on the MFC section, which indicated permanent deformation in every layer; however, the unbound aggregate layers sustained the most rutting. Similarly, the rut depth measurements taken throughout pavement trafficking also show that the B747 lane rutted more quickly than the B777 lane indicating that the base damage in the B747 lane is quickly followed by degradation and rutting in the subgrade (7).

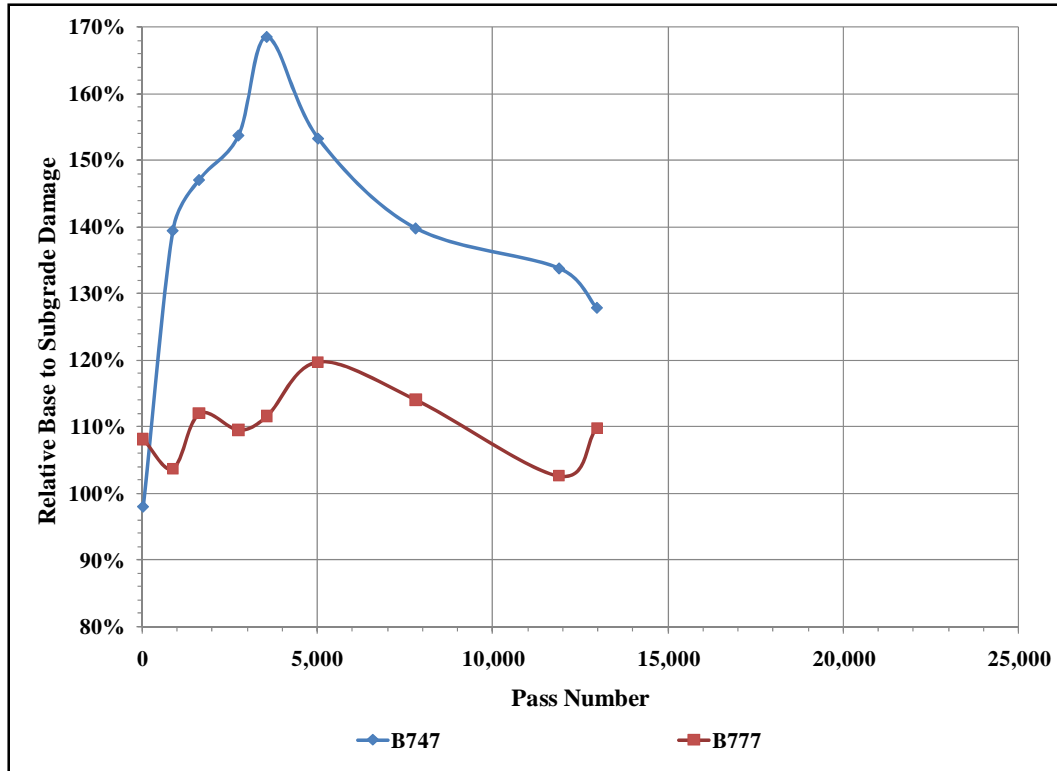


FIGURE 8 Relative base to subgrade damage for MFC test section

Figure 9 shows that the amount of base damage caused by the B777 and B747 type gears reverses with the 6-wheel B777 type gear loading causing much more base damage in the MFS test section. Interestingly, an area of localized failure was found in the B777 lane of the MFS test section from the post traffic forensic analyses. In this area, the subgrade soil was observed to penetrate into the unbound aggregate layers, thus causing a much weaker base layer to develop (3). The HWD tests were conducted at 10 ft. (3 m) intervals and a comparison of the HWD test results based on longitudinal location clearly shows some of the localized failure zones of the unbound aggregate layers as stations 430 and 440 in Figure 10. This is further proof that comparing traffic lane and non-traffic HWD readings can provide valuable insight into specific layer quality. It also shows that the two loadings by the B747 and B777 type gears caused comparable damage to the pavement system and that construction quality control is very important to prevent local weak zones in the pavement.

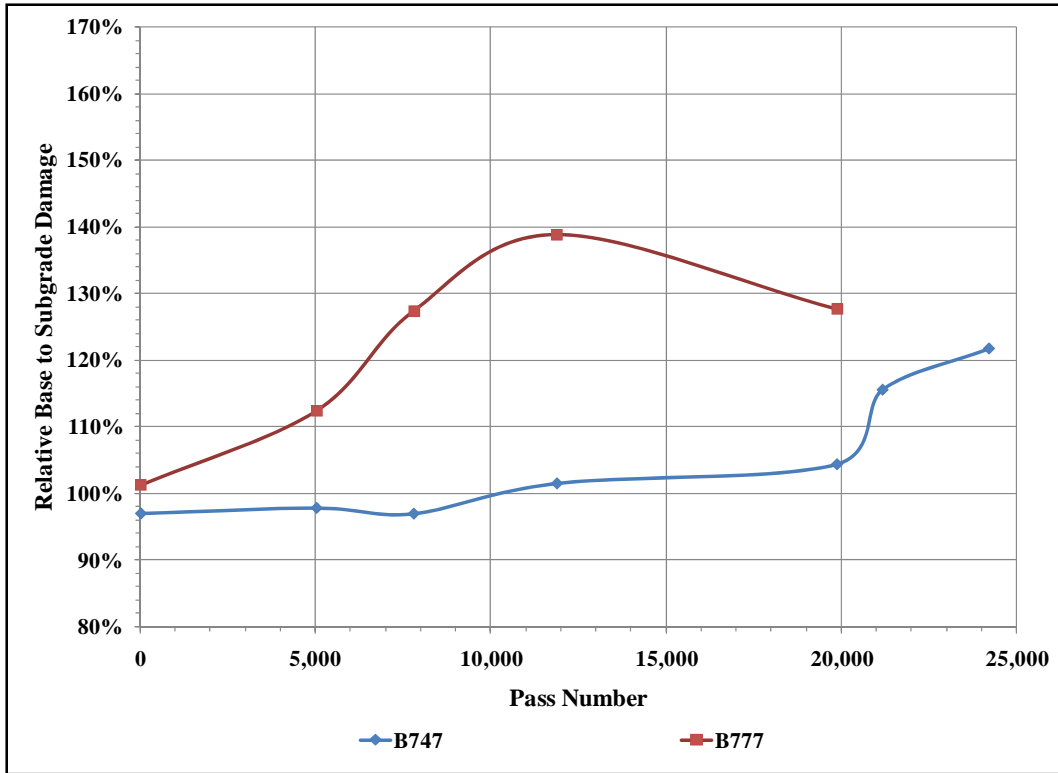


FIGURE 9 Relative base to subgrade damage for MFS test section

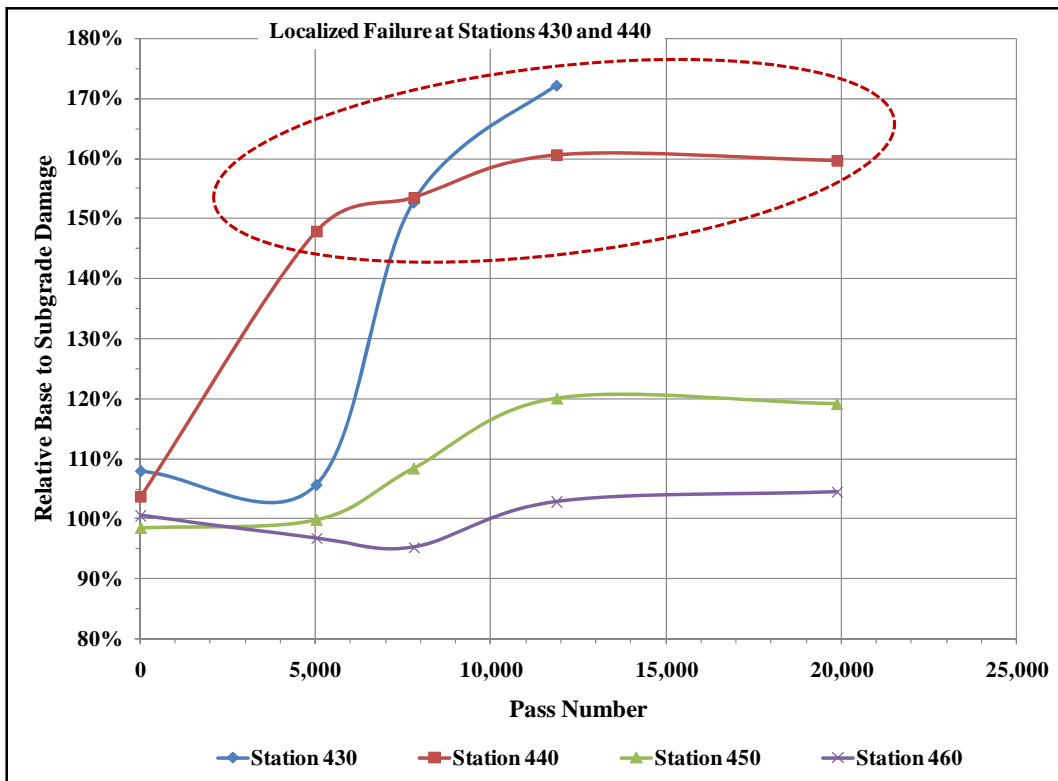


FIGURE 10 Relative base to subgrade damage at various stations by longitudinal location in the B777 lane of the MFS test section

Figures 11 and 12 show the relative base to subgrade damage for the LFC and LFS sections, which have much thicker base and subbase layers than the MFC and MFS sections. These low strength subgrade test sections did not accumulate much pavement rutting in the first 20,000 passes and thus the relative base to subgrade damage ratio should be small with little damage in either layer. However, after the wheel load was increased from 45,000 lbs (200 kN) to 65,000 lbs (290 kN) right at 20,000 passes, the rut development increased quickly. In the LFC section with a thin 5-in. (127-mm) asphalt concrete surface, there was significant rutting in the P154 subbase compared to that of the subgrade, which explains the increased percentages of the relative base to subgrade damage values shown in Figure 11. Figure 9 depicts the same increase in base damage in the MFS section B747 lane after 20,000 passes when the load is increased.

Another observation is that after 20,000 passes, the relative base to subgrade damage becomes erratic in the LFC and LFS sections in Figures 11 and 12, respectively. This is possibly because the HWD tests were not conducted routinely after a specific pass and the applied nine-position wander pattern (see Figure 2) had a dramatic effect on the shakedown behavior and retaining strength/stiffness of the unbound aggregate layers, as was highlighted recently by Donovan and Tutumluer (4). As a result, after certain gear wander positions the base layer became stronger, while after others, the wander-induced movement of the unbound aggregate particles weakened the layer.

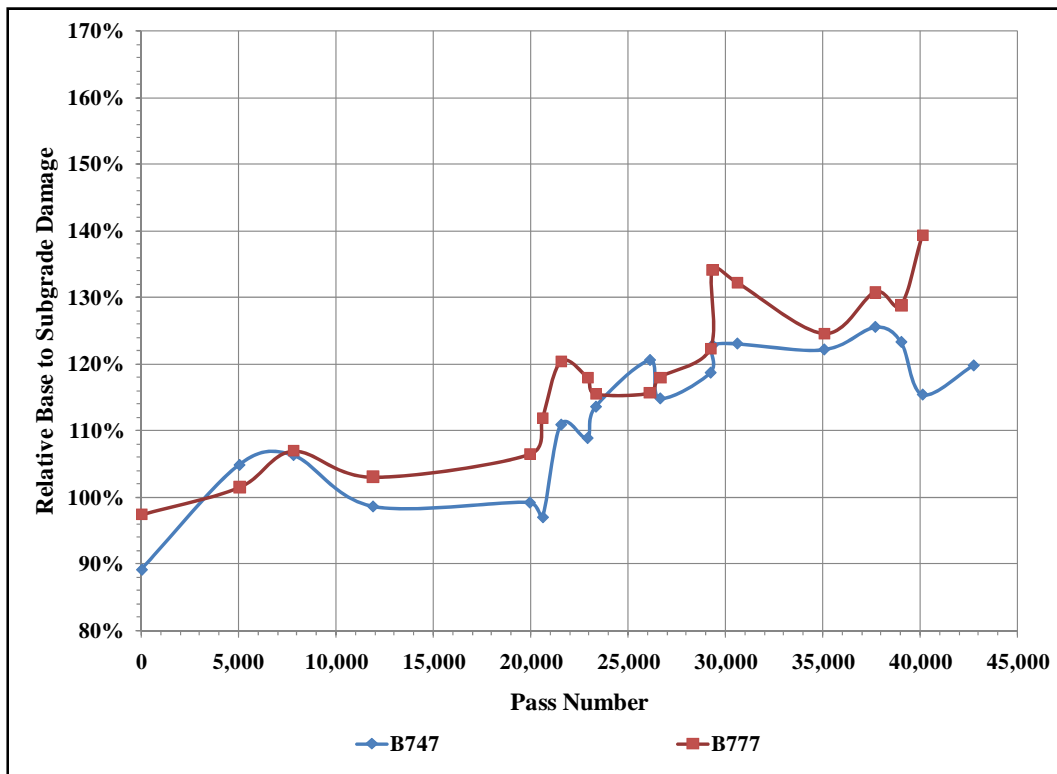


FIGURE 11 Relative base to subgrade damage for LFC test section

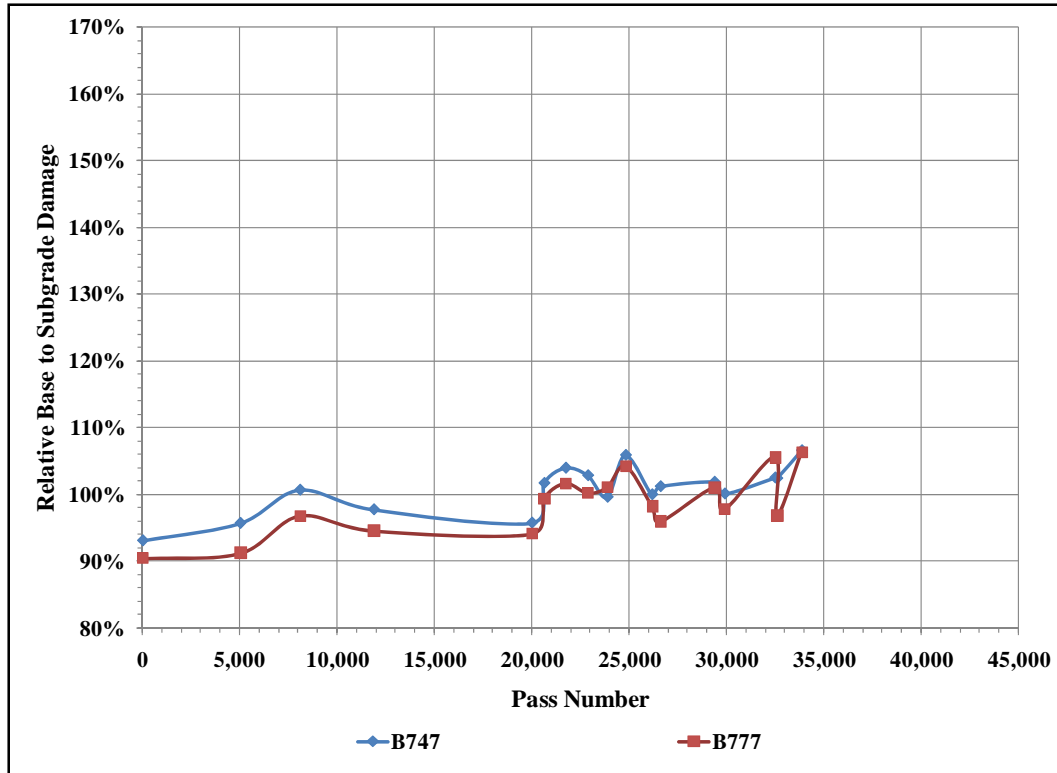


FIGURE 12 Relative base to subgrade damage for LFS test section

CONCLUSIONS

This paper introduced a new methodology to evaluate relative damage occurring in individual pavement layers from falling or heavy weight deflectometer (FWD or HWD) nondestructive testing. With FWD test data collected from both trafficked and non-trafficked pavement test sites, the Base Damage Index (BDI) and the Base Curvature Index (BCI) obtained from measured FWD deflection basins, and their modified formulations proposed for use with HWD data in this study, provide the means to distinguish between unbound aggregate base/subbase damage and subgrade damage, respectively. The approach was successfully applied to the Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF) first round of flexible pavement test sections to demonstrate that the analyzed HWD test data provided evidence of the increased base damage induced in the NAPTF airport pavement layers during trafficking partly due to the applied gear load wander. This was in accordance with the individual pavement layer recovered and unrecovered (inelastic or residual) deformation trends identified from analyzing the multi-depth deflectometer (MDD) data collected during trafficking. Further, comparisons with the individual layer permanent deformation trends recorded from the post traffic trench studies also validated the HWD data analysis results. By the use of the demonstrated FWD/HWD testing and data analysis methodology, comparing the modified BDI and BCI values from the traffic lanes and the non-traffic lanes can be quite valuable in identifying the area of pavement damage. The methodology is especially applicable to flexible pavements with thick granular base/subbase layers for assessing the degradation and rutting damage potential of the unbound aggregate layers in comparison to the pavement subgrade.

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