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CONDITION MONITORING OF BITUMINOUS PAVEMENTS SUBJECTED TO REPEATED DYNAMIC AIRCRAFT LOADING

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Abstract. The Heavy Weight Deflectometer (HWD) is one of the most commonly used devices for monitoring the structural condition of airport pavement infrastructure systems on a routine basis in a rapid and non-destructive manner. The HWD measures pavement surface response (ie deflections) to an applied dynamic load that simulates a moving wheel of an aircraft at moderate speeds. The pavement surface deflection basins obtained by the HWD tests is frequently used as an indicator of the load-bearing capacity of the pavement. These tests were conducted on flexible test pavements at the US Federal Aviation Administration's National Airport Pavement Test Facility (NAPTF) at various times to monitor the effect of simulated Boeing 777 and Boeing 747 aircraft gear trafficking on pavement structural condition. Multi-Depth Deflectometers (MDDs) installed within the pavement sections recorded the load-induced displacements in the pavement and in the subgrade. In this paper, the variations in HWD surface deflections acquired at different stages of NAPTF trafficking are compared with the MDD resilient displacements obtained under multiple-wheel heavy aircraft gear trafficking as well as with the periodic rut depth measurements. The results demonstrate the usefulness of routinely collected HWD surface deflection basins for reliable evaluating the structural performance of airport flexible pavements.

Keywords: New Generation Aircraft (NGA), Boeing 777, Boeing 747, Heavy Weight Deflectometer (HWD), NAPTF, Multi-Depth Deflectometer (MDD), surface deflections.

1. Introduction

Surface deflection is a reliable pavement structural response indicator for predicting general performance [1]. The pavement surface deflections are easily measurable using a non-destructive test device such as the Falling Weight Deflectometer (FWD) in highway pavements or a Heavy Weight Deflectometer (HWD) in airport pavements compared to other responses, such as stresses and strains. These deflections are the basic response of the pavement structure to the applied load [2]. Many highway agencies such as California Department of Transportation (DOT), the Asphalt Institute, Minnesota DOT, the U.K. Transport Road Research Laboratory (TRRL) utilise surface deflection for designing asphalt concrete (AC) overlays, predicting future pavement performance, and considering wheel loading magnitude effects [1].

Non-destructive tests using the FWD and HWD were conducted at various times on flexible test pavements at the US Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF). The NAPTF is a state-of-the-art full-scale airport pavement test facility located at William J. Hughes Technical Center near Atlantic City International Airport (New Jersey, USA). It was constructed to generate full-scale testing data to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of New Generation Aircraft (NGA) such as the Boeing 777 aircraft. The NAPTF was dedicated in April 1999 followed by a 10-month period of verification, shakedown, and pavement response testing. The first series of traffic tests (referred to as Construction Cycle 1 or CC1) began in February 2000 and was completed by September 2001.

The NAPTF test pavement area is 274,3 m (900 ft) long and 18,3 m (60 ft) wide. During the CC1 testing, the NAPTF had a total of nine test sections (six flexible and three rigid) built on three different subgrade materials: low-strength (target California Bearing Ratio [CBR] of 4), medium-strength (target CBR of 8), and high-strength (target CBR of 20).

During the CC1 traffic tests, a six-wheel Boeing 777 gear and a four-wheel Boeing 747 gear were tested on flexible test pavements until they were deemed failed. An inertial profiling device was used to measure the transverse surface profiles periodically during the traffic testing to monitor the development of rut depths. Multi-Depth Deflectometers (MDDs) installed within the pavement sections continuously measured the load-induced displacements during NAPTF trafficking. The elastic responses from the MDD provide a good measure of the resilient behaviour of pavement materials and they are linked to pavement performance [2–6].

2. Objective and scope

The primary objective of this paper is to compare the HWD surface deflections acquired periodically during NAPTF trafficking with the traffic-induced MDD resilient displacements for two medium-strength subgrade flexible test pavement sections; one with conventional granular base layer and the other with asphalt-stabilised base layer. Note that the HWD testing simulates a single-wheel dynamic loading situation, whereas the MDD measurements were obtained under six-wheel and four-wheel dynamic aircraft gear loading where multiple-wheel interaction can become a significant issue. HWD tests were periodically conducted during NAPTF trafficking while the MDD sensors recorded the displacement measurements with every pass. Trafficking continued until the test sections were deemed to be failed.

3. The National airport pavement test facility

The two NAPTF flexible test sections considered in this study are designated as follows: (a) MFC – a conventional granular base flexible pavement section resting on a medium-strength subgrade, and (b) MFS – an asphalt-stabilised base flexible pavement resting on a medium-strength subgrade. Cross-sectional views of the as-built test sections are shown in Fig 1. The items P-209 (crushed stone base), P-154 (gray quarry blend fines) and P-401 (plant mix bituminous pavement) are as per standard specifications detailed in the FAA Advisory Circular No AC 150/5370-10A.

The P-401 was used in both the AC surface layer and in the stabilised layer in the MFS section. A CL-CH soil classification (ASTM Unified Soil Classification System) material known as Dupont Clay (DPC) was used for the medium-strength subgrade. The naturally occurring sandy soil material (SW-SM soil classification) at the NAPTF site underlies each subgrade layer.

The NAPTF subgrades were constructed in controlled lifts of approx 200 mm (8 in) with the imported soils. Resilient modulus tests (ASTM D1587) were conducted on Shelby thin-wall tube samples extracted from the completed subgrades.These samples were obtained from test pits opened just prior to the initiation of traffic testing. Resilient modulus (E_R) is defined as the repeatedly applied wheel load stress divided by the recoverable strain determined after shakedown of the material. The subgrade resilient modulus generally varied from approx 34 to 86 MPa (5 000 to 12 500 psi) for medium-strength soils, depending on confining pressure and deviator stress for the medium-strength subgrade soils. The medium-strength subgrade soil had a plastic limit of 28,8, Liquid Limit (LL) of 48,5, and Plasticity Index (PI) of 19,7.

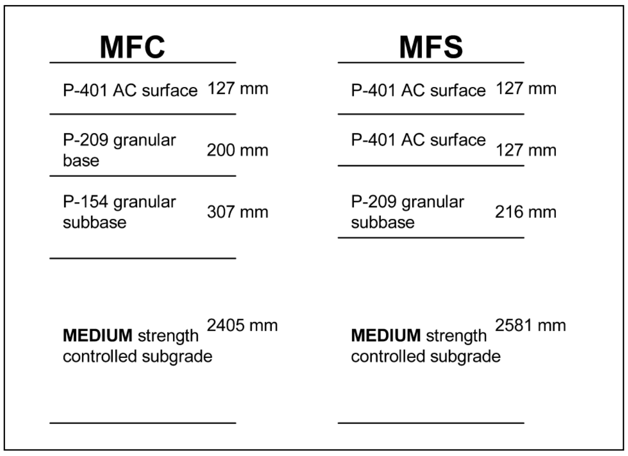

Fig 1. Cross-sectional views of as-constructed NAPTF flexible test sections

Resilient modulus tests and triaxial shear tests were conducted on P-209 and P-154 granular materials using the standard test procedure described in AASHTO T294-94. Based on resilient modulus characterisation of repeated triaxial testing data using the K-Θ stress-dependent model ($E_R = K\Theta^n$; Θ is bulk stress; K and n are statistical parameters), K values of 28,2 MPa (4,088 psi) and 17,5 MPa (2,534 psi), and n values of 0,60 and 0,65 were obtained for P-209 base and P-154 subbase materials, respectively.

During CC1 traffic testing, a six-wheel dual-tridem (B777) landing gear, with 1372 mm (54 in) dual spacing and 1448 mm (57 in) tandem spacing was loaded on the north wheel track (LANE 2) while the south side (LANE 5) was loaded with a four-wheel dual-tandem (B747) landing gear having 1118 mm (44 in) dual spacing and 1473 mm (58 in) tandem spacing. The NAPTF test vehicle and the aircraft gear configurations used during the CC1 traffic testing are shown in Fig 2. The wheel loads were set to 20,4 tonnes (45 000 lbs) each and the tire pressure was 1295 kPa (188 psi). The traffic speed was 8 km/h (5 mph) throughout the traffic test program.

To realistically simulate transverse aircraft movements, a wander pattern consisting of a fixed sequence of 66 vehicle passes (33 travelling in the east direction and 33 traveling in the west direction), arranged in nine equally spaced wander positions (or tracks) at intervals of 260 mm (10,25 in), was used during traffic testing. This wander pattern simulates a normal distribution of aircraft traffic with a standard

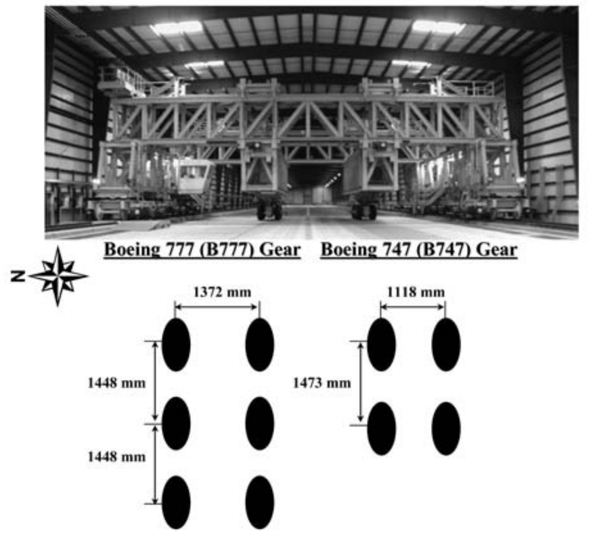

Fig 2. NAPTF traffic test vehicle and test gear configuration details

deviation (σ) of 775 mm (30,5 in) that is typical of multiple gear passes in airport taxiways.

The NAPTF failure criterion was the one established in the US Army Corps of Engineers' (US COE) Multi-Wheel Heavy Gear Load (MWHGL) tests conducted at Vicksburg, Mississippi [7]. Failure is defined as the presence of at least 25,4 mm (1 in) surface upheaval adjacent to the traffic lane. This is linked to a structural or shearing failure in the subgrade.

It is important to note that in the 25,4 mm (1 in) surface upheaval failure criterion, there is no limit on the maximum rut depth. Thus, a surface upheaval of 25,4 mm (1 in) may be accompanied by a 13 mm (0,5 in) rut depth or rut depths in excess of 50 to 75 mm (2 to 3 in) with no limit on the maximum allowable rut depth. However, according to the Unified Facilities Criteria (UFC), rut depths in excess of 25,4 mm (1 in) is considered as “High” severity rutting and it constitutes a significant functional failure requiring major maintenance activities [8].

4. Experimental: non-destructive tests

Non-destructive tests using Heavy Weight Deflectometer (HWD) were conducted on NAPTF flexible pavement test sections at various times. The HWD tests are commonly used to assess the structural integrity of airport runways in a non-destructive manner. Many studies have addressed the interpretation of pavement surface deflection measurements as a tool to characterise pavement-subgrade systems [9, 10].

There are many advantages to using HWD, in lieu of, or supplement traditional destructive tests. Most important is the capability to quickly gather data at several locations while keeping a runway, taxiway, or apron operational during these 2-minute to 3-minute tests, provided the testing is under close contact with Air Traffic Control. The HWD equipment measures pavement surface deflections from an applied dynamic load that simulates a moving wheel. The deflection data collected with the HWD equipment can provide both qualitative and quantitative data about the strength of a pavement at the testing time [11].

The HWD tests were conducted using a KUAB 2m HWD device acquired by the FAA. The FAA HWD equipment was configured with a 305 mm (12 in) loading plate and a 27–30 msec pulse width was used during testing [12, 13]. The surface deflections were measured with six seismometers at offsets of 0 mm [D_0]; 305 mm (12 in) [D_1]; 610 mm (24 in) [D_2]; 914 mm (36 in) [D_3]; 1219 mm (48 in) [D_4]; and 1524 mm (60 in) [D_5] intervals from the centre of the HWD load plate.

HWD tests were performed at nominal force amplitudes of 53 kN (12,000-lb), 107 kN (24,000-lb), and 160 kN (36,000-lb). This paper primarily focuses on results from HWD tests conducted at a nominal force amplitude of 160 kN (36,000-lb). HWD tests were performed on the untrafficked centreline (C/L), B777 traffic lane and B747 traffic lane at approx 3,05 m (10 ft) intervals in each flexible test section at periodic intervals throughout the traffic testing. The location and orientation of HWD test lanes together with MDD locations are shown in Fig 3. All test data referenced in this paper are available for download on the FAA Airport Pavement Technology website: http://www.airporttech.tc.faa.gov/naptf/. Detailed analyses of NAPTF HWD test results are presented elsewhere [14].

5. Experimental: Multi-Depth Deflectometer (MDD) instrumentation

MDDs manufactured by Construction Technology Laboratories (CTL), were installed to record the load-induced displacement at multiple depths within the pavement structure [15]. Each MDD consisted of seven Displacement Transducers (DTs) placed at strategic locations to capture the multiple-wheel load interaction effects. The MDD was anchored at a depth where no significant displacement was expected. The anchor depth was 2,7 m (9 ft) for the medium-strength subgrade test sections. The surface DT measured displacements relative to the anchor, whereas the other DTs measured displacements relative to the surface layer. Five MDDs were installed per flexible test section: two in each traffic path and one in the Centreline of the test pavements (Fig 3).

The MDD data (response-time histories) recorded per gear pass is available for download at the FAA Airport Technology Website. The response-time history for each gear pass was separated into rebound and residual displacements. The fully recoverable response is the rebound (elastic) displacement while the residual displacement is considered a permanent or inelastic deformation. Typically, the MDD

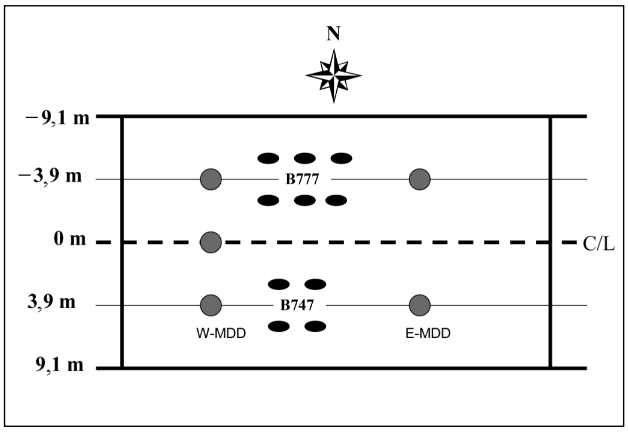

Fig 3. Heavy Weight Deflectometer (HWD) test lane locations

rebound displacements are used to characterise the resilient behaviour of the NAPTF flexible pavement sections. For stable conditions, the residual displacements will be negligible after a small number of load repetitions due to shake-down and measured displacements will remain essentially resilient (recoverable) [3]. This is a common assumption in many mechanistic-empirical pavement design criteria, where performance is a function of resilient response [4]. The MDD displacement results from NAPTF medium-strength flexible test sections are discussed in detail by Hayhoe and Garg [16], Hayhoe et al [17], and Gopalakrishnan et al [18].

6. Rut depth measurements

Rutting is a major distress in airport flexible pavements [19]. It appears as longitudinal depressions in the wheel paths and may be accompanied by small upheavals to the sides. Permanent deformation in any or all of the pavement layers and/or subgrade under repeated traffic loading contributes to the total accumulation of pavement surface rutting [20].

During NAPTF traffic testing, Transverse Surface Profile (TSP) measurements were made at two locations (west side and east side) to monitor the progression of rutting in the test sections. A manually propelled inertial profiling device was used to measure the transverse surface elevation profiles. A recommended test speed of 2,0 km/h (1,24 mph) was used and the profile elevation was recorded once every 250 mm (9,84 in). A comprehensive literature review on the benefits and uses of TSP measurements is provided by White et al [21].

Using the TSP measurements, for a given number of traffic load repetitions (N), maximum surface ruts were extracted from each traffic lane. For a given TSP, the maximum surface rut depth in a traffic lane was defined as the minimum profile elevation occurring within the width of that traffic lane (9,1 m [30 ft]). The TSP rut depth measurements (west location) are plotted against in Fig 4 for medium-strength test sections (MFC and MFS). The results from NAPTF rutting study showed that the mean rut depths between the B777 and B747 gear trafficking do not differ significantly in all four NAPTF flexible test sections [14]. During the NAPTF construction, static temperature sensors were installed at different depths along the test sections to record the pavement temperatures at different day time. The variations in AC layer mid-depth temperatures during NAPTF traffic testing are plotted in Fig 5 for all four NAPTF flexible test sections.

7. Results: comparison between HWD and MDD dynamic deflections

The US Army Corps of Engineers' CBR method of pavement design uses deflection as the critical response to design airport pavement. Asphalt Concrete (AC) strain (fatigue cracking) and subgrade stress/strain (rutting) are strongly correlated with surface deflection. In two comprehensive ILLI-PAVE (a 2-D finite-element pavement structural model) based studies for full-depth AC [22] and conventional flexible pavements [23] reliable algorithms were developed relating Subgrade Stress Ratio (SSR = ratio of subgrade deviator stress to subgrade compressive strength) and AC flexural strain to surface deflections.

In the past, pavement surface deflections were used as an indicator of the airport pavement life. In a study conducted at Waterways Experiment Station (WES), a strong relation was found between elastic (or recoverable) deflection and allowable load repetitions on flexible pavements [24]. The results from other studies at WES showed that an aircraft wheel load causing an elastic deflection of about 0,635 mm (0,25 in) could be expected to fail the pavement with repeated loading in excess of 2000 coverages [25]. For wide-tire, low-pressure loads, the limiting deflection might exceed 0,84 mm (0,33 in), and for narrow-tire high-pressure loads, the limiting deflection might be less than 0,38 mm (0,15 in).

Bush and Thompson developed a FWD-based evaluation procedure to predict the allowable F-4 aircraft load and the allowable aircraft passes for marginal flexible pavements [26]. Among the estimators considered in the study, the Impact Stiffness Modulus (ISM) was found to be the best estimator of pavement performance for low-volume airfield pavements. The ISM, used by the Corps of Engineers for characterising pavement structures, is analogous to the spring constant (k) of a spring-mass system. The ISM is applied FWD plate load divided by deflection under the centre of the plate. Gopalakrishnan studied the surface deflection basins from periodically conducted HWD tests on NAPTF flexible test sections and found them to be useful in characterising the pavement structural deterioration under repeated aircraft gear loading [14].

Garg and Marsey compared the results of NAPTF HWD tests and static load tests prior to traffic testing [2]. The HWD tests were performed on the top of the MDDs,

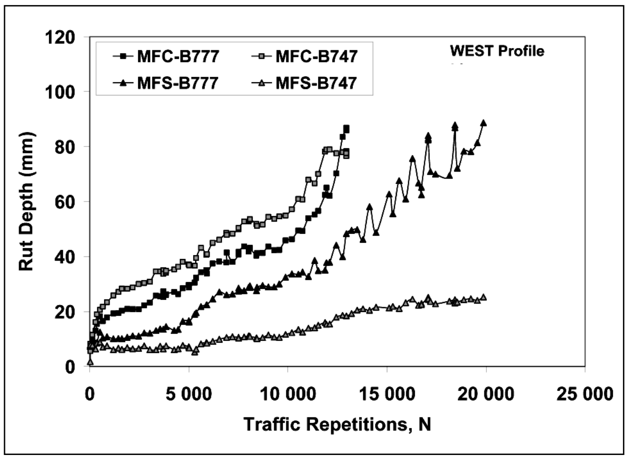

Fig 4. Rut depth progression during traffic testing

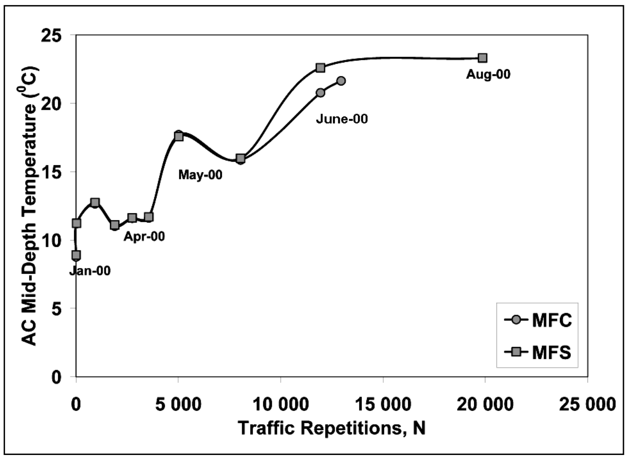

Fig 5. Variation in asphalt concrete mid-depth temperature during traffic testing

and the pavement deflections were measured by sensors mounted on the HWD equipment as well as the MDDs. For the static load tests, the aircraft wheel was positioned over the MDDs and the MDDs measured the pavement deflections. It was found that the relative surface deflections for different NAPTF flexible pavement structures from HWD tests and static tests are very different. Garg and Marsey reasoned that the load conditions under HWD loading are similar to a "single-wheel" load case with dynamic loading, whereas in the case of static tests a six-wheel gear configuration was used and wheel load interactions became a significant issue [2].

In this study, the results from NAPTF HWD tests at different stages of trafficking were compared with MDD measurements under dynamic traffic loading. To enable a comparison between HWD and MDD results, the HWD deflections recorded at an impulse load level of 160 kN (36 000 lbs) were normalised to the aircraft wheel load of 20,4 tonnes (45 000 lbs) used during the traffic testing. This is a valid assumption since the NAPTF HWD test results showed a linear load-deflection relationship [2, 13, 14].

The comparison between HWD D0s and MDD surface deflections (average at different wander positions) are shown in Figs 6 and 7 for B777 traffic lane and B747 traffic lane, respectively, in MFC test section. Similar results are shown in Figs 8 and 9 for MFS test section. Note that HWD deflection is generally a function of diameter of loading plate, applied load, and pavement structure as a whole.

Comparison of surface deflections for medium-strength test sections from HWD tests and MDDs show good agreement, especially in the MFC test section. Note that, as mentioned previously, the loading conditions are different in the two methods: the loading conditions under HWD loading are similar to a single-wheel load case with dynamic loading; whereas the MDD measurements correspond to dynamic loading of a six-wheel (B777) or four-wheel (B747) gear configuration. Yet, the results between the two methods are comparable, although this was not true when the HWD results were compared with those of MDD static load tests, as shown by Garg and Marsey [2]. Also, in this case, the dynamic deflections obtained under B777 and B747 loading are very similar throughout the duration of trafficking in the MFC test section.

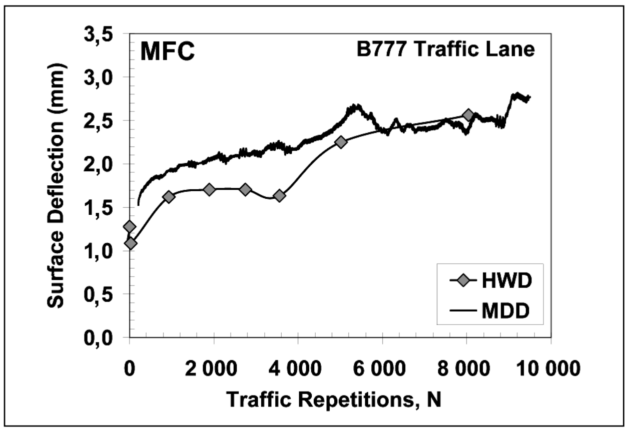

Fig 6. Comparison between HWD and MDD surface deflections in B777 traffic lane (MFC)

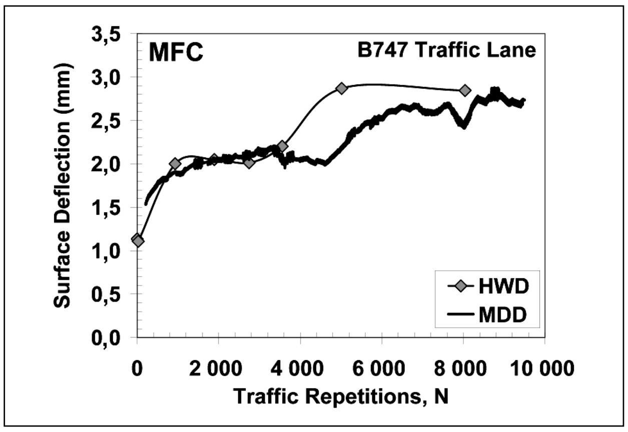

Fig 7. Comparison between HWD and MDD surface deflections in B747 traffic lane (MFC)

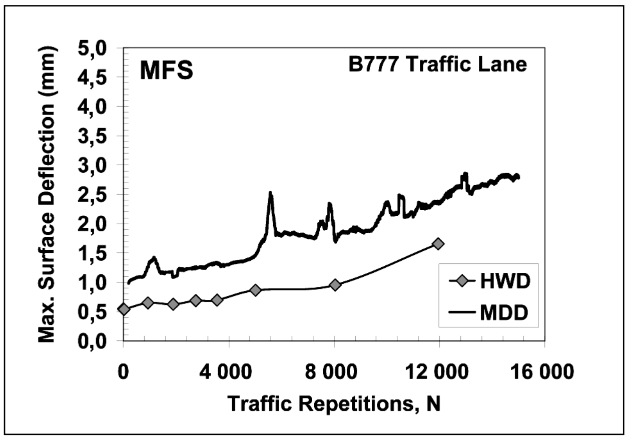

Fig 8. Comparison between HWD and MDD surface deflections in B777 traffic lane (MFS)

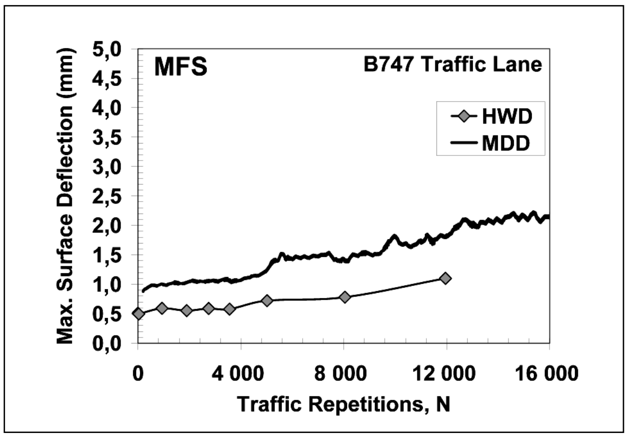

Fig 9. Comparison between HWD and MDD surface deflections in B747 traffic lane (MFS)

The rapid increase in surface deflection values in B777 traffic lane of the MFS test section after 5000 passes is not due to trafficking, but due to a localised failure in the subbase layer as revealed by the post-traffic trench study results [27]. This is also reflected in the rutting measurements (Fig 4). At 19 900 passes, 89 mm (3,5 in) of rut depth was observed in the B777 traffic lane with upheaval outside the traffic path. The post-traffic trench study results showed that both the MFC and MFS test sections failed at the subgrade level [27, 28].

These results demonstrate the usefulness of surface deflection basins acquired from periodically conducted HWD tests as a tool for characteris the airport pavement structural deterioration under repeated multiple-wheel heavy aircraft gear loading. Both the MDD and the HWD results support the validity of developing deflection-based design criteria for airport pavements serving the new generation aircraft such as the Boeing 777 aircraft.

8. Conclusions

Non-destructive tests using the HWD were conducted at different times during traffic testing of flexible test pavements at the US FAA's National Airport Pavement Test Facility (NAPTF). During the first series of traffic tests, a six-wheel Boeing 777 (B777) gear and a four-wheel Boeing 747 (B747) gear were tested on flexible test pavements until they were deemed failed. Multi-Depth Deflectometers (MDDs) installed within the pavement sections continuously measured the load-induced displacements during NAPTF trafficking. In this paper, HWD surface deflections acquired periodically during NAPTF trafficking were compared with the traffic-induced MDD resilient displacements for two medium-strength flexible test sections at the NAPTF. The following are the research findings:

1. As expected, both the HWD deflections and MDD displacements are significantly influenced by variations in asphalt concrete pavement temperature.
2. The results between the two methods (HWD and MDD) are comparable under dynamic loading conditions, although this was not true when the HWD results were compared with those of MDD static load tests in a previous research.
3. It is interesting to note that both the HWD and MDD deflections closely follow the pavement surface rutting trends.
4. In general, the HWD and MDD surface deflections obtained under six-wheel B777 and four-wheel B747 repeated traffic loading are comparable. The significant increase in the deflections as well as the rutting measurements in the B777 traffic lane of the MFS test section after 5000 passes is due to a localised subbase failure and therefore this case should be treated separately.
5. The results demonstrate the usefulness of surface deflection basins acquired from periodically conducted HWD tests as a tool for characterising the airport pavement structural deterioration under repeated multiple-wheel heavy aircraft gear loading and support the validity of developing deflection-based airport pavement design criteria.
6. The MDD in-depth elastic responses are useful for characterising the resilient behaviour of pavement systems under repeated loading while the MDD inelastic or residual responses can be used in studying the permanent deformation behaviour of individual pavement layers.

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References

1. NCHRP 1-26. Calibrated Mechanistic Structural Analysis Procedures for Pavements, Final Report, National Cooperative Highway Research Program Project 1-26, Tranportation Research Board, National Research Council, Washington, DC, 1990. 90 p.
2. GARG, N. and MARSEY, W. H. Comparison between Falling Weight Deflectometer and Static Deflection Measurements on Flexible Pavements at the National Airport Pavement Test Facility (NAPTF). In: Proc of the Federal Aviation Administration Airport Technology Transfer Conference, Chicago, Illinois, 2002. 11 p.
3. LEDBETTER R. H. General Deformation (Elastic and Inelastic) and Stress Distribution Theory in Soils. Technical Report No S-77-10, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Sept, 1977. 122 p.
4. GOMEZ-RAMIREZ, F. M. and THOMPSON, M. R. Aircraft Multiple Wheel Gear Load Interaction Effects on Airport Flexible Pavement Responses. In: Proc of the Airfield Pavement Specialty Conference, ASCE, Reston, Virginia, 2001. 12 p.
5. CROCKFORD, W. W.; BENDANA, L. J.; YANG, S. K.; RHEE, S. K. and SENADHEERA, S. P. Modeling Stress and Strain States in Pavement Structures Incorporating Thick Granular Layers. Final Report, Texas Transportation Institute Contract No F08635-87-C-0039, Texas A&M University, College Station, April 1990. 90 p.
6. BEJARANO, M. and THOMPSON, M. R. Subgrade Soil Evaluation for the Design of Airport Flexible Pavements. Final Report, FAA COE Report No 8, Dept of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, 1999. 115 p.
7. AHLVIN, R. G.; ULERY, H. H.; HUTCHINSON, R. L. and RICE, J. L. Multiple-Wheel Heavy Gear Load Pavement Tests. Technical Report No AFWL-TR-70-113, US Army Engineer Waterways Experiment Station, Vicksburg, Mississipi, 1971. 95 p.
8. US COE. O&M: PAVER, Asphalt Surfaced Airfields Pavement Condition Index (PCI) – Unified Facilities Criteria (UFC), UFC 3-270-06. US Army Corps of Engineers (Preparing Activity), Naval Facilities Engineering Command, Air Force Civil Engineering Support Agency, 2001. 250 p.
9. BUSH III, A. J. and BALADI, G. Y. Nondestructive Testing of Pavements and Backcalculation of Moduli. 3rd Vol, ASTM Special Technical Publication (STP) 1026, ASTM International, West Conshohocken, Pennsylvania, 1989. 600 p.
10. TAYABJI, S. D. and LUKANEN, E. O. Nondestructive Testing of Pavements and Backcalculation of Moduli. ASTM Special Technical Publication (STP) 1375, ASTM International, West Conshohocken, Pennsylvania, 2000. 650 p.
11. FAA. Use of Nondestructive Testing in the Evaluation of Airport Pavements. FAA Advisory Circular No 150/5370-11A, Office of Airport Safety and Standards, Federal Aviation Administration, 2004. 73 p.
12. GUO, E. H. and MARSEY, W. Verification of Curling in PCC Slabs at FAA National Airport Pavement Test Facility. In: Proc of the Airfield Pavement Specialty Conference, ASCE, Reston, Virginia, 2001. 15 p.
13. McQUEEN, R. D.; MARSEY, W. and ARZE, J. M. Analysis of Nondestructive Data on Flexible Pavement Acquired at the National Airport Pavement Test Facility. In: Proc of the Airfield Pavement Specialty Conference, ASCE, Chicago, Illinois, 2001. 12 p.
14. GOPALAKRISHNAN, K. Performance Analysis of Airport Flexible Pavements Subjected to New Generation Aircraft. PhD thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois, 2004. 650 p.
15. De BEER, M.; HORAK, E. and VISSER, A. T. The Multidepth Deflectometer (MDD) System for Determining the Effective Elastic Moduli of Pavement Layers. Nondestructive Testing of Pavements and Backcalculation of Moduli. ASTM STP 1026, ASTM International, West Conshohocken, Pennsylvania, 1989. 20 p.
16. HAYHOE, G. H. and GARG, N. Subgrade Strains Measured in Full-Scale Traffic Tests with Four- and Six-Wheel Landing Gears. In: Proceedings of the Federal Aviation Administration Airport Technology Transfer Conference, Chicago, Illinois, 2002. 34 p.
17. HAYHOE, G. F.; GARG, N. and DONG, M. Permanent Deformations During Traffic Tests on Flexible Pavements at the National Airport Pavement Test Facility. In: Proc of the Airfield Pavement Specialty Conference, ASCE, Reston, Virginia, 2003. 23 p.
18. GOPALAKRISHNAN, K.; THOMPSON, M. R. and MANIK, A. Multi-Depth Deflectometer Dynamic Response Measurements under Simulated New Generation Aircraft Loading. *Journal of Testing and Evaluation*, ASTM, Vol 34, No 6, 2006. 8 p.
19. RAWE, R. P.; RUHL, T. A. and SUNTA, R. J. Results of the 1989 ASCE Airfield Pavement Survey. In: Proc of Airfield Pavement Specialty Conference, ASCE, New York, 1997. 22 p.
20. THOMPSON, M. R. and NAUMAN, D. Rutting Rate Analysis of the AASHO Road Test Flexible Pavements. *Transportation Research Record 1384*, TRB, Washington DC, 1993. 12 p.
21. WHITE, T. D.; HADDOCK, J. E.; HAND, A. J. T. and FANG, H. Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements. NCHRP Report 468, Transportation Research Board, National Research Council, Washington, DC, 2002. 65 p.
22. GOMEZ-ACHECAR, M. and THOMPSON, M. R. ILLI PAVE Based Response Algorithms for Full Depth Asphalt Concrete Pavements. *Transportation Research Record 1095*, TRB, Washington DC, 1986. 16 p.

23. THOMPSON, M. R. and ELLIOT, R. P. ILLI-PAVE Based Response Algorithms for Design of Conventional Flexible Pavements. *Transportation Research Record 1043*, TRB, Washington DC, 1985. 15 p.
24. US Army COE. Deflection-Coverage Relationship for Flexible Pavements. Miscellaneous Paper S-71-18, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, 1971. 35 p.
25. AHLVIN, R. G. Origin of Developments for Structural Design of Pavements. Technical Report GL-91-26, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, 1991. 107 p.
26. BUSH, A. L. and THOMPSON, M. R. Predicting Capacities of Low Volume Airfield Pavements. In: Proc of the 3rd International Conference on Bearing Capacity of Roads and Airfields, Trondheim, Norway, 1990. 12 p.
27. HAYHOE, G. F. and GARG, N. Posttraffic Testing on Medium-Strength Subgrade Flexible Pavements at The National Airport Pavement Test Facility. In: Proc of the Airfield Pavement Specialty Conference, ASCE, Reston, Virginia, 2003. 11 p.
28. HAYHOE, G. H. Traffic Testing Results from the FAA's National Airport Pavement Test Facility. In: Proc of the Second International Conference on Accelerated Pavement Testing, University of Minnesota, Minneapolis, Minnesota, Oct 2004. 23 p.

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