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Evaluation of accelerated deterioration in NAPTF flexible test pavements

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Abstract: Previous research studies have successfully demonstrated the use of artificial neural network (ANN) models for predicting critical structural responses and layer moduli of highway flexible pavements. The primary objective of this study was to develop an ANN-based approach for backcalculation of pavement moduli based on heavy weight deflectometer (HWD) test data, especially in the analysis of airport flexible pavements subjected to new generation aircraft (NGA). Two medium-strength subgrade flexible test sections, at the National Airport Pavement Test Facility (NAPTF), were modeled using a finite element (FE) based pavement analysis program, which can consider the non-linear stress-dependent behavior of pavement geomaterials. A multi-layer, feed-forward network which uses an error-backpropagation algorithm was trained to approximate the HWD backcalculation function using the FE program generated synthetic database. At the NAPTF, test sections were subjected to Boeing 777 (B777) trafficking on one lane and Boeing 747 (B747) trafficking on the other lane using a test machine. To monitor the effect of traffic and climatic variations on pavement structural responses, HWD tests were conducted on the trafficked lanes and on the untrafficked centerline of test sections as trafficking progressed. The trained ANN models were successfully applied on the actual HWD test data acquired at the NAPTF to predict the asphalt concrete moduli and non-linear subgrade moduli of the medium-strength subgrade flexible test sections.

Key words: Airport flexible pavements, Heavy weight deflectometer (HWD), Artificial neural networks (ANN), Elastic moduli, New generation aircraft (NGA)
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INTRODUCTION

The Federal Aviation Administration (FAA)'s National Airport Pavement Test Facility (NAPTF) is located near the Atlantic City International Airport, New Jersey, USA. It was constructed to generate full-scale test data needed to develop pavement design procedures for the new generation of large civil transport aircraft, including the Boeing 777 (B777) and Boeing 747 (B747). During the first series of tests, two gear configurations, a six-wheel dual-tridem landing gear (B777) in one lane and a four-wheel dual-tandem landing gear (B747) in the other lane were tested simultaneously. Non-destructive tests (NDTs) were conducted at regular time intervals as trafficking continued.

The elastic layer moduli backcalculated from NDT results are good indicators of pavement layer condition (Xu *et al*., 2001) as well as required inputs for the a priori mechanistic analysis and design of a flexible pavement. The backcalculation approach is particularly appealing for characterizing subgrade soils, which display large variability in subgrade modulus (as large as 35%~50% over few miles of a pavement) (Thompson *et al*., 1998).

Conventional elastic layer program (ELP) based backcalculation softwares assume that pavement materials are linear-elastic, homogenous and isotropic. The non-linearity or stress-dependency of resilient modulus for unbound granular materials and cohesive fine-grained subgrade soils is well documented in (Hicks, 1970; Thompson and Robnett, 1979). Previous studies have observed the non-linearity of underlying layers at the NAPTF. Gomez-Ramirez and

Thompson (2002) reported the presence of material non-linearity at NAPTF by separately analyzing the individual layer compression from multi-depth deflectometer (MDD) readings. Garg and Marsey (2002) have similarly observed the stress-dependent nature of the granular and subgrade layers in NAPTF flexible test sections. Therefore, it is more realistic to use non-linear layer moduli for conducting NAPTF pavement structural analysis and for studying the variation in moduli with trafficking.

ILLI-PAVE is a 2D axi-symmetric pavement finite element (FE) software developed at the University of Illinois (U of I) at Urbana-Champaign (Raad and Figueroa, 1980). It incorporates stress-sensitive material models and it is considered to provide a more realistic representation of the pavement structure and its response to loading (NCHRP, 1990).

ILLI-PAVE is capable of considering only a single wheel load in contrast to ELPs which are capable of handling multiple wheel loads. Using the pavement response test results from the NAPTF and ILLI-PAVE structural models, Gomez-Ramirez and Thompson (2002) further verified the principle of superposition for six-wheel B777 and four-wheel B747 landing gear configurations. Several studies conducted at the FAA sponsored U of I Center of Excellence for Airport Pavement Technology (Garg *et al*., 1998; Thompson and Garg, 1999) have supported the extension of the ILLI-PAVE approach to multiple-wheel heavy gear load (MWHGL) aircraft.

The primary objective of this study was to develop a neural network based approach for backcalculation of airport flexible pavement moduli based on NDT data in the analysis of pavements serving the new generation aircraft (NGA) such as B777. The reason for using ANN to accomplish this task is that once trained, ANNs offer mathematical solutions that can be easily calculated in real-time on even the basic personal computers, unlike conventional backcalculation programs. Also, ANN can learn a backcalculation function that is based on much more realistic models of pavement response (e.g., ILLI-PAVE) than that is used in traditional-basin matching programs.

In the development of the new mechanistic-empirical pavement design guide for the American Association of State Highway and Transportation Officials (AASHTOs), ANNs have been recognized as nontraditional, yet very powerful computing techniques and were employed in preparing the concrete pavement analysis package of the design guide. Previous research at the U of I successfully demonstrated the use of ANN models for the analysis of concrete pavements serving the B777 aircraft and its applicability for analyzing flexible pavement systems (Ceylan, 2002). Recent studies confirmed the applicability of predicting the critical structural responses and the non-linear moduli of pavement geomaterials using ANN models trained with ILLI-PAVE under typical highway loadings (Ceylan *et al*., 2005).

The current research described in this paper focuses on developing an ANN-based approach for backcalculation of airport flexible pavement layer moduli based on heavy weight deflectometer (HWD) test data. The developed models were validated using actual field data acquired at the NAPTF from two medium-strength subgrade flexible test sections. The results from this study were also compared with those obtained using a conventional ELP-based backcalculation program. Although this was a preliminary study with limited scope specifically targeted towards the backcalculation of pavement layer moduli from HWD data acquired at the NAPTF, the results nonetheless highlight the potential for extending this concept for developing generic ANN-based models which would be useful in the analysis of routine HWD test data collected at flexible airfield pavements. This could be accomplished by training the ANN models developed in this study over a broad range of input values.

NATIONAL AIRPORT PAVEMENT TEST FACILITY

The NAPTF test pavement area is 274.3 m (900 ft) long, 18.3 m (60 ft) wide, and 2.7 m (9 ft) to 3.6 m (12 ft) deep. It has a total of nine test sections (six flexible and three rigid sections) 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). Two different base sections are used in flexible test sections: conventional (granular) and stabilized (asphalt concrete (AC)). The naturally-occurring sandy-soil material at the NAPTF site underlies each subgrade layer.

The two NAPTF flexible test sections considered in this study are designated as follows: (a) MFC—conventional granular base flexible pavement section resting on a medium-strength subgrade, and (b) MFS—asphalt-stabilized base flexible pavement resting on a medium-strength subgrade. The cross-sectional details of the medium-strength flexible test sections are shown in Fig.1.

MFC		MFS	
P-401 AC surface	127 mm	P-401 AC surface	127 mm
P-209 granular base	200 mm	P-401 AC base	127 mm
P-154 granular subbase	307 mm	P-209 granular subbase	216 mm
Medium-strength controlled subgrade	2405 mm	Medium-strength controlled subgrade	2581 mm

Fig.1 NAPTF flexible pavement test sections considered in this study

The items, P-209 (crushed stone), P-154 (grey quarry blend fines) and P-401 AC are as per standard specifications detailed in the FAA Circular No. AC 150/5370-10A. A CL-CH soil classification (ASTM Unified Soil Classification System) material known as DuPont Clay (DPC) was used for the medium-strength subgrade. Note that the P-401 AC was used in the surface layer and in the stabilized base layer as well in the MFS section.

NAPTF TRAFFIC TESTING

The NAPTF was dedicated on 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 (CC1) traffic testing, began in February 2000 and was completed in September 2001.

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 a four-wheel dual-tandem (B747) landing gear having 1118 mm (44 in) dual spacing and 1473 mm (58 in) tandem spacing was loaded on the south side (Lane 5).

The test machine and the gear configurations used during the first round of traffic testing are shown in Fig.2. The wheel loads were set to 20.4 t (45000 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 traveling 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.

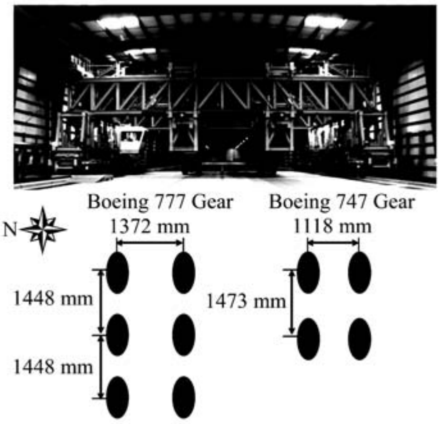

Fig.2 NAPTF traffic test gear configurations

The NAPTF failure criterion was the one established in the US Army Corps of Engineers' MWHGL tests (Ahlvin, 1991). 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.

NON-DESTRUCTIVE TESTS

NDTs using both Falling Weight Deflectometer (FWD) and HWD were conducted on NAPTF flexible pavement test sections at various time.

The FWD test is one of the most widely used tests for assessing the structural integrity of pavement systems in a non-destructive manner and to determine the in-situ moduli of the pavement layers. In the case of airfield pavements, an HWD test, which is similar to an FWD test, but using higher load levels, is used. Many studies have addressed the interpretation of FWD/HWD pavement deflection measurements as a tool to characterize pavement-subgrade systems

(Bush and Baladi, 1989; Tayabji and Lukanen, 2000).

The HWD tests were mainly conducted at the NAPTF to monitor the effect of time and full-scale trafficking on the structural condition of the pavement test sections. To monitor the effect of time and traffic on pavement structural responses, HWD tests were conducted on the trafficked lanes and on the untrafficked centerline of NAPTF flexible test sections at different stages of trafficking. For HWD testing, the FAA HWD equipment configured with a 305 mm (12 in) loading plate and a 27~30 ms pulse width was used.

The FAA HWD equipment has seismometers (for measuring deflections) which utilize a spring for reference and Linear Voltage Differential Transformer (LVDT) for the sensor. The deflections were measured at offsets of 0 mm (D_0), 305 mm (D_1), 610 mm (D_2), 914 mm (D_3), 1219 mm (D_4), and 1524 mm (D_5) intervals from the center of the load.

The HWD tests were performed at nominal force amplitudes of 53 kN (12 kip), 107 kN (24 kip), and 160 kN (36 kip). This paper focuses on the 160 kN HWD test results as they will be more representative of responses obtained under heavy aircraft gear loading. These tests were performed on the untrafficked centerline (C/L), B777 traffic lane and B747 traffic lane at approximately 3.05 m (10 ft) intervals in each flexible test section. The location and orientation of HWD test lanes are illustrated 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/).

GENERATION OF ILLI-PAVE SYNTHETIC DATABASE

The NAPTF flexible test sections were separately modeled as 2D, axisymmetric FE structures using the as-constructed layer thicknesses. The individual pavement layers were characterized as follows.

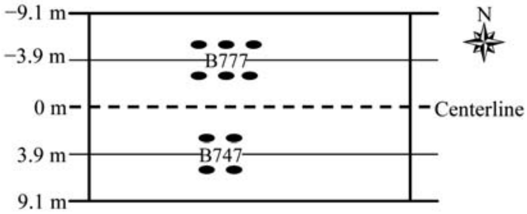

Fig.3 Heavy weight deflectometer (HWD) test lanes

The AC surface layer and the natural sand layer beneath the subgrade were characterized as a linear elastic material. Stress-dependent elastic models along with Mohr-Coulomb failure criteria were applied for the base, subbase and subgrade layers. The stress-hardening K-θ model was used for the base and subbase layers:

$$E_R=\sigma_d/\varepsilon_R=K\theta^n, \tag{1}$$

where E_R is resilient modulus (kPa), θ is bulk stress (kPa), K and n are statistical parameters. It has been shown that an inverse relationship exists between K and n (Rada and Witczak, 1981).

The fine-grained low-strength subgrade was modeled using the bi-linear model (Thompson and Robnett, 1979) for characterizing the resilient modulus:

$$E_R=\begin{cases}E_{Ri}+K_1(\sigma_d-\sigma_{di}), & \sigma_d<\sigma_{di},\\ E_{Ri}+K_2(\sigma_d-\sigma_{di}), & \sigma_d>\sigma_{di},\end{cases} \tag{2}$$

where σ_d is applied deviator stress (kPa), and K_1 and K_2 are statistically determined coefficients from laboratory tests.

The bi-linear model is a commonly used resilient modulus model for subgrade soils. Based on extensive repeated laboratory testing data at the U of I, Thompson and Elliot (1985) indicated that the "breakpoint" resilient modulus (E_{Ri}), typically associated with a repeated deviator stress (σ_{di}) of about 41 kPa (6 psi), is a good indicator of the subgrade soil's resilient modulus.

The effect of 160 kN (36000 lb) HWD loading was simulated in ILLI-PAVE. A total of 5000 datasets were generated for each test section by randomly varying the layer moduli parameters over typical ranges. During the initial phase, it was decided to use separate ANN models for each section. Of the total number of datasets, 3750 data vectors were used in training the ANN and the remaining 1250 data vectors were utilized for testing the network after the training was completed. The ranges of layer properties used in training the ANN are summarized in Table 1.

Table 1 Range of layer properties used in training the ANN

Pavement layer	Thickness (mm)	Layer modulus parameter	Poisson's ratio
P-401 AC	MFC: 127 MFS: 254	690~18000 MPa	0.35
P-209	MFC: 200 MFS: 216	*K*: 11~140 MPa *n*: 0.2~0.8	0.35
P-154	MFC: 307	*K*: 11~140 MPa *n*: 0.2~0.8	0.35
Subgrade	MFC: 2405 MFS: 2581	11~140 MPa	0.45
Local sand	3660	310 MPa	0.40

ANN ARCHITECTURE

A generalized *n*-layer feedforward ANN which uses an error backpropagation (BP) training algorithm (based on gradient-descent optimization technique) (Rumelhart *et al.*, 1986) was implemented. The BP model developed in this study can allow for a general number of inputs, hidden layers, hidden layer elements, and output layer elements. Two hidden layers were found to be sufficient in solving a problem of this size. Therefore the architecture was reduced to a four-layer feedforward network.

A four-layer feedforward network consists of a set of sensory units (source nodes) that constitute an input layer, two hidden layer of computation nodes, and an output layer of computation nodes. The following notation is generally used to refer to a particular type of architecture that has two hidden layers: (# inputs)-(# hidden neurons)-(# hidden neurons)-(# outputs). For example, the notation 10-40-40-3 refers to an ANN architecture that takes in 10 inputs (features), has 2 hidden layers consisting of 40 neurons each, and produces 3 outputs.

An ANN-based backcalculation procedure was developed to approximate the HWD backcalculation function. Using the ILLI-PAVE synthetic database, the ANN was trained to learn the relation between the synthetic deflection basins (inputs) and the pavement layer moduli (outputs). The details of the ANN architecture are presented in (Gopalakrishnan, 2004).

ANN inputs and outputs

Deflection basin parameters (DBPs) derived from FWD/HWD deflection measurements are shown to be good indicators of selected pavement properties and conditions (Hossain and Zaniewski, 1991). Xu *et al.*(2001) used DBPs in developing new relationships between selected pavement layer condition indicators and FWD deflections by applying regression and ANN techniques. Apart from the six independent deflection measurements (D_0 to D_5), some of the commonly used DBPs were included as inputs for training the ANN (Table 2).

Table 2 HWD deflection basin parameters considered in this study

DBP	Formula
Area	$Area=6(D_0+2D_1+2D_2+D_3)/D_0$
Area under pavement profile (AUPP)	$AUPP=(5D_0-2D_1-2D_2-D_3)/2$
Area index (AI)	$AI_4=(D_3+D_4)/(2D_0)$
Base curvature index (BCI)	$BCI=D_2-D_3$ $BCI_2=D_5-D_4$
Base damage index (BDI)	$BDI=D_1-D_2$
Deflection ratio (DR)	$DR=D_1/D_0$

Each DBP supposedly represents the condition of specific pavement layers. For example, AUPP is sensitive to the AC layer properties whereas BCI and AI_4 are expected to reflect the condition of subgrade. The desired outputs from the ANN are: AC modulus (E_{AC}), subgrade modulus (E_{Ri}), base modulus parameter (K_b or n_b) and subbase modulus parameter (K_s or n_s). Note that by predicting either K or n, the other parameters can be determined using the relation proposed by Rada and Witczak (1981).

Prediction of pavement moduli using best-performance ANN models

Separate ANN models were used for each desired output rather than using the same architecture to determine all the outputs together. The most effective set of input features for each ANN model was determined based on both engineering judgment and past experience gained through research studies conducted at the U of I. Parametric analyses were performed by systematically varying the choice and number of inputs and number of hidden neurons to identify the best-performance networks.

A summary of the sensitivity analyses performed to select the best-performance networks for predicting AC modulus (E_{AC}) and subgrade modulus (E_{Ri}) in NAPTF test sections are shown in Table 3. Note that the ANN inputs are similar for both test sections. In general, the testing root mean square errors (RMSEs) for the two output variables were slightly lower than the training ones. In Fig.4, the ANN-predicted pavement layer moduli values and the ILLI-PAVE target values are compared using the 1250 test data vectors. Due to space constraints, results are displayed only for the MFS test section. Similar results were obtained for the MFC section (Gopalakrishnan, 2004). Average absolute errors (AAEs), calculated as sum of the individual absolute errors divided by the 1250 independent testing patterns, are also shown in Fig.4. Excellent agreement is found between the predicted and target values for both AC modulus E_{AC} and subgrade modulus E_{Ri}. However, the base and subbase modulus parameters could not be predicted with reasonable accuracy and therefore the results are omitted from further discussion.

Table 3 Best-performance ANN moduli prediction models

NAPTF section	Output	Inputs	Network architecture	Training RMSE	Testing RMSE
MFC	E_{AC}	D_0 to D_5	6-40-40-1	0.49 GPa	0.47 GPa
	E_{Ri}	D_0 to D_5, BCI, AI_4	8-40-40-1	5.90 MPa	5.60 MPa
MFS	E_{AC}	D_0 to D_5	6-40-40-1	4.70 GPa	4.60 GPa
	E_{Ri}	D_0 to D_5, BCI, AI_4	8-40-40-1	5.60 MPa	5.40 MPa

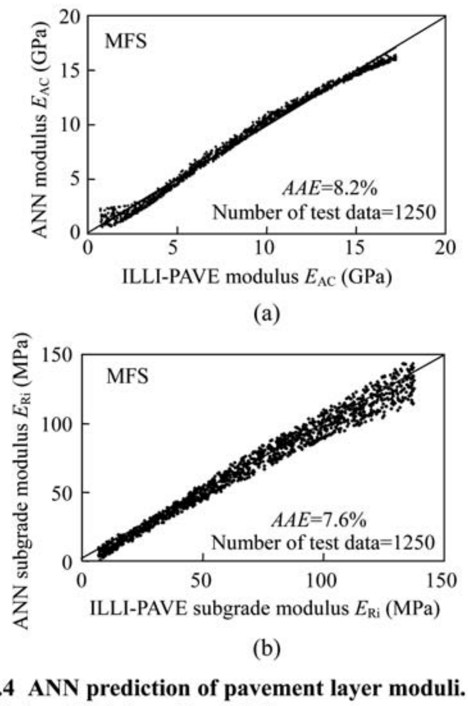

Fig.4 ANN prediction of pavement layer moduli. (a) AC modulus; (b) Subgrade modulus

One of the major reasons for developing this ANN-based moduli backcalculation procedure is to reliably evaluate the structural integrity of the NAPTF pavement test sections as they were subjected to traffic loading. The NAPTF test sections were subjected to trafficking until they exhibited failure (i.e., until they exhibited 25.4 mm surface upheaval adjacent to the traffic lane).

Performance of ANN models using NAPTF field data

To study the loss of stiffness in NAPTF flexible pavement sections resulting from trafficking, the AC and subgrade layer moduli values were backcalculated from the 160 kN (36 kip) HWD data acquired at the NAPTF using the ANN prediction models developed in this study.

The ANN predicted results were then compared with those obtained using a conventional modulus backcalculation program, BAKFAA (previously known as FAABACKCAL) which assumes the pavement materials to be linear elastic. The BAKFAA was developed under the sponsorship of the FAA Airport Technology Branch and is based on the Layered Elastic Analysis program (LEAF) layered elastic computation program (Hayhoe, 2002). In this program, the pavement layer moduli are adjusted to minimize the root mean square (RMS) of the differences between FWD/HWD sensor measurements and the LEAF-computed deflection basin for a specified pavement structure. A standard multidimensional simplex optimization routine is then used to adjust the moduli values (McQueen *et al*., 2001). The detailed backcalculation results for NAPTF sections using the BAKFAA are reported in (Gopalakrishnan, 2004).

Note that the 160 kN (36 kip) HWD testing was performed at different stages during the trafficking on B777 traffic lane, B747 traffic lane and the untrafficked centerline (C/L) of the test pavement (Fig.3). It is reasonable to assume that the variation in moduli values in the C/L is mainly due to climatic effects. Thus, the changes in AC and subgrade moduli values in the traffic lanes can be compared to the corresponding C/L values and the degree of structural deterioration induced by B777 trafficking and B747 trafficking can be assessed.

During NAPTF construction, static temperature sensors were installed at different depths along the test sections to record the pavement temperatures at different time of the day. The temperature gages (TGs) were placed at 13 mm (0.5 in), 64 mm (2.5 in), and 114 mm (4.5 in) below the AC surface.

The seasonal variations in average daily pavement temperatures computed per depth during traffic testing were analyzed. The temperature measurements indicated that the temperatures in the AC layer showed no significant variation with respect to depth (Gopalakrishnan, 2004). It should be noted that the NAPTF is an indoor testing facility. The variations in AC layer mid-depth temperatures in the MFC and MFS test sections during NAPTF traffic testing are plotted against the number of load repetitions (*N*) in Fig.5.

The variations in ANN predicted AC moduli (E_{AC}) values with the number of traffic load repetitions (*N*) are displayed in Fig.6 for MFC and MFS test sections. Note that the changes in E_{AC} values in the untrafficked C/L are mainly due to the changes in the AC temperature. As expected, E_{AC} is significantly influenced by changes in AC temperature. In the MFC test section, the B747 traffic lane E_{AC} values are consistently lower than those obtained from the B777 traffic lane indicating the relative severity effects. Note that at around 3000 traffic load repetitions, the E_{AC} for the untrafficked C/L is 12 GPa, while it is 6.8 GPa (57% of C/L value) for the B777 traffic lane and 2.9 GPa (24% of C/L value) for the B747 traffic lane. In the laboratory fatigue testing of AC specimens in constant strain mode, failure has been widely defined as 50% reduction in the initial stiffness (Ghuzlan, 2001). Sharp and Johnson-Clarke (1997) suggested that a pavement may be considered to be failed when moduli are reduced by more than 50%.

A longitudinal crack was observed on the B747 side at around 3000 passes. A crack on the B777 side of the pavement was observed close to 4500 passes. Although, the pavement temperature has decreased from 12.2 °C (at 931 passes) to 11.1 °C (at 3000 passes), the E_{AC} values, instead of showing an increase, have decreased significantly in both the traffic lanes indicating loss of stiffness resulting from trafficking.

In the MFS test section, the backcalculated E_{AC} values are strongly correlated with the pavement temperature. The C/L values and the traffic lane values remain close to each other throughout the trafficking.

The effect of trafficking on ANN backcalculated subgrade modulus values (E_{Ri}) is captured in Fig.7 for MFC and MFS sections. In the MFC section, the E_{Ri} value is 120 MPa during the early stages of trafficking, but consistently decreases during trafficking and reaches a value of 93 MPa at 12952 passes (point of termination of trafficking on MFC section). The traffic lane E_{Ri} values are scattered around the C/L values, but are close to each other. In the MFS test section, the E_{Ri} values are close to 105 MPa throughout the trafficking in both the trafficked lanes as well as in the untrafficked centerline.

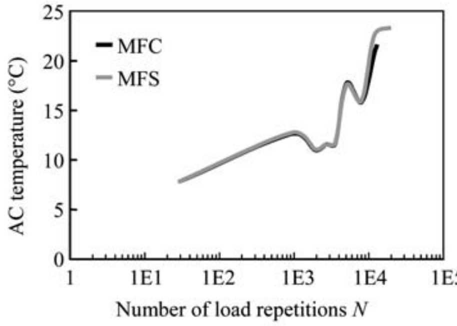

Fig.5 Variations in pavement temperature during NAPTF trafficking

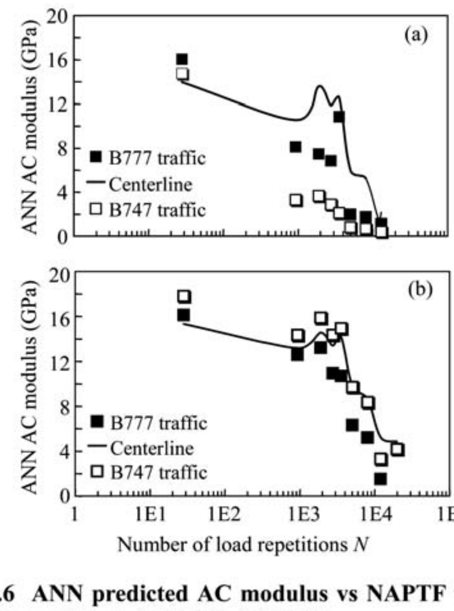

Fig.6 ANN predicted AC modulus vs NAPTF traffic load repetitions. (a) MFC; (b) MFS

The NAPTF rutting study results showed that, in general, the mean rut depths between the B777 traffic lane and B747 traffic lane do not differ significantly throughout the trafficking (Gopalakrishnan, 2004). The post-traffic trench investigations revealed that both the subgrade and the subbase layers contributed to the total pavement rutting in both the MFC and MFS test sections (Hayhoe and Garg, 2003).

The comparison between the ANN predicted moduli values and BAKFAA backcalculated moduli values are presented in Fig.8 for AC modulus and subgrade modulus. It should be noted that the rut depths in the NAPTF flexible test sections reached significant levels (76 mm to 102 mm) towards the end of traffic testing and therefore the HWD test results and hence the backcalculated moduli values showed significant variability during the final stages of traffic testing (Gopalakrishnan, 2004).

It is seen that the ANN predicted E_{AC} values are consistently higher than the BAKFAA values in the MFS test section, whereas the opposite is true in the MFC test section. Similarly, there are variations between the ANN predicted subgrade modulus values and the BAKFAA computed values. Note that the ANN model predicts the non-linear stress-dependent subgrade resilient modulus, E_{Ri}, whereas the subgrade modulus backcalculated by BAKFAA is based on the assumption that the subgrade soils are linear elastic. The differences in results between the two methodologies could also be attributed to the pavement structural model used in response computations. BAKFAA uses the FAA LEAF multi-layered elastic analysis program whereas the ILLI-PAVE FE based program models the pavement as a 2D axisymmetric solid of revolution and employs nonlinear stress-dependent models and failure criteria for granular materials and fine-grained soils.

It is expected that the prediction of stress-dependent E_{Ri} would improve if multiple HWD load levels (53, 107 and 160 kN) are used in the generation of ILLI-PAVE synthetic database and in the development of the ANN algorithms. The stress-dependent elastic moduli of the unbound base/subbase pavement layers could not be successfully predicted using the

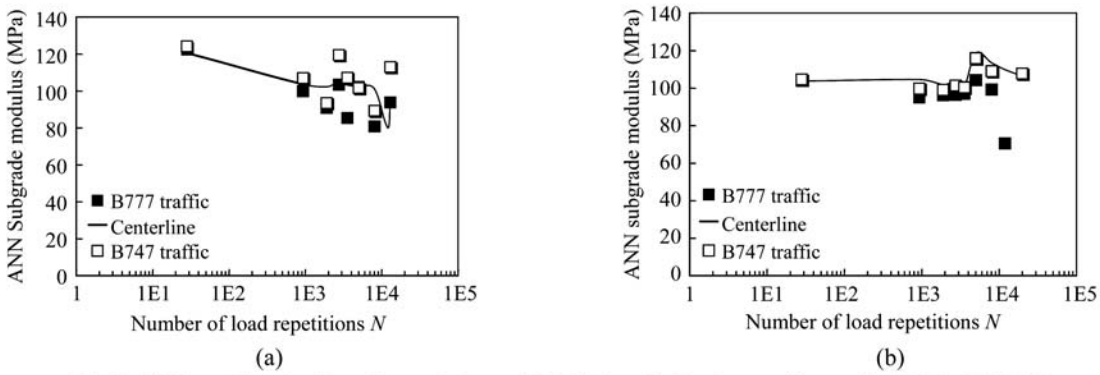

Fig.7 ANN predicted subgrade modulus vs NAPTF traffic load repetitions. (a) MFC; (b) MFS

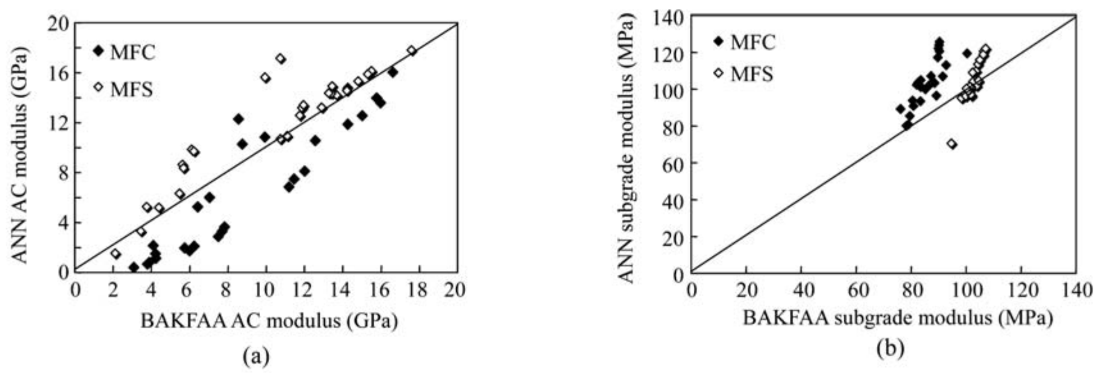

Fig.8 ANN predictions compared with conventional backcalculation program results. (a) AC modulus; (b) Subgrade modulus

ANN approach in this study. Further research is needed to develop robust ANN models for predicting base/subbase moduli parameters. It is proposed that by including the ANN-predicted E_{AC} and E_{Ri} values as inputs to the ANN, the chances of accurately predicting base/subbase moduli will increase. Also, the robustness of the ANN can be improved by incorporating noise in the training datasets as demonstrated by other recent studies (Meier and Rix, 1995; Meier *et al*., 1997; Pekcan *et al*., 2006).

DISCUSSION AND CONCLUSION

The HWD test is one of the most widely used tests for assessing the structural integrity of airport pavements in a non-destructive manner. The elastic moduli of the individual pavement layers, backcalculated from the HWD test data, are effective indicators of layer condition as well as required inputs to mechanistic-based analysis and design of pavements. The ELP based backcalculation programs do not account for the stress-dependency of unbound granular materials (used in the base and subbase layers) and fine-grained cohesive soils (used in the subgrade layer) and therefore do not produce realistic results.

In this study, an ANN-based approach was developed for backcalculation of pavement moduli based on HWD test data, especially in the analysis of airport flexible pavements subjected to NGA. An FE pavement analysis software which can account for the non-linear stress-dependent behavior of the unbound granular and subgrade layers was used to model two medium-strength flexible test sections at the NAPTF and generate the training and testing datasets for the ANN development.

The developed ANN-based backcalculation models successfully predicted AC and non-linear subgrade moduli. However, the unbound base/subbase layer moduli could not be predicted with reasonable accuracy. The ANN-based pavement moduli prediction models were applied to actual HWD data acquired during NAPTF trafficking and the results were consistent. Although this was a preliminary study with limited scope specifically targeted towards the backcalculation of pavement layer moduli from HWD data acquired at the NAPTF, the results nonetheless highlight the potential for extending this concept for developing generic ANN-based models which would be useful in the analysis of routine HWD test data collected at flexible airfield pavements. This could be accomplished by training the ANN models developed in this study over a broad range of input values and by incorporating noise in the ANN training process.

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