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NEURAL NETWORKS BASED MODELS FOR
MECHANISTIC-EMPIRICAL DESIGN OF RUBBLIZED
CONCRETE PAVEMENTS

Halil Ceylan, A.M. ASCE and Kasthurirangan Gopalakrishnan, A.M. ASCE

ABSTRACT: Rubblization is an in-place rehabilitation technique that involves breaking the concrete pavement into pieces. This process results in a structurally sound, rut resistant base layer which prevents reflective cracking (by obliterating the existing concrete pavement distresses and joints) that can then be overlaid with Hot-Mix Asphalt (HMA). The design of the structural overlay thickness for rubblized projects is difficult as the resulting structure is neither a true rigid pavement nor a true flexible pavement. The HMA overlay thickness design methodology currently used in the state of Iowa is purely empirical. In the Mechanistic-Empirical (M-E) design approach developed for the analysis and design of rubblized concrete pavements in Iowa, the tensile strain at the bottom of the HMA layer (\(\epsilon_t\)) is used to predict fatigue life using an HMA fatigue design algorithm and the vertical compressive strain on top of the subgrade layer (\(\epsilon_c\)) is used to consider subgrade rutting. In the current study, the use of Artificial Neural Networks (ANN)-based structural models for predicting the critical strains based on FWD deflection data, is successfully demonstrated. The ANN-based structural models were validated by comparing the ANN-based strain predictions with the field-measured strains from an instrumented trial project at highway IA-141 located in Polk County, Iowa.

INTRODUCTION

Portland Cement Concrete (PCC) pavements usually deteriorate with time due to distresses caused by a combination of traffic loads and weather conditions. Among the various alternatives available for rigid pavement rehabilitation, the use of Hot-Mix Asphalt (HMA) overlay is regarded as relatively quick and inexpensive measure to repair the deteriorated PCC pavement. However, the performance of HMA overlay is hindered due to the occurrence of reflective cracking, resulting in significant reduction of pavement serviceability (Sherman, 1982). Reflective cracking is minimized by reducing the slab action using various fractured slab techniques, including rubblization, crack and seat, and break and seat. Rubblization is an in-place rehabilitation technique that involves breaking the concrete pavement into pieces having a nominal maximum size of about 75 mm or less above and 200 mm or less below any reinforcement (Asphalt Institute, 2000). The results from a
A comprehensive investigation conducted by PCS/Law (PCS/Law 1991), the National Asphalt Pavement Association (NAPA) study (NAPA, 1994), and a nationwide survey conducted by the Florida Department of Transportation (DOT) (Ksaibati et al., 1999) all indicate that rubblization is the most utilized procedure for addressing reflection cracking (Heckel, 2002; LaForce, 2006).

Proper drainage is critical to the success of a rubblization project. In areas of weak subgrade or high water table, the drainage system should be functioning as far in advance of the rubblizing as possible to allow the subgrade to be as stable as possible (Wolters, 2003). In the nationwide survey on rubblization practices across the United States, most states indicated the need to add edge drain to the rubblized pavements before rubblization (Ksaibati et al., 1999).

HMA overlay thickness design procedures for rubblized PCC pavements have been proposed by the NAPA (NAPA, 1994) and the Asphalt Institute (1989) based on the structural number-layer coefficient principles used in the American Association of State Highway and Transportation Officials (AASHTO) guide. Thompson (1999) summarized the deficiencies associated with the AASHTO-based procedures and proposed Mechanistic-Empirical (M-E) based design concepts and procedures for the analysis and design of HMA overlay thickness for rubblized PCC pavements.

In the latest Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP, 2004), the design of an HMA overlay for fractured PCC slabs is similar to the design of a new flexible pavement structure. Typical values for the elastic modulus of the fractured slab layer are recommended in the MEPDG. The design analysis for HMA overlays on fractured slabs consider thermal and alligator cracking, and rutting. Reflection cracking is not considered in the fractured slab analysis (Rodezno et al., 2005).

The HMA overlay thickness design methodology currently used in the state of Iowa is purely empirical. In an effort to shift towards mechanistic-based design, a study was undertaken to develop a mechanistic-empirical design methodology for HMA overlaid rubblized PCC slabs at the Iowa State University under the sponsorship of Iowa Highway Research Board (Ceylan et al., 2005a). A subset of this research was to validate the design system structural response (strains) predictions using field measurements from an instrumented rubblized pavement section in Iowa. In this study, the concept of using Artificial Neural Networks (ANN) based structural models for predicting the critical structural responses (HMA and subgrade strains) based on Falling Weight Deflectometer (FWD) data is demonstrated.

**RUBBLIZATION EXPERIENCE IN IOWA**

Rubblization is currently the most-widely used PCC slab fracturing technique (Thompson, 2006). Iowa’s first rubblization project was constructed in 1996 in Dubuque County. Data collected during 2003 and 2004 from projects rubblized between 1997 and 2003 indicate a total of 21 rubblization projects in Iowa. A schematic of counties with rubblization projects in Iowa is displayed in Figure 1.
Recently, in the year 2001, a Jointed Plain Concrete Pavement (JPCP) section on highway IA-141, Des Moines, Polk County was rubblized and HMA strain gauges were instrumented. It is located approximately one mile north of the I-80/I-35 junction near Des Moines, Iowa.

As shown in Figure 2, there were four instrumented rubblized PCC test sections labeled T9 thru T12, each spanning five miles long on highway IA-141. The instrumented test sections were located in the southbound lanes. The strain gauges were placed in the outside lane.

Sections T9 and T10 comprise a nominal 190-mm (7.5-in) HMA overlay over a 254-mm (10-in) rubblized PCC slab while sections T11 and T12 comprise a nominal 230-mm (9-in) HMA over the same 254-mm (10-in) rubblized PCC slab. The PCC slab was rubblized using a Antigo® MHB, covering the full width of the lane (see Figure 3). The rubblized slab exhibited smaller pieces in the top half (approximately 25.4-mm [1-in] to 76.2-mm [3-in] size), while the bottom half comprised of particles up to about 203-mm (8-in.).

FIG. 1. Rubblization projects in Iowa
FIG. 2. Schematic of instrumented rubblized test sections on Iowa highway IA-141

High quality HMA strain gauges (manufactured by Dynatest PAST 2AC™) were used for measuring the tensile strains at the bottom of the HMA overlay. These were located in-line with the anticipated outer wheel path, and placed on the surface of the rubblized PCC slab by embedding in sand/bituminous emulsion slurry (see Figure 3). Sections T9 and T12 each had two strain gauges spaced 0.61 m (2 ft) apart (labeled 2 and 3; 10 and 11, respectively), while Sections T10 and T11 had three gauges spaced 0.61 m (2 ft) apart (labeled 4, 5, and 6; 7, 8, and 9, respectively) (see Figure 2). At the location of each set of gauges, a thermocouple was installed to allow measurement of the temperature at the bottom of the overlay/top of the rubblized PCC interface. The construction operations on these test sections were undertaken on September 15, 2001.

FIG. 3. Rubblization of IA 141 using Multi-Head Breaker and HMA strain gauge instrumentation
ANN-BASED STRUCTURAL MODELS

In the mechanistic-empirical HMA overlay thickness design methodology, which was adapted in this study, critical pavement structural responses (stresses, strains, and deflections) are related to various types of distresses (rutting and fatigue cracking) through transfer functions.

The critical structural responses considered in this design process include the horizontal tensile strain at the bottom of HMA layer \( (\varepsilon_t) \) and the vertical compressive strain on the surface of subgrade \( (\varepsilon_c) \). Based on the recommendations of the advisory committee, the multi-layer linear elastic analysis program, JULEA, was selected for computing the structural responses. A rapid structural analysis approach was developed in this study to facilitate design computations in batch mode. Given that both the critical strains are functions of geometry and elastic modulus of each pavement layer, it should be feasible to estimate the strains given the values of layer thickness and the moduli, using a trained ANN model. Research studies have shown that the effects of stress-dependent modulus and Poisson’s ratio, especially in the base layers, could be substantial especially in thin asphalt pavements (Park and Lytton, 2004).

A synthetic database was generated using JULEA by computing the critical strains \( (\varepsilon_t \text{ and } \varepsilon_c) \) for a wide range of layer thicknesses and moduli values. The HMA layer thicknesses varied between 51 mm to 305 mm (2 in to 12 in) and the rubblized PCC layer thicknesses between 152 mm to 356 mm (6 in to 14 in) in 50-mm (2-in) increments. The moduli values ranged from 1,724 MPa (250,000 psi) to 13,790 MPa (2,000,000 psi) for HMA; 345 MPa (50,000 psi) to 862 MPa (125,000 psi) for the rubblized PCC, and 34.5 MPa (5,000 psi) to 345 MPa (50,000 psi) for the subgrade. A total of 2,600 data sets were generated based on different combinations of the layer thicknesses and moduli values.

ANN Prediction models were derived by relating the critical strains to layer thicknesses and moduli values using the synthetic database. As part of the future work, a pavement structural model which can accommodate stress-dependent resilient modulus models for the unbound granular base and subgrade materials will be utilized to enhance the predictive capabilities of the design system. The elastic layered programs used in flexible pavement analysis assume linear elasticity. Pavement geomaterials do not, however, follow a linear type stress-strain behavior under repeated traffic loading.

ANN Prediction of Strains

Over the past few years, several studies have successfully demonstrated the use of trained ANN for accurately predicting critical structural responses, layer moduli, and deflection profiles of both flexible and rigid pavement systems (Ceylan, 2002; Ceylan et al., 2005b). In the development of the new Mechanistic-Empirical Pavement Design Guide (MEPDG), ANNs were recognized for their rapid prediction ability and robustness and were used in preparing the concrete pavement analysis package.
In this study, a multi-layered, feed-forward neural network trained using an error backpropagation algorithm (commonly referred to as backpropagation ANNs) was employed for the prediction of critical responses, $\varepsilon_t$ and $\varepsilon_c$. Backpropagation type ANNs are very powerful and versatile networks that can be taught a mapping from one data space to another using examples of the mapping to be learned. The learning process performed by this algorithm is called ‘backpropagation learning’ which is mainly an ‘error minimization technique’ (Haykin, 1999).

For the prediction of $\varepsilon_t$ and $\varepsilon_c$, six inputs, i.e., thickness of HMA ($H_1$), transformed thickness of rubblized PCC layer and subbase layer ($H_2$), and four FWD surface deflections ($D_0$, $D_{12}$, $D_{24}$, and $D_{36}$) at 305-mm (12-in.) offsets starting from centre deflection ($D_0$) were used. The Odemark’s concept of equivalent thickness was used to transform the thickness of rubblized PCC layer and subbase layer (Ceylan et al., 2005a). Based on the parametric analysis, two hidden layers with 60 nodes in each layer were found to be sufficient in this case. Thus, the final ANN architecture could be represented as 6-60-60-2 (6 inputs, 60 nodes in the 1st and 2nd hidden layers, and 1 output node, respectively).

The synthetic database generated by JULEA program was used for ANN training and testing. Out of the 2,800 data sets, 2,500 data sets were used for training the ANN and the remaining 300 data sets were used for testing. The Mean Squared Error (MSE) was used to track the performance of the network during the training process (see Figure 4). The almost constant MSEs obtained for the last 5,000 epochs indicate adequate training for this network.

FIG. 4. Training progress of ANN-based structural models

Once the network was successfully trained, it was tested using the 300 test data vectors. Excellent agreement was found between the ANN predicted strains and the target
strains, as shown in Figure 5. Average absolute errors (AAEs) were calculated as sum of the individual absolute errors divided by the 300 independent testing patterns.

The ANN-based structural models developed in this study could be used to compute the critical strains based on FWD test data and layer thicknesses and estimate the remaining structural life of rubblized pavements.

In general, HMA fatigue is the controlling overlay thickness design criterion for practically all rubblized PCC pavements (Thompson, 1999). In the Asphalt Institute (1981) design method, the allowable number of load repetitions, \( N_f \), to cause fatigue cracking is related to the tensile strain at the bottom of the HMA (\( \varepsilon_t \)) and to the HMA modulus (\( E_1 \)). Similarly, the allowable number of load repetitions to cause subgrade rutting, \( N_d \), is related to vertical compressive subgrade strain (\( \varepsilon_c \)).

![Prediction performance of the ANN-based structural models](image)

**FIG. 5.** Prediction performance of the ANN-based structural models
Validation of ANN-based Structural Models Using Field Data

The rubblized trial sections on highway IA 141 were revisited and a series of tests were performed. The Iowa DOT FWD equipment was located as closely as possible over each strain gauge. Three drops were made (nominally 40-kN [9,000-lb] load) and the surface deflections were recorded. The peak strains measured in the embedded gauges were also recorded. An Iowa DOT truck, loaded to closely simulate a ‘standard’ axle condition, was driven over the gauges at creep speed. The strain history (strain vs. time) in the gauges was measured. The temperature measured at the bottom of the HMA overlay was recorded.

Table 1 summarizes the tensile strain values at the bottom of the HMA overlay obtained from the testing done on different trial sections on IA-141. The moduli values were backcalculated from the FWD data using the MODULUS backcalculation program (Uzan, 1988) and the results are reported elsewhere (Ceylan et al., 2005a). The HMA tensile strain values obtained under the FWD load and the standard truck axle load are compared with the ANN model predictions in Table 1. The ANN model predicted strain values were obtained from the FWD data.

From Table 1, it can be observed that the strains recorded on gauges 10 and 11 have consistently provided low values when compared to gauges 7, 8 and 9. It is suspected that this may be due to a misalignment of these gauges during the construction process. Tensile strains at the bottom of the HMA layer recorded under the FWD are generally in agreement with the ANN model predicted results, thus providing a measure of validity to the use of the ANN-based structural models. Strains recorded under the ‘standard’ truck axle are more variable and of generally lesser magnitude than those under the FWD. This is contrary to what is expected (i.e., lower truck speed loading → reduced HMA modulus → higher HMA strains). The reason for this behavior is not known although part of it could be attributed to the difficulty of aligning the truck directly over the strain gauges and the dual tire configuration of the truck.

SUMMARY AND CONCLUSIONS

In the M-E design approach developed for the analysis and design of rubblized concrete pavements in Iowa, the tensile strain at the bottom of the HMA layer ($\varepsilon_t$) is used to predict fatigue life using an HMA fatigue design algorithm and the vertical compressive strain on top of the subgrade layer ($\varepsilon_c$) is used to consider subgrade rutting. In this study, the use of Artificial Neural Networks (ANN)-based structural models for predicting the critical strains based on FWD deflection data, is successfully demonstrated.

A multi-layer elastic analysis program was used to generate a database of results for developing the ANN-based structural models for predicting the critical structural responses. A multi-layered, feed-forward neural network trained using an error backpropagation algorithm (commonly referred to as backpropagation ANNs) was employed for the prediction of critical strains, $\varepsilon_t$ and $\varepsilon_c$. The ANN-based structural models were validated by comparing the ANN-based strain predictions with the field-
measured strains from an instrumented trial project at highway IA-141 located in Polk County, Iowa.

**TABLE 1.** Comparison of Field-measured and ANN-predicted HMA Tensile Strains

<table>
<thead>
<tr>
<th>Month</th>
<th>HMA Strain Gauge</th>
<th>HMA Thickness, mm</th>
<th>HMA Tensile Strain (microstrain)</th>
</tr>
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<tbody>
<tr>
<td>Sep 2001 (18 °C)</td>
<td></td>
<td></td>
<td>FWD</td>
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<tr>
<td>2</td>
<td>190</td>
<td>55</td>
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<td>11</td>
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**REFERENCES**


