Predicting Rutting Performance of Pavement Granular Layers at the FAA's National Airport Pavement Test Facility

By:

In Tai Kim and Erol Tutumluer
Department of Civil and Environmental Engineering
University of Illinois
205 N. Mathews, Urbana, IL 61801
USA
Phone: (217) 333-8637; Fax: (217) 333-1924
tutumlue@uiuc.edu
itkim@uiuc.edu

PRESENTED FOR THE
2004 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2004

ABSTRACT

After the first round of testing at the Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF) was completed, significant rutting was found to take place in the flexible pavement test sections' granular base and subbase layers, designated as P209 base and P154 subbase according to FAA's construction specifications. To account for the rutting performances of these substantially thick granular layers, a comprehensive set of repeated load triaxial tests were conducted in the laboratory on these P209 base and P154 subbase granular materials. Based on the constant confining pressure (CCP) type laboratory test results, which consider vertical repeated traffic loading directly above a pavement element, mathematical models were developed to predict maximum permanent deformations occurred under both Boeing 777 and 747 gear/wheel loads. A comparison of the measured and predicted permanent deformations indicated that a good match for the measured rut magnitudes could be achieved when the variation of stress states in the granular layers were properly accounted for in the prediction models. The rates at which permanent deformations accumulated in the granular layers with number of load applications, however, could not be fully modeled using the prediction models developed based on the laboratory CCP test data only. For a better understanding and improved modeling of the field mechanisms of rut development and accumulation with number of passes, prediction models need to also consider the effects of dynamic field stress states and shear stress reversals that take place under moving wheel loads.

INTRODUCTION

The National Airport Pavement Test Facility (NAPTF), located at the William J. Hughes Technical Center near Atlantic City, New Jersey, was completed and dedicated in April 1999 to represent the most carefully constructed facility ever conceived for evaluating airport pavements. The NAPTF had 9 pavement test items and 10 transition sections built on three different subgrades. Target strengths of the subgrades were 4 CBR (low-strength), 8 CBR (medium-strength), and 20 CBR (high-strength). There were six flexible pavement test items and three rigid pavement test items. Among the transition sections, five were rigid pavements and five were flexible pavements. Both P209 granular base and P154 granular subbase materials, according to FAA's construction specifications, were extensively used in the construction of flexible and rigid pavement sections. These considerably thick granular layers commonly used in airport pavements serve the primary purpose of load distribution through aggregate interlock that is essential to the integrity of the pavement. It is, therefore, important to be able to assess properly their rutting performances under repeated aircraft loading.

A current FAA Center of Excellence research project at the University of Illinois has focused on applying realistic field stress states on the P209/P154 granular materials and investigating in the laboratory proper test procedures for predicting the amount of field rutting. For this purpose, laboratory specimens of both P209 and P154 materials have been studied in a comprehensive laboratory testing program with special emphasis given to the airport layered pavement structures, magnitude of the heavy aircraft wheel loads and dynamic effects under moving wheel load conditions.

This paper summarizes research findings on characterizing and predicting the permanent deformation behavior of the P209/P154 NAPTF granular base and subbase materials used

recently in the construction and testing of the first round of NAPTF flexible pavement test sections. A comprehensive laboratory study included conducting repeated load triaxial tests at various dynamic vertical stresses under constant confining pressure (CCP) conditions, which corresponded to typical field stress states experienced in the granular pavement layers directly under aircraft gear/wheel loading. Rutting models developed based on these test results will be presented and compared for prediction performances with the results of the FAA NAPTF testing.

NAPTF LOW STRENGTH FLEXIBLE PAVEMENT BASE AND SUBBASE PERFORMANCES

The determination of performance properties is necessary to evaluate the development and occurrence of distresses in the trafficked NAPTF flexible pavement sections. As is the case for most airfield pavements, the NAPTF flexible pavements test sections were designed to primarily fail in an excessive surface rutting type failure. The pavement layers that are protected from such excessive rutting are the weakest subgrade soil layer and the overlying subbase/base unbound aggregate layers constructed for the purpose of protecting the subgrade. The most important performance indicator for the P209/P154 airport base/subbase layers is therefore the permanent deformation (rutting) potential of these unbound aggregate materials.

The NAPTF flexible pavements constructed on the low strength subgrades, low strength flexible conventional (LFC) and low strength flexible stabilized (LFS), were also the ones that were the most susceptible to excessive permanent deformations with the substantially thick granular P209/P154 base/subbase layers. The typical LFC and LFS pavement cross-sections and their nominal layer thicknesses are illustrated in Figure 1. Two aircraft gear configurations, dual tandem (Boeing 747) and dual tridem (Boeing 777), were applied on the test sections initially with wheel loads up to 45,000 lbs (20.4 tonnes) each. For the low strength sections, after 20,000 passes, the wheel load was increased up to 65,000 lbs (29.5 tonnes) in order to fail the pavements causing a surface upheaval of 1-inch (25.4-mm) in the rutted transverse profiles. The traffic speed was set at 5 mph (8 km/h).

Trafficking of the constructed NAPTF pavement test sections was completed in 2001. Flexible pavement section distress/failure was indicated mainly by rutting of up to 4-inches (100-mm) permanent deformations observed on the surface. In these pavements, considerable rutting, determined from multi depth deflectometer (MDD) data and test section forensic analyses, was found to take place in both P209 base and P154 subbase layers as reported by Garg [1].

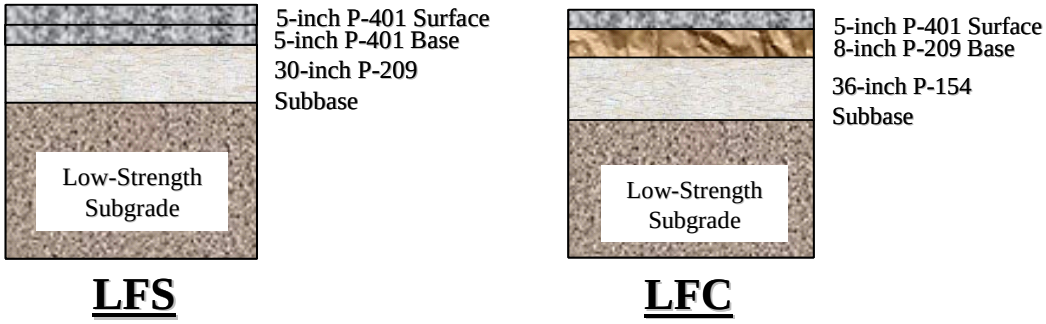


Figure 1 The NAPTF pavement cross-sections of LFS and LFC test sections

The following trends in the permanent deformation behavior were observed after trafficking of the first round of NAPTF LFC and LFS pavement test sections as obtained from the recorded MDD data (see Garg [1]):

(1) In the low strength flexible stabilized (LFS) sections, the major contribution to permanent deformation was from the 30-inch (762-mm) thick P209 base at the wheel loads of 45,000 lbs (20.4 tonnes) for the first 20,000 passes. When the wheel loads increased to 65,000 lbs, (29.5 tonnes) subgrade was determined to be the major contributor. The subgrade was well protected by the upper layers until loading was raised to 65,000 lbs (29.5 tonnes) (see Figure 2).

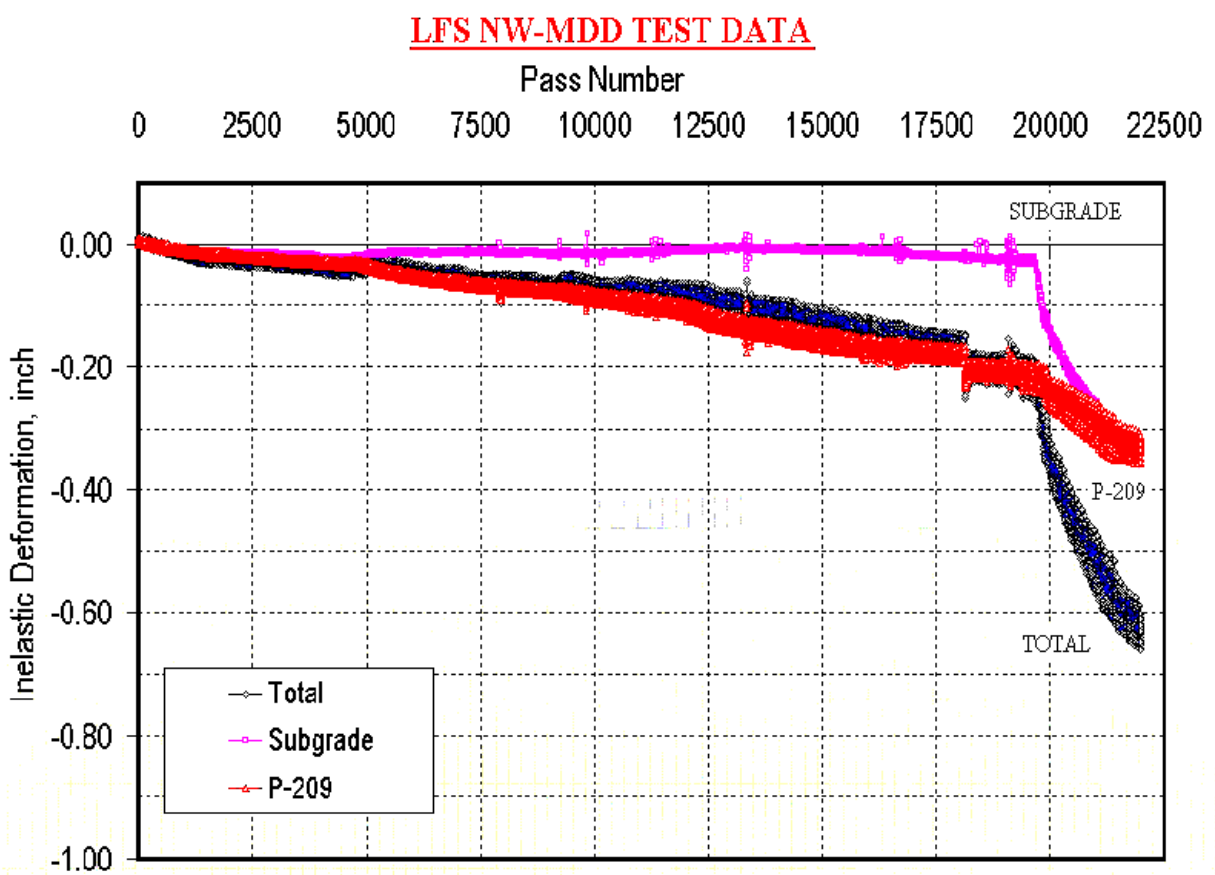


Figure 2 Rutting performance of the low strength stabilized LFS test section (after Garg [1])

(2) In the low strength flexible conventional (LFC) sections, the major contribution to permanent deformation was from the 36-inch (914-mm) thick P154 subbase at the wheel loads of 45,000 lbs (20.4 tonnes) for the first 20,000 passes. As the wheel loading was increased to 65,000 lbs (29.5 tonnes), the accumulation rate of permanent deformation increased significantly in the P209/P154 granular base/subbase layers and in the subgrade soil, as shown in Figure 3.

Since the NAPTF low strength, LFC and LFS, flexible pavement test sections had the thickest granular layers with highest permanent deformation contributions in the pavement structure, they were also deemed the most challenging in permanent deformation predictions and, therefore, utilized for field performance validation and calibration of the permanent deformation models developed in this study.

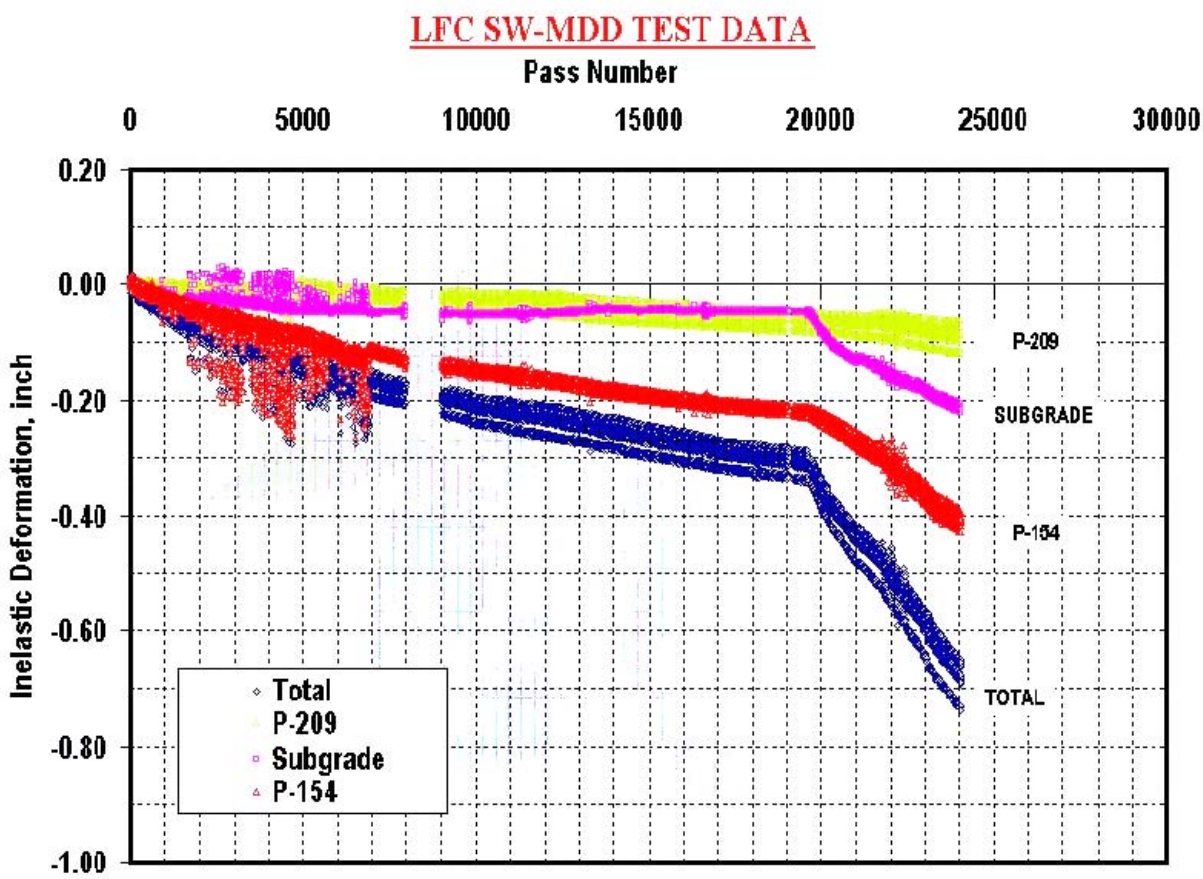


Figure 3 Rutting performance of the low strength conventional LFC test section (after Garg [1])

LABORATORY TEST PROGRAM AND RUTTING MODELS

The FAA specified granular base and subbase materials P209 and P154, both crushed aggregate, were selected for permanent deformation testing using an advanced repeated load triaxial testing device previously introduced and referred to as the UI-FastCell (see Tutumluer and Seyhan [2] and Kim et al. [3]). Figure 4 shows the gradation curves for the P209 and P154 materials. Table 1 reports on the compaction properties, maximum dry densities and optimum moisture contents, determined from modified Proctor (AASHTO T180) testing. The P209 aggregate had a high friction angle of 61.7 degrees with cohesion of 19.2 psi (132 kPa), whereas, the friction angle and cohesion intercept for the P154 subbase material were determined to be 43.9 degrees and 26.4 psi (182 kPa), respectively.

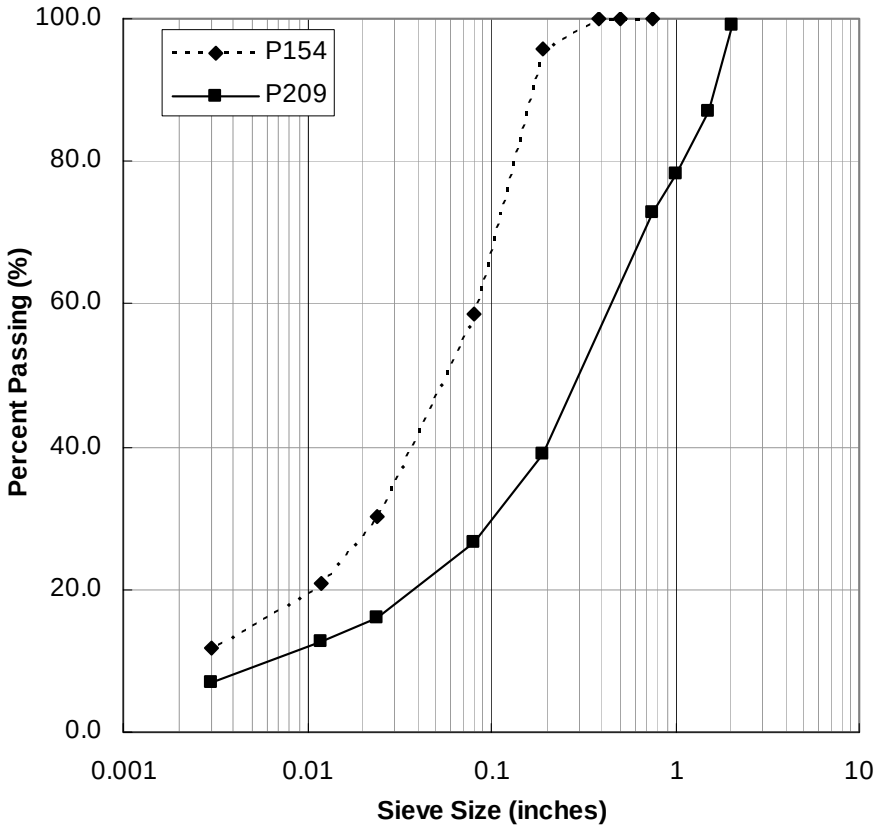


Figure 4 Gradation curves for the P209 and P154 materials

Table 1 The modified Proctor compaction properties for P154 and P209 materials

Materials	**P209**	**P154**
Maximum Dry Density, pcf (kN/m^3)	154.9 (24.2)	128.3 (20.5)
Moisture Content, %	5.1	6.5

The permanent deformation models to be compared for prediction performances were developed from the constant confining pressure (CCP) type tests that consider primarily the implications of the vertical aircraft wheel loads on the P209 and P154 specimens. In the CCP tests, different magnitudes of vertical wheel load stresses are repeatedly applied on laboratory specimens under constant all-around confining pressures [no dynamic stresses are applied in the horizontal directions]. The variable confining pressure (VCP) repeated load triaxial tests, on the other hand, offer much wider loading possibilities by cycling confining pressure in phase with the axial deviator stress to simulate varying dynamic stress states that typically occur in the field

under moving wheel loading. Nonetheless, this paper primarily focuses on the effects of applied stress magnitudes under vertical pulsing [represented by dynamic vertical to static horizontal stress ratios] on the permanent deformation accumulation. The CCP test results, therefore, correspond to the field conditions realized directly under the wheel where the highest applied stress ratios are also experienced in the granular layers and, as a result, the highest vertical permanent deformations are commonly recorded (see Kim et al. [3]).

Table 2 shows the typical stress states used to evaluate the effects of applied stress magnitudes and stress ratios on the permanent deformation accumulation. The permanent deformation accumulation increases as the stress ratio increases and confining pressure decreases as previously reported by Kim et al. [3]. Note that it is required to realistically consider: (1) relatively high stress magnitudes in airport granular layers under heavy aircraft gear loads (heavier than highway load magnitudes) and (2) high stress ratios σ_1/σ_3, where σ_1 is the total vertical stress and σ_3 is the total horizontal stress, acting on a representative pavement element. Kim et al. [3] reported stress ratios as high as $\sigma_1/\sigma_3 = 10$ to occur directly under wheel loading and cause significantly higher permanent deformations than those measured in the conditioning stage of the standard AASHTO T307–99 [4] resilient modulus test procedure, which applies a stress ratio of $\sigma_1/\sigma_3 = 2$ only. In permanent deformation testing, each deviator stress σ_d (= σ_1-σ_3) and confining pressure σ_3 pair, often referred to as a stress state shown in Table 2, was applied on different P209/P154 specimens with the deviator stress σ_d repeatedly pulsed for a total of 10,000 cycles to complete the test for a total of 13 permanent deformation tests conducted for each of the P209 and P154 materials.

Table 2 Permanent deformation test program for the P154 and P209 materials following CCP conditions

Stress Ratio $\sigma_1/\sigma_3 = 4$		Stress Ratio $\sigma_1/\sigma_3 = 6$		Stress Ratio $\sigma_1/\sigma_3 = 8$		Stress Ratio $\sigma_1/\sigma_3 = 10$	
σ_d (psi)	σ_3 (psi)	σ_d (psi)	σ_3 (psi)	σ_d (psi)	σ_3 (psi)	σ_d (psi)	σ_3 (psi)
9	3	14	3	21	3	27	3
15	5	25	5	35	5	45	5
24	8	40	8	56	8	*	*
30	10	50	10	*	*	*	*

* : could not be applied due to high stress states and test equipment limitation.

A permanent strain database, consisting of 3250 stress-strain data sets, was formed for each of the P209 and P154 materials from a total of 13 CCP tests run at 13 stress states. The objective was to develop a model to best describe the permanent deformation behavior of P209 and P154 aggregates with the number of load repetitions and the applied static/dynamic stress states.

Various mathematical forms such as linear, nonlinear, logarithmic, hyperbolic, were investigated using multiple regression analyses. Considering the typical exponential growth of permanent strains with number of load applications (N) in the triaxial tests, the power or logarithmic functions were found to be the most suitable. Four such models studied are listed in Table 3.

Table 3 Permanent strain models developed from P209 and P154 test data*

Materials	**Regression Correlation Coefficient (R^2)**	
	P209	**P154**
Model 1 : $\varepsilon_p = A*\sigma_3^B*N^C$	0.03	0.04
Model 2 : $\varepsilon_p = A*\sigma_d^B*N^C$	0.50	0.42
Model 3 : $\varepsilon_p = A*(\sigma_d/\sigma_d)^B*N^C$	0.62	0.78
Model 4 : $\varepsilon_p = A*\sigma_d^B*\sigma_3^C*N^D$	0.84	0.83

*: A, B, C, and D are model parameters obtained from regression analyses.

Comparing the regression correlation coefficients (R^2s), i.e., the goodness of the statistical fit, obtained for the 4 models developed from the P209 and P154 permanent deformation database, Model 4 was by far the best one giving the highest correlation coefficients. This model properly considered the effects of two independent applied stresses, deviator stress (σ_d) and confining pressure (σ_3), and the number of load repetitions (N). Model 4 was therefore chosen as the most appropriate for predicting permanent deformation accumulation for the P209 and P154 aggregates under various CCP stress states. Table 4 lists the model parameters obtained from regression analyses for Model 4, which was used for predicting the NAPTF P209/P154 base/subbase measured permanent deformations. Note that none of the 4 models given in Table 3 take into account the variable confining pressure (VCP) stress states and the effects of moving wheel loading conditions. For an improved prediction of rutting potential due to the most damaging possible field (compression and extension) stress states, these variable confinement (or horizontal pulsing) effects were recently deemed important to properly consider in permanent deformation model development (see Tutumluer and Kim [5]).

MODEL VALIDATION WITH NAPTF TRAFFICKING DATA

For validating the newly developed CCP models, essentially Model 4, using the NAPTF trafficking field data, individual rut accumulations in the granular layers had to be predicted accurately with the increasing number of load applications (or number of wheel passes). This necessitated the estimation of the most accurate stress distributions in the P209/P154 granular layers to use as input in the permanent deformation models. Two finite element programs, ILLI-PAVE (Raad and Figueroa [6]) and GT-PAVE (Tutumluer [7]), were used to analyze NAPTF LFC and LFS pavement test sections to compute as accurately as possible the field stresses

acting on the P209/P154 granular layers under single wheel loading of the Boeing 777 and 747 gears. Both ILLI-PAVE and GT-PAVE programs consider the nonlinear stress dependent modulus behavior of granular bases and subgrade soils. The ILLI-PAVE and GT-PAVE finite element solutions predicted considerably high granular layer stress states, for example, vertical stresses as high as 74 psi (510 kPa) in the LFC P154 subbase layer under a Boeing 777 single wheel. Note that such high stresses approach closely the strength properties of these unbound aggregate materials, which can explain the excessive shake down and permanent deformations took place in the P209/P154 layers as reported in the NAPTF tracking data.

Table 4 Model parameters obtained for P209 and P154 aggregate materials

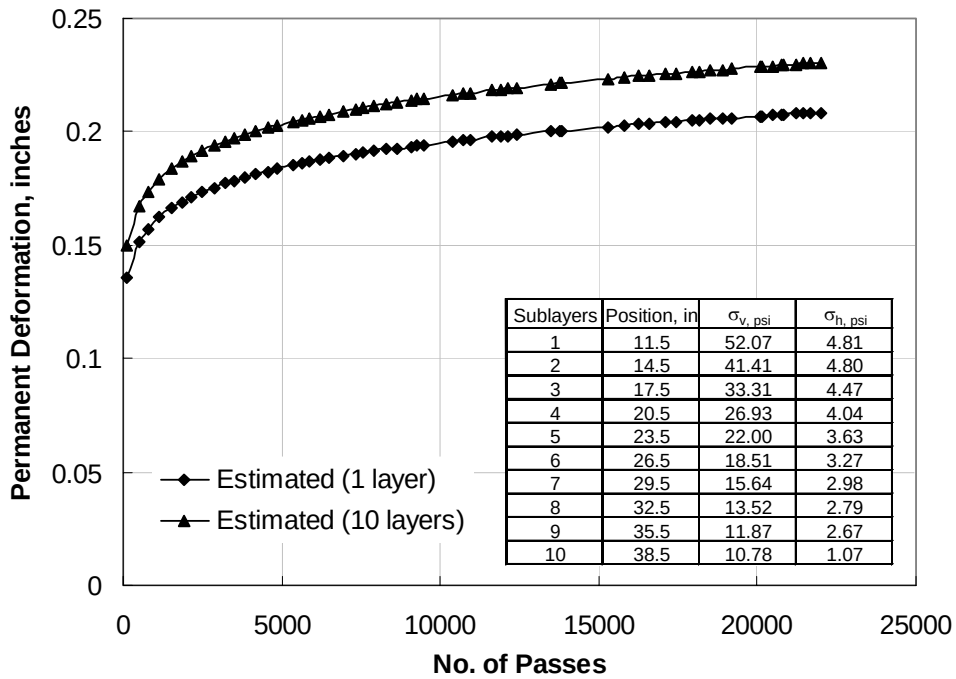
Model Parameters	**Model 4 – P209**	**Model 4 – P154**
A	0.0730	0.0296
B	0.8229	0.9462
C	-0.7389	-0.8031
D	0.0848	0.0665

Two different approaches were taken in utilizing the finite element predictions for the granular layer stress states as inputs to the permanent strain models. In the first approach, an average stress state was estimated at mid-depth of the granular layer and used as an input to the permanent strain models. The predicted permanent strain was then multiplied by the total thickness of the granular layer to compute the total layer permanent deformation. In the second approach, the granular layer was divided into several sublayers and the permanent strain in each sublayer was computed by the model individually using the average stress states predicted at mid-depth of that sublayer. The predicted permanent strain in each sublayer was then multiplied by the thickness of that sublayer. The total granular layer permanent deformation was finally obtained as the summation of all the sublayer deformations.

Figure 5 shows permanent deformations predicted following the two different approaches for the LFS P209 base layer. According to Model 4 given in Table 3, the permanent deformations were predicted as power functions of the number of passes (N) and the stress states (σ_d and σ_3). Figure 5 also presents the P209 sublayer stress states estimated following the second approach in a tabular format. Both the 1-layer and 10-layer (or 10-sublayer) results are somewhat close in predicting similar accumulations of permanent deformation with increasing number of Boeing 777 wheel passes showing only 0.02 in. (0.5 mm) difference in the results at 20,000 passes. For simplicity, only the permanent deformation predictions obtained following the first approach will be presented and compared from here on with the measured rut values of NAPTF granular layers.

Figure 6 compares the NAPTF trafficking field data with the (1-layer) permanent deformation predictions for the LFS pavement P209 base course layer. Although the measured ruts in the P209 granular layer accumulated following an approximately linear trend, due to the

functional form of the model used, the permanent deformation predictions indicate the power function accumulation with the number of passes. It is apparent that the prediction model needs to be revised to reflect this somewhat linear dependency of number of passes for a better modeling of the rut development in the NAPTF granular layers. On the other hand, the measured maximum rut in the P209 layer was predicted rather accurately at around 20,000 passes using the Model 4 power function approximation. After, 20,000 passes, the rate of permanent deformation accumulation increased considerably due to the increase in wheel loading to 65,000 lbs (29.5 tonnes). Note that the permanent deformations were still predicted according to the 45,000-lb (20.4-tonnes) wheel load stress states and, therefore, should not be expected to match the measured ruts after 20,000 passes, as shown in Figure 6.



Sublayers	Position, in	$\sigma_{v,\ psi}$	$\sigma_{h,\ psi}$
1	11.5	52.07	4.81
2	14.5	41.41	4.80
3	17.5	33.31	4.47
4	20.5	26.93	4.04
5	23.5	22.00	3.63
6	26.5	18.51	3.27
7	29.5	15.64	2.98
8	32.5	13.52	2.79
9	35.5	11.87	2.67
10	38.5	10.78	1.07

Figure 5 Rutting predictions for the LFS P209 base layer following two approaches

Figure 7 and 8 compare the NAPTF trafficking field data with the permanent deformations predicted for the LFC pavement P154 subbase and P209 base layers, respectively. Again, the NAPTF measured ruts in both the P154 and P209 granular layers of the LFC pavements accumulated with number of wheel passes following a linear trend rather than the power function curve predicted by Model 4 in Table 3. Nevertheless, the measured maximum granular layer ruts, i.e., the magnitudes of permanent deformation in the P209/P154 layers, were again predicted somewhat accurately at around 20,000 passes using the Model 4 power function approximation. After 20,000 passes, the rate of permanent deformation accumulation increased considerably due to the increase in wheel loading to 65,000 lbs (29.5 tonnes). As a result, the permanent deformations predicted after 20,000 passes using Model 4 do not match the measured ruts, as shown in Figures 7 and 8.

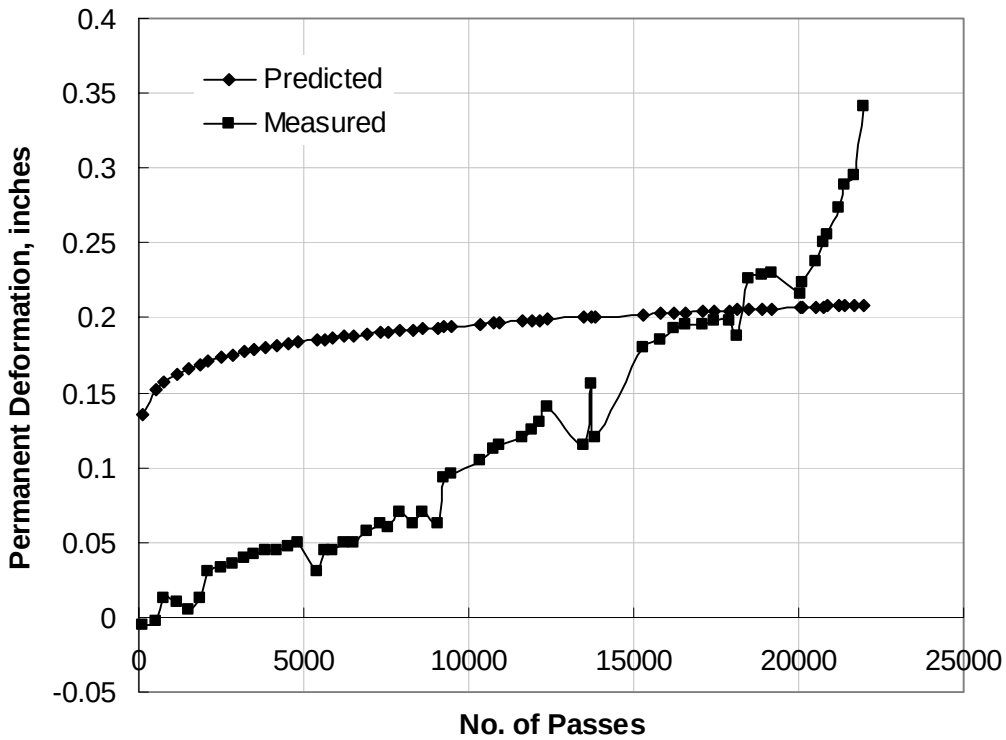


Figure 6 Measured and predicted permanent deformations in the LFS P209 base layer

SUMMARY/CONCLUSIONS

The FAA's National Airport Pavement Test Facility (NAPTF) rutting performance data for the low strength subgrade flexible pavement test sections were utilized to validate permanent deformation models developed for the granular base and subbase layers, designated as P209 base and P154 subbase materials according to FAA's construction specifications. The functional form of the prediction models chosen for rutting performance analysis properly considered the effects of two independent stresses, deviator and confining stresses applied on specimens under constant confining pressure (CCP) type laboratory testing, and the number of load repetitions. The variation of stress states in the NAPTF P209/P154 granular layers under wheel loading and their effects on rut development were adequately entered in the prediction models calibrated with laboratory determined model parameters. Using the models, the maximum rut accumulations were predicted accurately in the P209 and P154 granular layers of the NAPTF low strength pavement test sections at 20,000 wheel passes. In general, the magnitudes of permanent deformations were better predicted than the rates of permanent deformation accumulation with number of load applications. This was primarily due to the fact that the prediction models and their functional forms were developed based on the CCP test data, which only considered vertical repeated traffic loading (vertical pulsing) directly above a pavement element. A better understanding of the field rut development with individual load applications requires considerations of rotating dynamic stress fields (including shear stress reversals) under moving wheels and wander patterns applied in full scale testing.

Current efforts in permanent deformation model development also concentrate on the use of laboratory VCP test data. The important considerations of rotating stress fields (including shear stress reversals) under moving wheels and wander patterns applied in full scale testing can be studied in VCP testing. It is hoped that processing together of both the CCP and VCP type test results will help account for the most damaging field conditions and result in an improved characterization of the granular layer permanent deformation behavior.

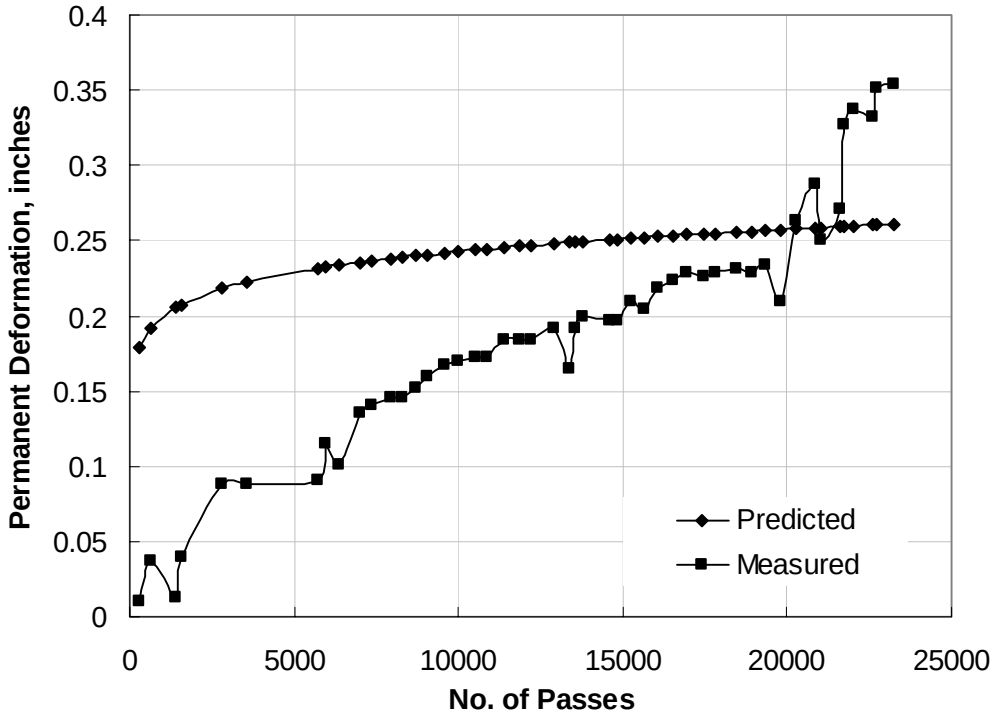


Figure 7 Measured and predicted permanent deformations in the LFC P154 subbase layer

ACKNOWLEDGEMENTS

This paper was prepared from a study conducted in the Center of Excellence for Airport Technology. Funding for the Center of Excellence is provided in part by the Federal Aviation Administration under Research Grant Number 95-C-001. The Center of Excellence is maintained at the University of Illinois at Urbana-Champaign in partnership with Northwestern University and the Federal Aviation Administration. Ms. Patricia Watts is the FAA Program Manager for Air Transportation Centers of Excellence and Dr. Satish Agrawal is the FAA Airport Technology Branch Manager.

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This paper does not constitute a standard, specification, or regulation.

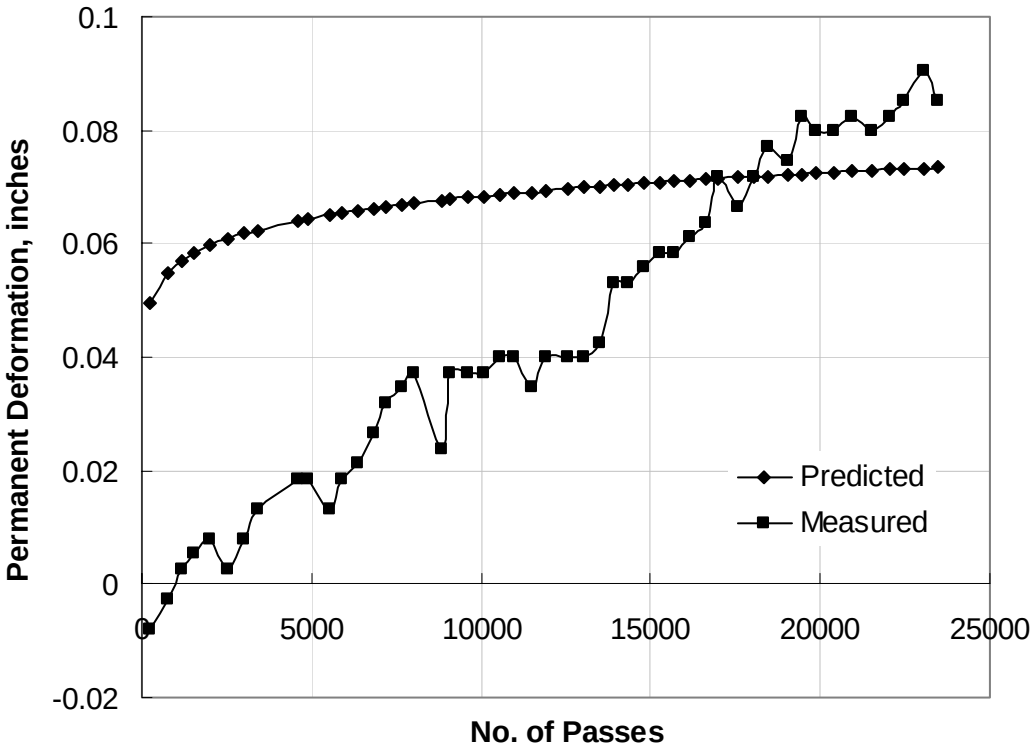


Figure 8 Measured and predicted permanent deformations in the LFC P209 base layer

REFERENCES

1. Garg, N., "Permanent Deformation Behavior of the Granular Layers Tested at the National Airport Pavement Test Facility," (http://www.airtech.tc.faa.gov/NAPTF/Download/) Presented at the 82nd Annual Transportation Research Board Meeting, Washington, D.C., January 14, 2003.

2. Tutumluer, E. and U. Seyhan, "Laboratory Determination of Anisotropic Aggregate Resilient Moduli Using A New Innovative Test Device," Transportation Research Record 1687, Journal of the Transportation Research Board, National Research Council, Washington, D.C., pp. 13-21, 1999.

3. Kim, I.T., Kwon, J., and E. Tutumluer, "Rutting of Airport Pavement Granular Layers," In Proceedings of the 2003 ASCE Airfield Pavement Specialty Conference, Las Vegas, Nevada, USA, 2003.

4. AASHTO T307-99, Determining the resilient modulus of soils and aggregate materials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 20th Edition, AASHTO, Washington D.C., 2000.

5. Tutumluer, E. and I.T. Kim, "Permanent Deformation Behavior of Airport Pavement Granular Layers," In Proceedings of the 3rd International Conference on Deformation Characteristics of Geomaterials (ISLYON03), Lyon, France, September 22-24, 2003; also In "Deformation

Characteristics of Goematerials," Edited by Di Benedetto et al., Swets & Zeitlinger, Lisse, pp. 345-352, 2003.

6. Raad, L., and Figueroa, J. L., "Load Response of Transportation Support Systems," Journal of Transportation Engineering Division, ASCE, Vol. 106, No. TE1, January 1980.

7. Tutumluer, E., "Predicting Behavior of Flexible Pavements with Granular Bases", Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, 1995.