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Neural networks based concrete airfield pavement layer moduli backcalculation

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Abstract

The Heavy Weight Deflectometer (HWD) is a Non-Destructive Test (NDT) equipment used to assess the structural condition of airfield pavement systems. This paper presents an Artificial Neural Networks (ANN) based approach for non-destructively estimating the stiffness properties of rigid airfield pavements subjected to full-scale dynamic traffic testing using simulated new generation aircraft gears. HWD tests were routinely conducted on three Portland Cement Concrete (PCC) test items at the Federal Aviation Administration's (FAA) National Airport Pavement Test Facility (NAPTF) to verify the uniformity of the test pavement structures and to measure pavement responses during full-scale traffic testing. Substantial corner cracking occurred in all three of the rigid pavement test items after 28 passes of traffic had been completed. Trafficking continued until the rigid items were deemed failed. The study findings illustrate the potential of ANN-based models for routine and real-time structural evaluation of rigid pavement NDT data.

Keywords

concrete pavements, finite elements, neural networks, new generation aircraft, pavement layer moduli backcalculation

Disciplines

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Comments

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Neural Networks Based Concrete Airfield Pavement Layer Moduli Backcalculation

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ABSTRACT

The Heavy Weight Deflectometer (HWD) is a Nondestructive Test (NDT) equipment used to assess the structural condition of airfield pavement systems. This paper presents an Artificial Neural Networks (ANN) based approach for nondestructively estimating the stiffness properties of rigid airfield pavements subjected to full-scale dynamic traffic testing using simulated new generation aircraft gears. HWD tests were routinely conducted on three Portland Cement Concrete (PCC) test items at the Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF) to verify the uniformity of the test pavement structures and to measure pavement responses during full-scale traffic testing. Substantial corner cracking occurred in all three of the rigid pavement test items after 28 passes of traffic had been completed. Trafficking continued until the rigid items were deemed failed. The study findings illustrate the potential of ANN based models for routine and real-time structural evaluation of rigid pavement NDT data.

Key words: Neural networks, pavement moduli backcalculation, finite elements, new generation aircraft, concrete pavements.

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Introduction

The National Airport Pavement Test Facility (NAPTF) is located at the Federal Aviation Administration's (FAA) William J. Hughes Technical Center near Atlantic City International Airport, New Jersey, USA. It was constructed to support the development of advanced mechanistic-based airport pavement design procedures based on sound theoretical principles and with models verified from appropriate full-scale test data. The advanced design procedures will take advantage of emerging computational abilities that offer the ability to analyze complex pavement structures and flexibility to evaluate the effects of complex gear configurations under both traffic and environmental loads.

Similar experimental efforts are being carried out under the Airbus A-380 Pavement Experimental Program at Toulouse, France to provide comparative experimental data between different aircraft landing gears, considering especially the Airbus A-380, and to provide full-scale data towards a better understanding of airport pavement behavior (Fabre et al. 2004).

The NAPTF is a fully enclosed state-of-the-art full-scale test facility. The first series of test pavements, referred to as Construction Cycle 1 (CC-1), consisted of nine instrumented test pavements (six flexible and three rigid) that were 18.3 m (60 ft) wide and total 274.3 m (900 ft) in length. The nine test pavements were 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). This study focuses on the rigid pavement sections.

Supported on rails on either side, a specially designed test vehicle can apply loads of up to 34,020 kg (75,000 lb) per wheel on two landing gears with up to six wheels per gear and is programmed for a controlled aircraft wander simulation. There are 1,050 sensors installed in the pavement test items recording environmental and dynamic pavement responses in support of NAPTF operations. Data is acquired, processed, stored, and disseminated from the individual sensors using three data collection systems interconnected by wire and wireless local area networks (Tuebert et al. 2002).

During the first series of traffic tests, a six-wheel landing gear (simulative of Boeing 777 [B777] landing gear) in one lane and a four-wheel landing gear (simulative of Boeing 747 [B747] landing gear) in the other lane were trafficked simultaneously until the test pavements were deemed failed. Non-Destructive Tests (NDTs) using both Falling Weight Deflectometer (FWD) and Heavy Weight Deflectometer (HWD) were conducted to document the uniformity of pavement and subgrade construction as well as to monitor the effect of full-scale trafficking on pavement response and performance over time. This paper focuses on analyzing the rigid pavement NDT data.

Rigid Pavement Test Sections

During the first construction cycle (CC-1), a total of forty-five, 6 x 6 m (20 x 20 ft) Portland Cement Concrete (PCC) slabs were placed in three rigid pavement test items as part of the overall test pavement at the NAPTF. Each NAPTF test section is identified using a three-character code, where the first character indicates the subgrade strength (L for low, M for medium, and H for high), the second character indicates the test pavement type (F for flexible and R for rigid), and third character signifies whether the base

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material is conventional (C) or stabilized (S). The three rigid pavement sections are designated as follows: (a) LRS – rigid pavement with stabilized base over low-strength subgrade, (b) MRS – rigid pavement with stabilized base over medium-strength subgrade, and (c) HRS – rigid pavement with stabilized base over high-strength subgrade.

Cross-sections of the as-constructed PCC test pavements are presented in Fig. 1. The items P-501 (PCC), P-306 (Econocrete), and P-154 (granular subbase) are as per standard specifications detailed in the FAA Advisory Circular No. AC 150/5370-10A. A MH-CH soil classification (ASTM Unified Soil Classification System) material known as County Sand and Stone Clay (CSSC) was used for the low-strength subgrade while Dupont Clay (DPC) (CL-CH soil classification) 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 gradation information as well as the laboratory compaction properties for the subgrade soils and P-154 subbase (called as Grey Quarry Blend Fines) are summarized elsewhere (Hayhoe and Garg, 2001).

LRS		MRS		HRS	
P-501 PCC	280 mm	P-501 PCC	248 mm	P-501 PCC	229 mm
P-306 Econocrete	156 mm	P-306 Econocrete	149 mm	P-306 Econocrete	152 mm
P-154 granular subbase	213 cm	P-154 granular subbase	219 cm	P-154 granular subbase	168 cm
LOW strength controlled subgrade (CBR = 3-4)		MEDIUM strength controlled subgrade (CBR = 7-8)		HIGH strength controlled subgrade (CBR = 30-40)	

Fig. 1. Cross-sections of NAPTF rigid test items.

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 CC-1 traffic testing, began in February 2000 and was completed in September 2001. During CC-1 traffic testing, a simulated B777 landing gear, with 1,372-mm (54-in) dual spacing and 1,448-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 1,118-mm (44-in) dual spacing and 1,473-mm (58-in) tandem spacing.

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 metric tons (45,000 lbs)

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each and the tire pressure was 1,295 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 NAPTF traffic testing. For rigid pavement test sections, failure was defined in terms of structural cracking initiating at the joints at the bottom of the PCC layer (McQueen et al. 2002).

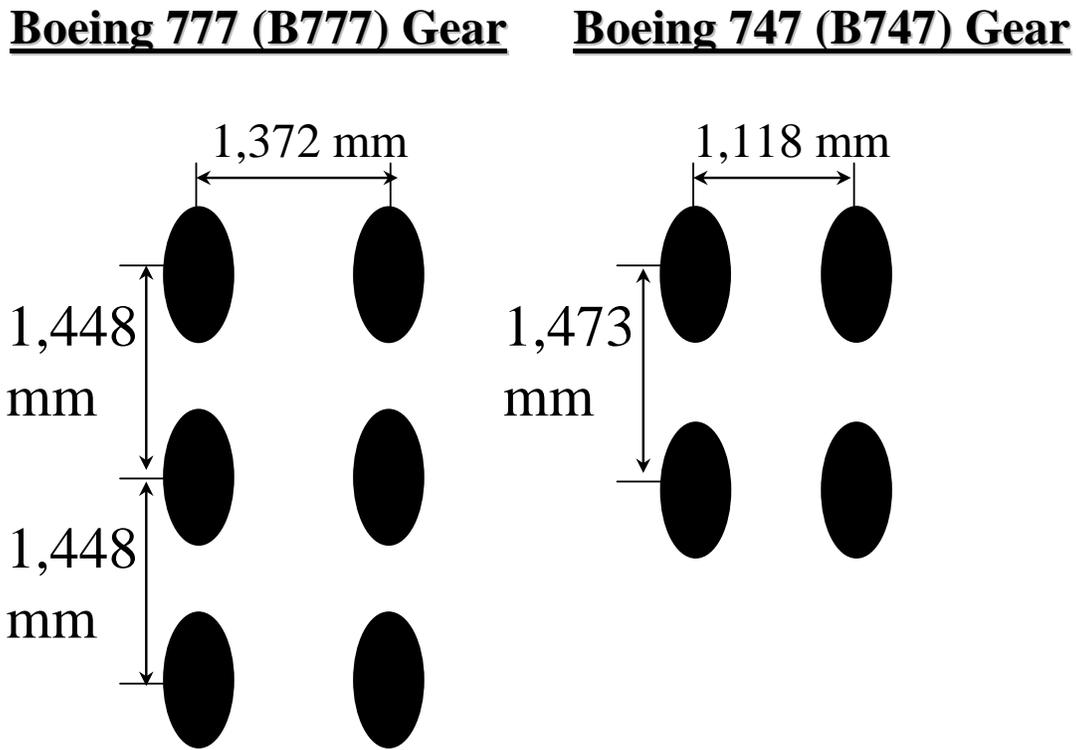


Fig. 2. NAPTF traffic test gear configuration details.

Non-Destructive Testing

Non-Destructive Tests (NDTs) using both FWD and HWD were conducted on NAPTF rigid pavement test sections at various times. The FWD tests are commonly used to assess the structural integrity of highway/airport pavements in a nondestructive manner. There are many advantages to using FWD/HWD tests, in lieu of, or supplement traditional destructive tests for pavement structural evaluation. 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. Without FWD/HWD, structural data must be obtained from numerous cores, borings, and excavation pits on an existing airport pavement. This can be very disruptive to airport operations. FWD/HWD tests are economical to perform and data can be collected at up to 250 locations per day. The

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FWD/HWD equipment measures pavement surface deflections from an applied dynamic load that simulates a moving wheel (FAA 2004).

The deflection data that are collected with the FWD/HWD equipment can provide both qualitative and quantitative data about the strength of a pavement at the time of testing (FAA 2004). Many studies have addressed the interpretation of pavement deflection measurements as a tool to characterize pavement-subgrade systems, with many of the main findings appearing in American Society for Testing and Materials (ASTM) special technical publications, including Bush and Baladi (1989) and Tayabji and Lukanen (2000). A picture of FWD equipment mounted behind a van is shown in Fig. 3.



Fig. 3. Picture of FWD equipment.

The FAA HWD equipment has seismometers (for measuring deflections) which utilize a spring for reference and Linear Variable 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. There is also an additional sensor placed 305-mm (12-in) in front of the load plate (D_{-1}). This arrangement of one sensor (D_{-1}) located in front of the loading plate makes it easy to obtain the load transfer in both directions at a joint. Note that the same sensor locations were used for FWD tests.

The HWD tests were conducted at nominal force amplitudes of 53.4-kN (12,000-lb), 106.7-kN (24,000-lb), and 160-kN (36,000-lb). The FWD/HWD test locations which are of interest in this study (slab center locations) are shown in Fig. 4. Note that LANE 1 was trafficked by six-wheel B777 gear loading while LANE 3 was trafficked by four-wheel B747 gear loading. LANE 2 was untrafficked. The same set of FWD/HWD testing points were used in all three rigid pavement sections.

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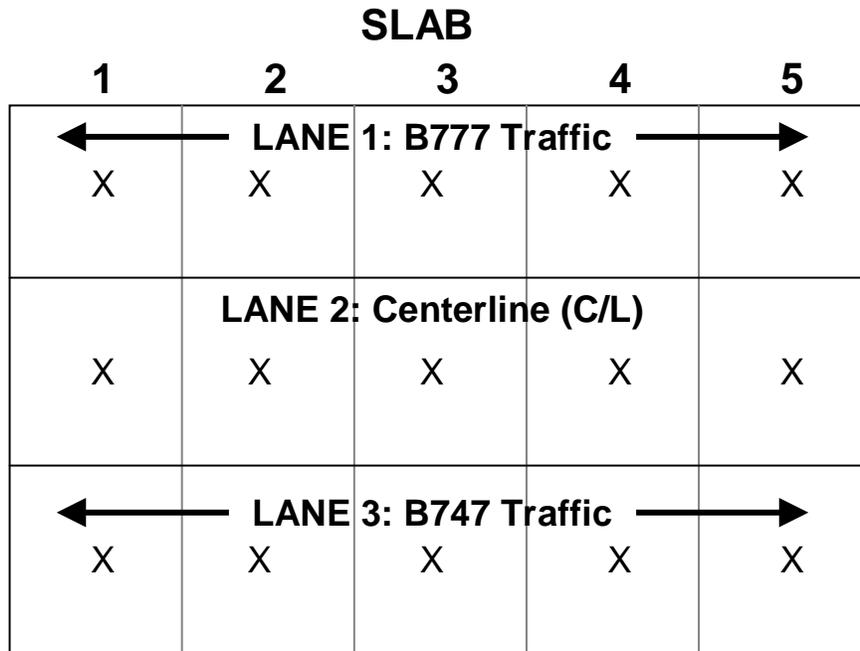


Fig. 4. NDT slab center test locations.

Guo and Marsey (2001) analyzed the results from FWD/HWD tests conducted on rigid test items between summer and winter of 1999 to investigate the slab curling behavior at NAPTF. The analysis of the FWD/HWD test data indicated that the measured deflections at the center of slabs remained almost the same but at the joints and corners, the measurements varied significantly. In wintertime, the deflections at the joints and corners were significantly larger than those measured in the summer. In addition, the joint load transfer capability was lower in winter. A stronger nonlinear relationship between corner deflections and loads was also observed in the wintertime. The test data also showed that the sum of deflections (SD) on two sides of a joint is almost independent to the load transfer capability defined by the ratio between deflections on the unloaded and loaded sides. The current study primarily focuses on analyzing the center slab HWD test data acquired during the traffic testing.

ANN Based Backcalculation Methodology

The elastic modulus of the slab, E , and modulus of subgrade reaction, k , are the two most important backcalculated concrete pavement properties. Over the years, researchers have developed many different methodologies for backcalculation of concrete pavement properties from NDT measurements, including the AREA method for rigid pavements (Ioannides et al. 1989, Ioannides 1990, and Barenberg and Petros 1991), ILLI-BACK (Ioannides 1994), graphical solution using ILLI-SLAB (Foxworthy and Darter 1989), use of regression analysis to solve AREA method for rigid pavements (Hall 1992 and Hall et al. 1996), use of best fit algorithm to find radius of relative stiffness (l) (Hall et al. 1996 and Smith et al. 1996), among others.

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Based on a backcalculation study of concrete pavement properties using 277 deflection basins obtained from the Denver International Airport (DIA), Rufino et al. (2002) studied the effect of slab modeling (number of layers, interface condition, and model type) as well as effect of different methodologies and sensor configurations on backcalculated pavement properties. It was found that backcalculated slab modulus of elasticity (E) is lower on average when the pavement layers on top of subgrade are bonded versus unbonded interface. Higher backcalculated k-values are obtained when the slab is modeled as plate compared to modeling the slab as elastic layer. Modeling of the slab and base as elastic layers seem to yield more reasonable backcalculated results since the interface bonding condition can be reflected both in the backcalculated slab elastic modulus and subgrade k-value.

In the current study, an Artificial Neural Network (ANN) based methodology was developed for rapid and accurate prediction of backcalculated concrete pavement properties from realistic FWD/HWD deflection basins acquired at the NAPTF during the first series of traffic tests (CC1 traffic testing). ANNs are valuable computational tools that are increasingly being used to solve resource-intensive complex problems as an alternative to using more traditional techniques. Ceylan (2002) employed ANNs in the analysis of concrete pavement systems and developed ANN-based design tools that incorporated the ISLAB 2000 (Tabatabaie and Barenberg 1978, Khazanovich 1994, and Khazanovich et al. 2000) finite element solutions into routine practical design at several orders of magnitude faster than ISLAB 2000.

Khazanovich and Roesler (1997) developed a program called DIPLOBACK for backcalculation of moduli values of composite pavements based on ANNs. ANNs have also been applied along with dimensional analysis to backcalculate joint properties from FWD testing (Ioannides et al. 1996). In the development of the new Mechanistic-Empirical Pavement Design Guide (MEPDG) for the American Association of State Highway and Transportation Officials (AASHTO), ANNs were recognized as nontraditional, yet very powerful computing techniques and ANN models were used in preparing the concrete pavement analysis package.

A multilayer perceptron feed-forward neural network which uses *backpropagation* algorithm, referred to as backpropagation ANN model in this study, was trained with results from the ISLAB 2000 finite element program and was used as an analysis tool for backcalculating concrete pavement properties from deflection profiles. Backpropagation ANNs are very powerful and versatile networks that can be taught a mapping from one data space to another using example of the mapping to be learned. The term "backpropagation network" actually refers to a multi-layered; feed-forward neural network trained using an error backpropagation algorithm. The learning process performed by this algorithm is called "backpropagation learning" which is mainly an "error minimization technique" (Haykin 1999). Backpropagation networks excel at data modelling with their superior function approximation capabilities (Haykin 1999).

A total of 41,106 data vectors generated by modeling slab-on-grade concrete pavement systems using ISLAB 2000 were used for ANN training and testing. Concrete pavements analyzed in this study were represented by a six-slab assembly, each slab having dimensions of 6.1 m by 6.1 m (20 ft by 20 ft). The dense liquid model, proposed by Winkler (1867), was used to characterize the subgrade behavior. To maintain the same level of accuracy in the results from all analyses, a standard ISLAB 2000 finite element

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mesh was constructed for the slab. This mesh consisted of 10,004 elements with 10,209 nodes.

The ISLAB 2000 solutions database was generated by varying E , k and thickness of PCC (h_{pcc}) over a range of values representative of realistic variations in the field. The E ranged from 6.9 to 103.4 GPa (1,000 to 15,000 ksi); k ranged from 13.6 to 217 MPa/m (50 to 800 psi/in); and h_{pcc} ranged from 152 to 635 mm (6 to 25 in) considering that most design thicknesses would be in this range. A Poisson's ratio (μ) of 0.15 was assumed for PCC. Thus a total of 41,106 ISLAB 2000 analyses (51 different values of $E \times 31$ different values of $k \times 26$ different values of h_{pcc}) conducted to represent a complete factorial of all the input values.

The ISLAB 2000 solutions database was first portioned to create a training set of 39,106 patterns (95 %) and an independent testing set of 2,000 patterns (5 %) to check the performance of the trained ANN models. In order for the network weights to compare the features to one another more easily, it is generally desirable to reduce each feature in the data set to zero mean and an approximately equal variance, usually unity. But, in this case, as the data was well controlled, all the features were reduced to similar orders of magnitude. Also, it is crucial that the training and test data both represent sampling from the same statistical distribution, which is also taken care of in this study. After doing a comprehensive parametric analysis, a network with two hidden layers was exclusively chosen for the ANN models trained in this study. Also, satisfactory results were obtained in the previous studies with these types of networks due to their ability to better facilitate the nonlinear functional mapping (Ceylan 2002, Ceylan et al. 2005).

A range of (-0.2, +0.2) was used for random initialization of all synaptic weight vectors in the network with a bias. For this problem, the *sigmoidal* function was chosen as the nonlinear activation function at the output end of all hidden neurons. Since, the final outputs (layer moduli) are real values rather than binary outputs, a *linear combiner* model was used for neurons in the output layer, thus omitting the nonlinear activation function. A smooth learning curve was achieved with a learning-rate parameter of 0.5 and a momentum of 0.5.

Separate ANN models were used for predicting each of the backcalculated concrete pavement properties, modulus of subgrade reaction (k) and slab modulus of elasticity (E). Two different ANN backcalculation models were designed by varying the input vectors for each of the outputs. For the first backcalculation model (BCM-6DEF- k), training and testing sets had seven input parameters of D_0 , D_{12} , D_{24} , D_{36} , D_{48} , D_{60} , and h_{pcc} and one output variable of k . The second backcalculation model (BCM-4DEF- k) had the same output variable (k) as in BCM-6DEF, but only five input variables of D_0 , D_{12} , D_{24} , D_{36} , and h_{pcc} . Similar backcalculation models were developed for predicting E .

The 7-60-60-1 architecture (7 inputs [6 deflections + PCC thickness], 60 nodes in the first and second hidden layers, and 1 output node, respectively) was chosen as the best architecture based on its lowest training and testing Mean Squared Errors (MSEs). Fig. 5 shows the training and testing MSE progress curves for the 7-60-60-1 network (for predicting k) at the end of 10,000 epochs. Both the training and testing curves for the output are in the same order of magnitude thus depicting proper training. The almost constant MSEs obtained for the last 5,000 epochs also provide a good indication of adequate training of this network.

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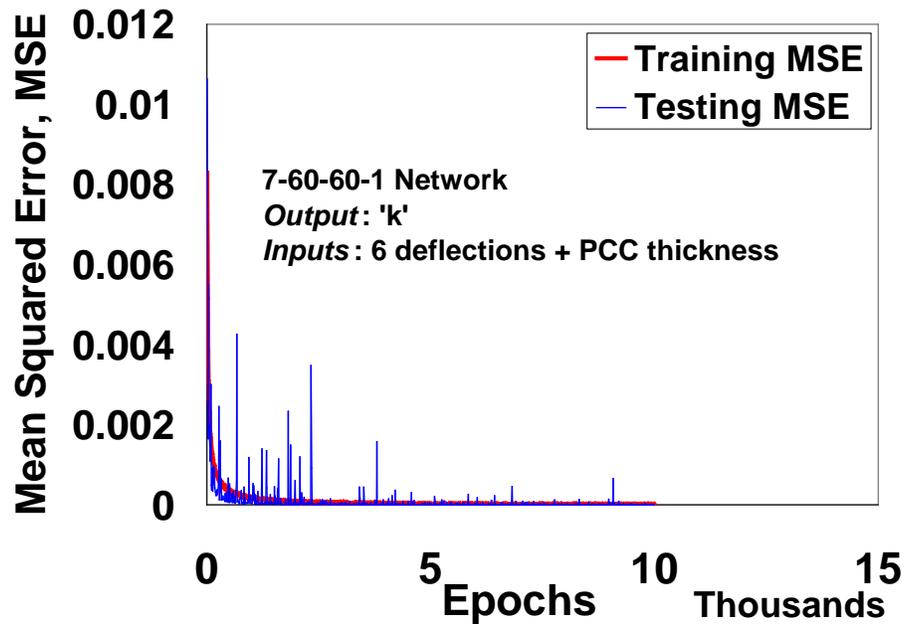


Fig. 5. ANN training progress curve.

Figs. 6 and 7 display the ANN predictions for both k and E , respectively using the 7-60-60-1 architectures. All ANN predictions for the 2,000 independent testing sets fall on the line of equality for both k and E , thus indicating a proper training and exceptional performance of the ANN backcalculation models. Average Absolute Errors (AAEs) were calculated as sum of the individual absolute errors divided by the 2,000 independent testing patterns. The AAE for the k -value using the BCM-6DEF- k model was 0.26%. Very similar results were obtained in training and testing the BCM-4DEF- k model, but are not reported here due to space constraints. The AAE for the k -value using the BCM-4DEF- k model was 0.35%. Similarly, the AAEs in predicting E using BCM-6DEF- E and BCM-4DEF- E were 0.32% and 0.34% respectively. Note that all these ANN models were developed for 40-kN (9,000-lb) FWD/HWD loading.

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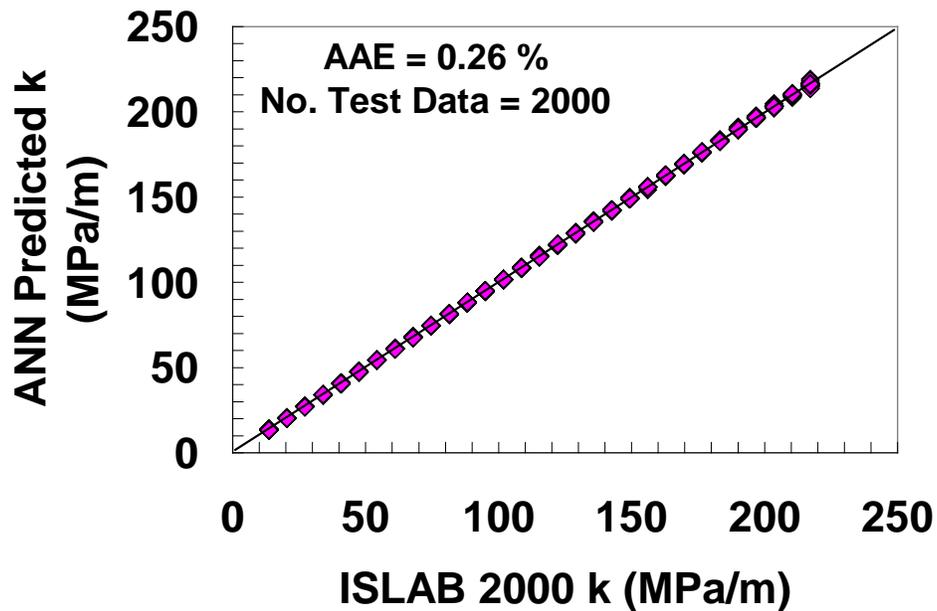


Fig. 6. ANN prediction of modulus of subgrade reaction (k).

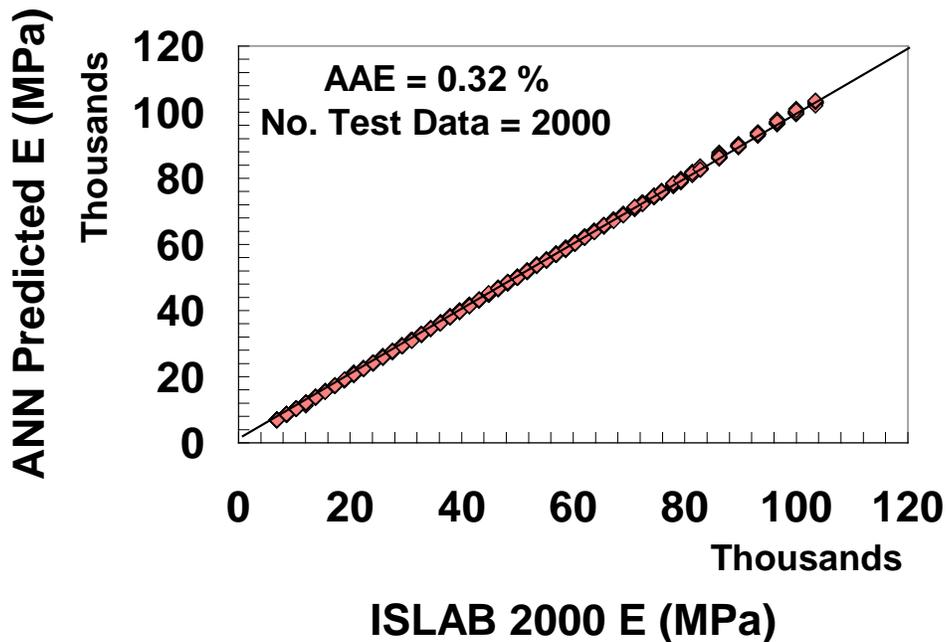


Fig. 7. ANN prediction of PCC modulus of elasticity (E).

ANN Predictions Using NAPTF Field Data

The developed ANN based backcalculation methodology was applied on the actual HWD deflection basins acquired at NAPTF during CC1 traffic testing. The objective was to investigate the effect of time and trafficking on the backcalculated concrete pavement

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system properties. The backcalculation results predicted using BCM-6DEF are presented here. Since the ANN models have been developed for slab-on-grade pavement systems, P-306 Econocrete layer underlying the PCC slab in NAPTF rigid test items were converted into an equivalent PCC slab thickness using a procedure discussed by Ceylan (2002). This equivalent thickness was used as the h_{pcc} input for the ANN backcalculation models.

The NAPTF HWD tests were conducted at nominal force amplitudes of 53.4-kN (12,000-lb), 106.7-kN (24,000-lb), and 160-kN (36,000-lb). The HWD tests were conducted on the following dates: November 19, 1999; February 11, 2000; March 20, 2000; April 7, 2000; and April 20, 2000. Note that the first set of traffic load repetitions were applied February 14, 2000.

The changes in 160-kN (36,000-lb) HWD peak center deflections (D_0 s) during NAPTF traffic testing are illustrated in Fig. 8 for LRS test item. Only the results from HWD tests conducted on the slab centers were used in the analysis. The average pavement temperature at the time of HWD testing as well as the cumulative number of load repetitions (N) are also displayed along with the test dates. The error bars corresponding to plus or minus one standard deviation are also shown. Note that for a normal distribution of values, approximately 68 percent of the values fall within plus or minus one standard deviation of the mean value. The average pavement temperature at the time of HWD testing as well as the cumulative number of load repetitions (N) are also displayed along with the test dates. Thus, the traffic lane deflection basins reflect the effect of both temperature and trafficking while the untrafficked centerline (C/L) deflections are influenced only by the changes in environment.

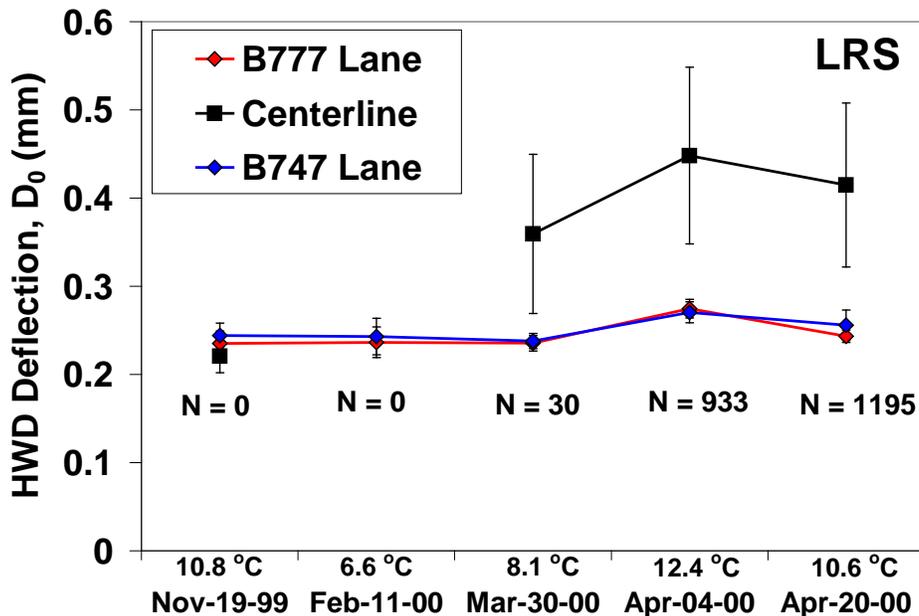


Fig. 8. Changes in HWD deflections during traffic testing.

Guo et al. (2002) analyzed the NAPTF rigid pavement traffic test data. Twenty-eight passes of the NAPTF test vehicle were applied on February 14, 2000. After

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completion of the initial twenty-eight passes, corner cracks were observed in test items MRS and HRS. No corner cracks were found in LRS after the first 28 passes. However, longitudinal cracks were observed in all slabs in LANE 2 (C/L) of LRS. This is reflected in the C/L HWD peak center deflections as seen in Fig. 8. In March 2000, traffic tests were resumed and continued until all the slabs cracked. Ultimately, several slabs were cracked into five and even six pieces (Guo et al. 2002). Corner cracks appeared in LRS during the resumed phase of testing. Trafficking was stopped in HRS test item on March 31, 2000 at 849 passes; in MRS test item on April 6, 2000 at 891 passes; and in LRS on April 10, 2000 at 1,195 passes.

Crack measurements showed that the HRS slabs exhibited the largest, and the LRS slabs exhibited the smallest, corner cracks. Furthermore, it was found that all pavement slabs were curled up at the corners, with the HRS slabs exhibiting the greatest amount of curling and the LRS slabs exhibiting the least amount of curling. The larger cracked corner areas observed on the HRS slabs are consistent with greater separation of the PCC slab corners from the Econocrete base (Guo et al. 2002). The HWD data collected prior to trafficking indicated significant increase of curling up of the slabs from the summer to the winter of 1999. The HRS test slabs (resting on the high-strength subgrade) were curled more than the LRS test slabs (resting on the low strength of subgrade) (Guo and Marsey 2001).

Since the ANN backcalculation models been developed for 40-kN (9,000-lb) loading, the 160-kN (36,000-lb) HWD deflection basins were normalized to a load level of 40-kN (9,000-lb). This is justified since the results from the sensitivity studies conducted at the NAPTF and Denver International Airport (DIA) showed linear FWD/HWD load-deflection behavior for both flexible and rigid pavements and it has been suggested that the amplitude of the FWD/HWD load is not critical provided the generated deflections are within the limits of all deflection sensors (Lee et al. 1997, McQueen et al. 2001, and Hoffman and Thompson 1981).

The normalized HWD surface deflections and the equivalent PCC slab thicknesses of the LRS, MRS, and HRS rigid test pavements were used in the BCM-6DEF-k to predict the k values. The ANN predictions of k values for the three test items are shown in Figs. 9 to 11, respectively. In these Figs., N denotes the number of load/traffic repetitions at the time of HWD testing. The results are plotted for B777 and B747 traffic lanes as well as untrafficked centerline. Also, the temperature at the time of HWD testing is displayed together with the HWD test dates. The variability in predicted k values increased significantly in all three test items as the number of load repetitions (N) increased due to the formation of cracks. Note that all three test items were designed such that all of them would have similar testing life. Previous studies have indicated that higher backcalculated k-values are obtained when the slab is modeled as plate compared to modeling the slab as elastic layer. Modeling of the slab and base as elastic layers seem to yield more reasonable backcalculated results since the interface bonding condition can be reflected both in the backcalculated slab elastic modulus and subgrade k-value (Rufino et al., 2002).

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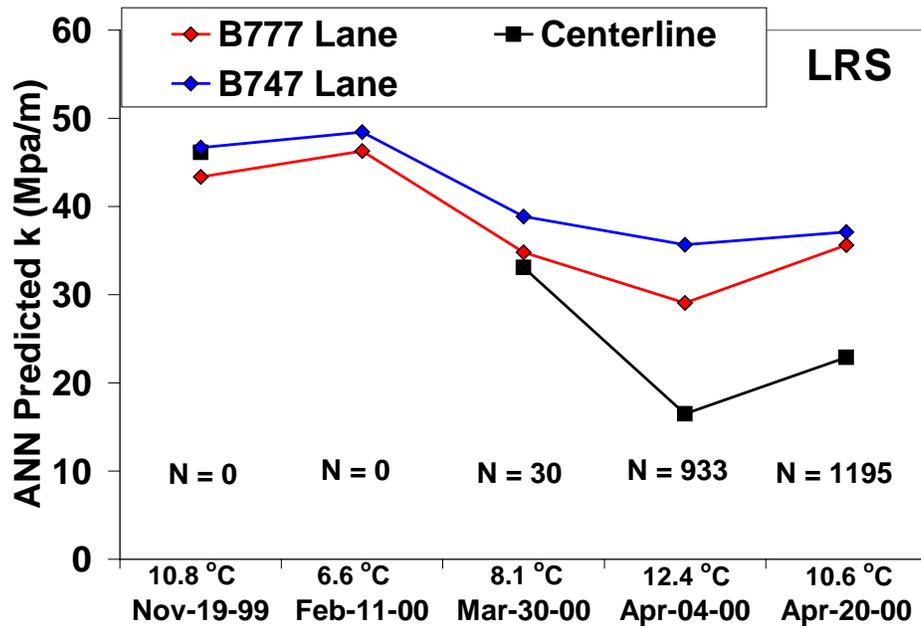


Fig. 9. Changes in ANN predicted k during traffic testing (LRS).

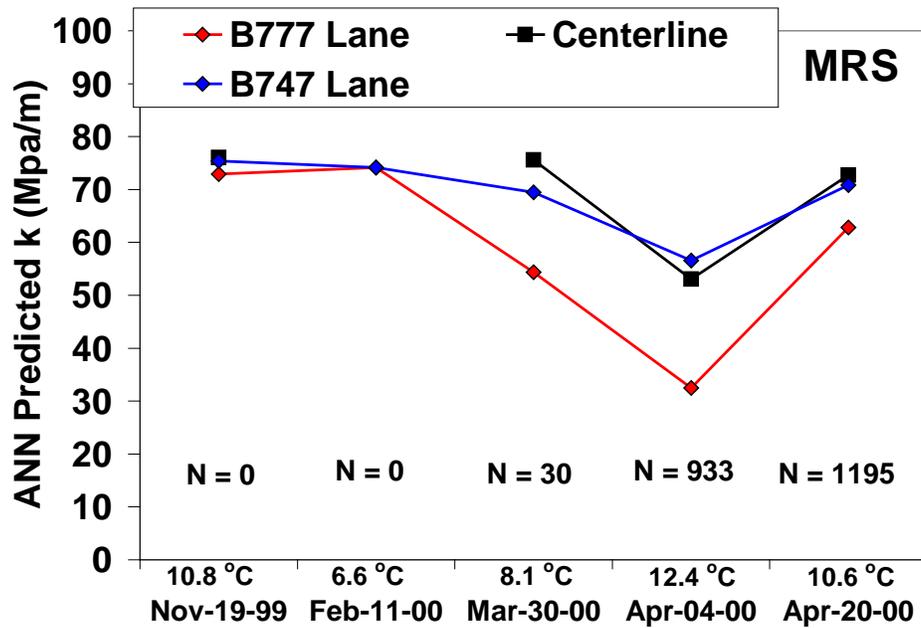


Fig. 10. Changes in ANN predicted k during traffic testing (MRS).

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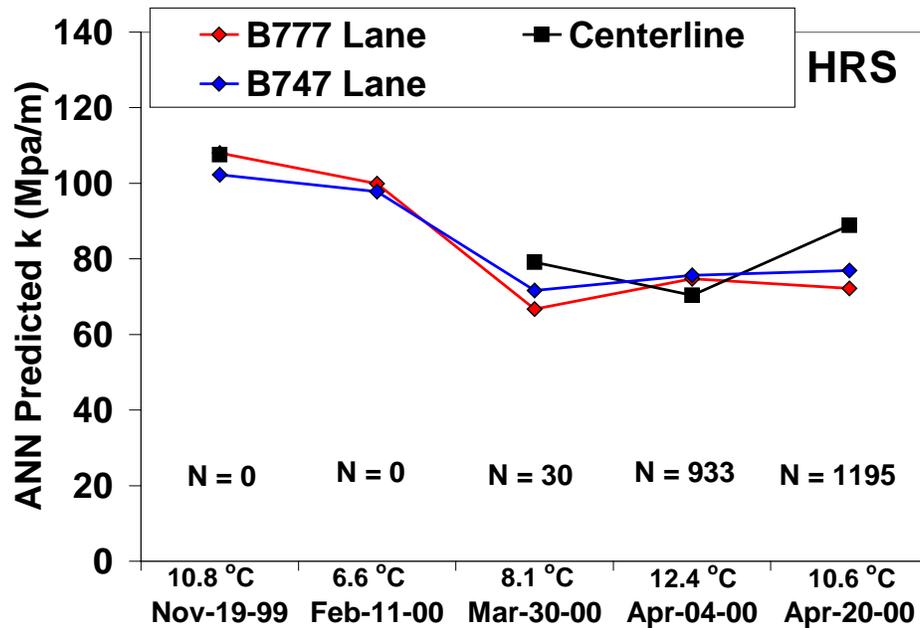


Fig. 11. Changes in ANN predicted k during traffic testing (HRS).

Unfortunately, the E values could not be successfully predicted using the ANN backcalculation models. This was as expected since backcalculated E values are very sensitive to pavement layer thicknesses and knowledge of actual degree of bonding in the field is required to make accurate moduli predictions. Comparisons of ANN predicted E values with the conventional backcalculation solutions based on closed-form equations are illustrated in Fig. 12. The closed-form equations for predicting E and k are:

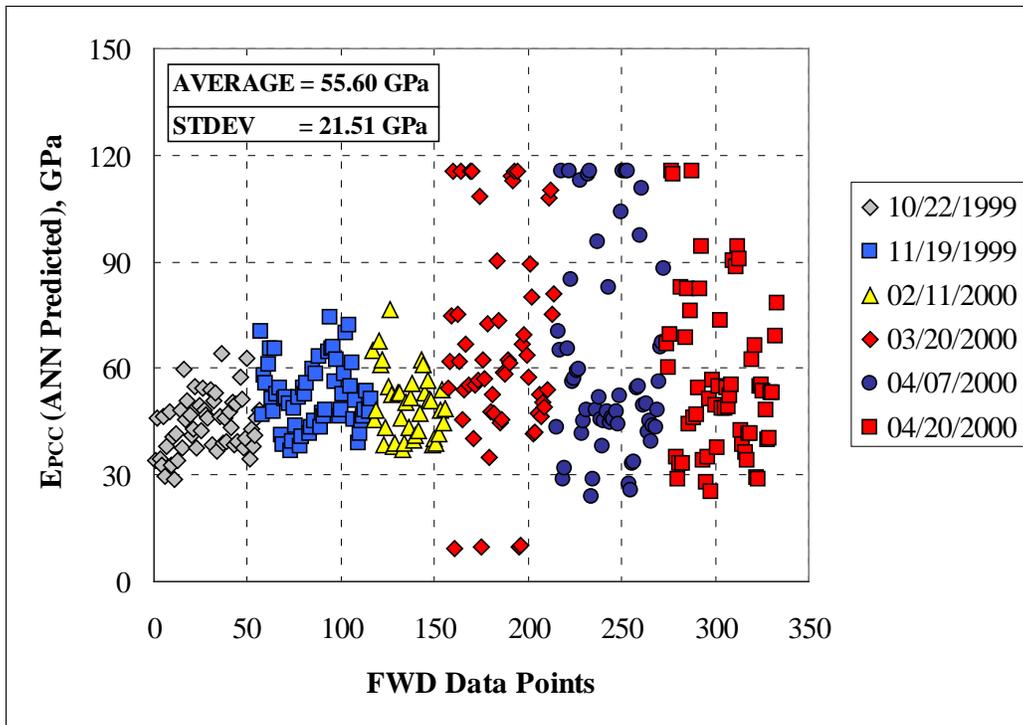
$$k = \left(\frac{P}{8D_0 l_k^2} \right) \left\{ 1 + \left(\frac{1}{2\pi} \right) \left[\ln \left(\frac{a}{2l_k} \right) - 0.673 \right] \left(\frac{a}{l_k} \right)^2 \right\} \quad (1)$$

$$E = \left(\frac{12l_k^4 k (1 - \mu^2)}{h^3} \right) \quad (2)$$

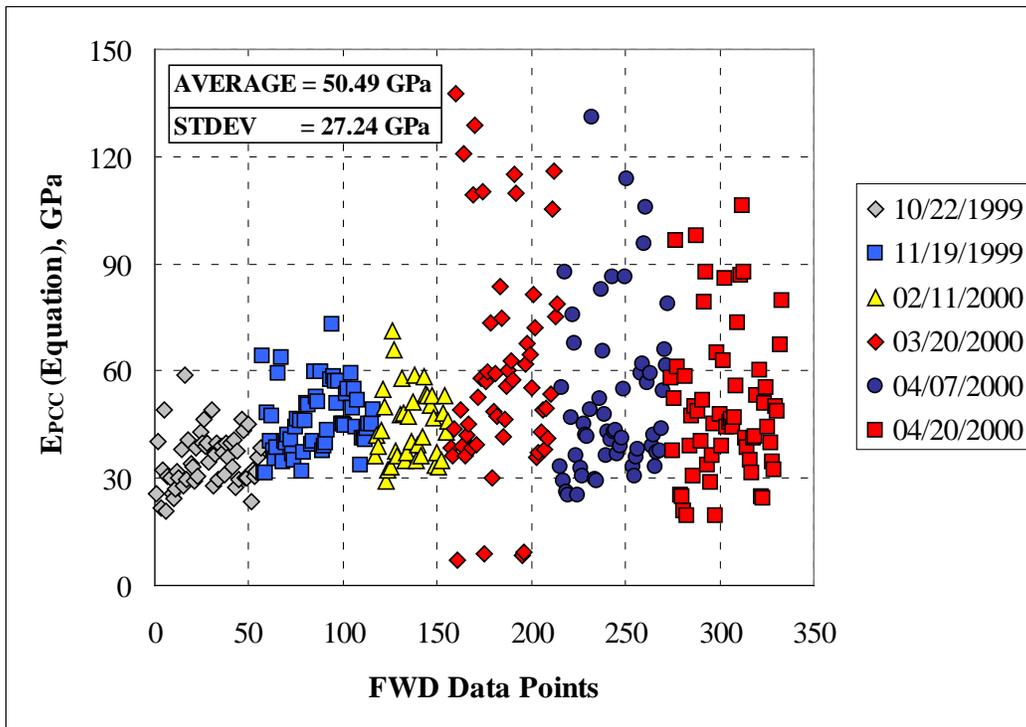
Where P is the HWD load in lbs; a is the radius of load plate (usually 15.2 cm [6 in]); h is the effective slab thickness in inches; l_k is the radius of relative stiffness (obtained from HWD surface deflections); and μ is PCC Poisson's ratio.

It is seen that the standard deviation of E predictions are lower for the ANN compared to that of conventional backcalculation solutions. Note that E was limited to 103.4 kPa during ANN training. This is why ANN model predictions of E have lower cut-off values [see Figure 12(a)] compared to the values backcalculated from the closed-form equations. Due to the interactions of numerous factors involved, such as slab curling and warping behavior, crack formations, etc., it is hard to distinguish the effect of trafficking alone on the backcalculated concrete pavement properties.

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(a)



(b)

Fig. 12. PCC layer modulus predictions for LRS section using (a) ANN; (b) conventional backcalculation solutions.

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It may be possible to achieve better predictions for E using ANN methodology by dividing the dataset into different small dataset in a way that each dataset might predict E moduli well and then combine the prediction/decision of this sub-ANN. Also, future research efforts will focus on studying the suitability of other types of ANN for enhanced predictability.

The modulus of subgrade reaction (k) is the stress that will cause one inch of deflection in the underlying soil. Soils such as clay will have a lower k -value compared to cement treated or asphalt treated bases. Research has shown that the value of k depends on certain soil characteristics such as density, moisture, soil texture and other factors that influence the strength of the soils. The k -value of a particular soil will also vary with size of the loaded area and the amount of deflection. The modulus of subgrade reaction is directly proportional to the loaded area and inversely proportional to the deflection. Modulus of subgrade reaction is obtained by conventional plate bearing tests as described in AASHTO T222, correlation with soil properties or other soil tests and also by backcalculation from FWD testing on concrete pavements.

It is observed that the k values for HRS are higher than that accepted for airport pavement design by the current FAA specification (i.e, 135 MPa/m or 500 psi/in). Guo et al. (2001) pointed out that the objective of the design specification is essentially different from that of the pavement response analysis. The design specification model intends to estimate pavement performance under variable traffic and environmental effects within its service life (usually 20 years for most airport pavements). Whereas the response model is utilized to predict response of a specific pavement under a well-defined load and/or environmental excitation(s) within a much shorter time span, from a few seconds to a few days. Therefore, for pavement life performance and short time load responses, different values of E and k are reasonable.

It is well known that the backcalculated pavement properties are strongly related to the backcalculation model (Rufino et al. 2002). For slab-on-grade systems, Ioannides (1990) proposed a closed-form procedure for backcalculating foundation properties based on principles of dimensional analysis by recognizing the existence of a unique relationship between AREA (Hoffman and Thompson 1981) and radius of relative stiffness (l_k). Once the radius of relative stiffness is known, Westergaard's maximum deflection solution (Westergaard, 1926) for interior loading can be used to backcalculate the subgrade k -value (see Eq. 1). Once the subgrade properties and radius of relative stiffness are known, the slab modulus of elasticity (E) can also be determined (see Eq. 2). This approach has been coded into a computer program called ILLI-BACK (Ioannides 1990).

The comparison between the backcalculated k values and ANN predicted k values are presented in Fig. 13. There is a good agreement between the two especially for the low-strength and medium-strength rigid test items. The ANN predictions are also in agreement with the results reported by Guo and Marsey (2001) based on HWD test data acquired prior to NAPTF traffic testing.

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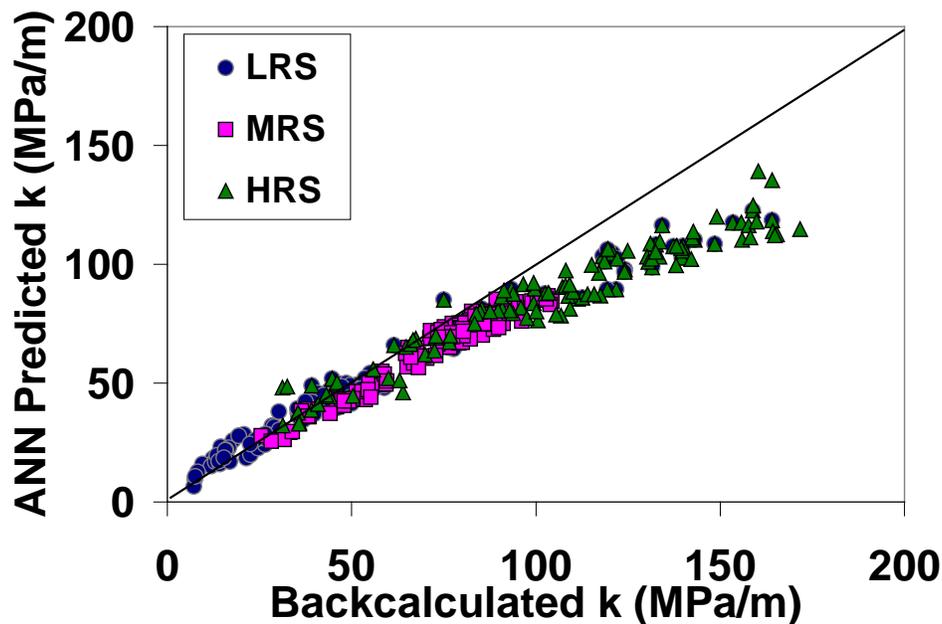


Fig. 13. ANN predictions of k compared with conventional backcalculation solutions.

Summary and Conclusions

The FAA's NAPTF was constructed to support the development of advanced mechanistic-based airport pavement design procedures. During the first series of traffic tests, a six-wheel Boeing 777 (B777) landing gear in one lane and a four-wheel Boeing 747 (B747) landing gear in the other lane were trafficked simultaneously until the test pavements were deemed failed. Non-destructive tests using both the FWD and HWD were conducted to document the uniformity of pavement and subgrade construction as well as to monitor the effect of full-scale trafficking on pavement response and performance over time.

ANN-based backcalculation models were developed using the ISLAB 2000 finite-element solutions for rapid and accurate prediction of backcalculated concrete pavement properties from realistic FWD/HWD deflection basins acquired at the NAPTF. It was shown that the modulus of subgrade reaction (k) could be successfully predicted using the ANN models. Unfortunately, the slab modulus of elasticity (E) could not be predicted from the field data although the ANN models showed exceptional performance in predicting the ISLAB 2000 solutions.

The study also illustrated the complexity of backcalculating properties of rigid pavements subjected to full-scale dynamic simulated aircraft traffic testing with gear wander. Apart from other complicating factors such as the slab curling and warping behavior, the test pavements exhibited corner cracks within few passes of traffic loading which further complicated the interpretation of FWD/HWD test results. The ANN predicted k values were in good agreement with those obtained using the closed-form solutions.

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It was shown that ANNs are capable of mapping complex relationships, such as those studied in complex finite element analyses, between the input parameters and output variables. The rapid prediction ability of the ANN backcalculation models (100,000 analyses in less than a second) makes them perfect evaluation tools for analyzing the NDT deflection data, and thus assessing the condition of rigid airfield pavements subjected to multiple-wheel heavy aircraft gear loading in real-time.

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References

- Barenberg, E. J., and K. A. Petros, 1991. *Evaluation of Concrete Pavements Using NDT Results, Project IHR-512*, University of Illinois at Urbana-Champaign and Illinois Department of Transportation, Report No. UILU-ENG-91-2006.
- Bush, A.J.III and Baladi, G.Y., 1989. *Nondestructive Testing of Pavements and Backcalculation of Moduli*, ASTM Special Technical Publication (STP) 1026, ASTM International, West Conshohocken, PA.
- Ceylan, H., 2002. *Analysis and Design of Concrete Pavement Systems Using Artificial Neural Networks*, Ph.D. Dissertation, University of Illinois, Urbana-Champaign, IL, December.
- Ceylan, H., Guclu, A., Tutumluer, E., and Thompson, M.R., 2005, *Backcalculation of Full-Depth Asphalt Pavement Layer Moduli Considering Nonlinear Stress-Dependent Subgrade Behavior*, *The International Journal of Pavement Engineering*, Vol. 6, No 3, pp. 171–182.
- FAA. 2004. *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.
- Fabre, C., Balay, J.M., and Mazars, A., 2004. *A380 Pavement Experimental Programme/Rigid Phase*. Proceedings of the 2002 Federal Aviation Administration Airport Technology Conference, Atlantic City, New Jersey.
- Foxworthy, P. T., and M. I. Darter, 1989. *ILLI-SLAB and FWD Deflection Basins for Characterization of Rigid Pavements*, *Nondestructive Testing of Pavements and Backcalculation of Moduli*, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 368-386.
- Guo. E. H. and Marsey, W. 2001. *Verification of Curling In PCC Slabs At FAA National Airport Pavement Test Facility*. Proceedings of the 2001 ASCE Airfield Pavement Specialty Conference, Chicago, IL.

- Reference** to this paper should be made as follows: Ceylan, H., Gopalakrishnan, K., and Bayrak, M. B. (2008). "Neural Networks Based Concrete Airfield Pavement Layer Moduli Backcalculation," *Journal of Civil Engineering and Environmental Systems*, Vol. 25, Issue no. 3, pp. 185-199.
- Guo, E. H., Hayhoe, G. F., and Brill, D. R., 2002. *Analysis of NAPTF Traffic Test Data for the First-Year Rigid Pavement Test Items*. Proceedings of the 2002 Federal Aviation Administration Airport Technology Conference, Atlantic City, New Jersey.
- Hall, K. T., 1992. *Backcalculation Solutions for Concrete Pavements*, Technical Memo Prepared for SHRP Contract P-020, Long-Term Pavement Performance Data Analysis.
- Hall, K. T., M. I. Darter, T. Hoerner, and L. Khazanovich, 1996. *LTPP Data Analysis – Phase I: Validation of Guidelines for K Value Selection and Concrete Pavement Performance Prediction*, Interim Report prepared for FHWA, ERES Consultants, Champaign, IL.
- Hayhoe, G.F. and Garg, N., 2001. *Material properties database for the test pavements at the National Airport Pavement Test Facility (NAPTF)*. Technical Report, 2001, Airport Technology Research and Development Branch, Federal Aviation Administration, NJ.
- Haykin, S. 1999. *Neural Networks: A Comprehensive Foundation*, Prentice-Hall Inc. NJ, USA.
- Hoffman, M. S. and M. R. Thompson, 1981. *Mechanistic Interpretation of Nondestructive Pavement Testing Deflections*, Report No. FHWA/IL/UI-190, Transportation Engineering Series No. 32, Illinois Cooperative Highway and Transportation Research Series No. 190, University of Illinois at Urbana-Champaign.
- Ioannides, A. M., E. J. Barenberg, and J. A. Lary, 1989. *Interpretation of Falling Weight Deflectometer Results Using Principals of Dimensional Analysis*, Proceedings, 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, pp.231-247.
- Ioannides, A. M., 1990. *Dimensional Analysis in NDT Rigid Pavement Evaluation*, *Journal of Transportation Engineering*, Vol.116, No. 1, pp.23-36.
- Ioannides, A.M., 1994. *Concrete Pavement Backcalculation Using ILLI-BACK 3.0*, Nondestructive Testing of Pavements and Backcalculation of Moduli, Vol. 2, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 103-124.
- Ioannides, A.M., D. R. Alexander, M. I. Hammons, and G. M. Davis, 1996. *Application of Artificial Neural Networks to Concrete Pavement Joint Evaluation*, *Transportation Research Record 1540*, Transportation Research Board, pp. 56-64.
- Khazanovich, L., 1994. *Structural Analysis of Multi-Layered Concrete Pavement Systems*, Ph.D. dissertation, University of Illinois, Illinois, USA.
- Khazanovich, L., and J. Roesler, 1997. *DIPLOBACK: Neural-Network-Based Backcalculation Programs for Composite Pavements*, Transportation Research Record 1570, Transportation Research Board, pp.143-150.
- Khazanovich, L., Yu, H.T., Rao, S., Galasova, K., Shats, E., and Jones, R., 2000, *ISLAB2000 - Finite Element Analysis Program for Rigid and Composite Pavements, User's Guide*, ERES Consultants, A Division of Applied Research Associates, Champaign, Illinois.
- Lee, X., Hovan, M., King, R., Dong, M., and Hayhoe, G. F., 1997. *Runway Instrumentation at Denver International Airport; Development of a Database*. Proceedings of 1997 ASCE Airfield Pavement Specialty Conference, Seattle, WA.

Reference to this paper should be made as follows: Ceylan, H., Gopalakrishnan, K., and Bayrak, M. B. (2008). "Neural Networks Based Concrete Airfield Pavement Layer Moduli Backcalculation," *Journal of Civil Engineering and Environmental Systems*, Vol. 25, Issue no. 3, pp. 185-199.

- McQueen, R.D., Marsey, W. and Arze, J.M., 2001. *Analysis of Nondestructive Data on Flexible Pavement Acquired at the National Airport Pavement Test Facility*. Proceedings of the 2001 ASCE Airfield Pavement Specialty Conference, Chicago, IL, 2001.
- McQueen, R.D., Rapol, J., and Flynn, R., 2002. *Development of Material Requirements for Portland Cement Concrete Pavements at the FAA National Airport Pavement Test Facility*. Proceedings of the 2002 FAA Airport Technology Transfer Conference, Atlantic City, New Jersey.
- Rufino, D., Roesler, J. and Barenberg, E. J., 2002. *Evaluation of Different Methods and Models for Backcalculating Concrete Pavement Properties Based on Denver International Airport Data*. Proceedings of the 2002 FAA Airport Technology Transfer Conference, Atlantic City, New Jersey.
- Smith, K. D., M. J. Wade, D. G. Peshkin, L. Khazanovich, H. T. Yu, and M. I. Dater, 1996. *Performance of Concrete Pavements, Volume II – Evaluation of In-Service Concrete Pavements*, Report No. FHWA-RD-95-110, ERES Consultants, Champaign, IL.
- Tabatabaie, A.M., and E.J. Barenberg, 1978. *Finite Element Analysis of Jointed or Cracked Concrete Pavements*, Transportation Research Record 671, Transportation Research Board, pp. 11-18.
- Tayabji, S.D. and Lukanen, E.O., 2000. *Nondestructive Testing of Pavements and Backcalculation of Moduli*. ASTM Special Technical Publication (STP) 1375, ASTM International, West Conshohocken, PA.
- Tuebert, C.A., Brill, D.R., and Qingge, J., 2002. *Data Management at the National Airport Pavement Test Facility (NAPTF)*. Proceedings of the 2002 Federal Aviation Administration Airport Technology Conference, Atlantic City, New Jersey.
- Winkler, E., 1867. *Die Lehre von der Elastizitat and Festigkeit, (The Theory of Elasticity and Stiffness)*, H. Dominicus, Prague, Czechoslovakia.
- Westergaard, H.M., 1926. *Stresses in Concrete Pavements Computed by Theoretical Analysis*, Public Roads, Vol. 07, pp. 25-35.