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Orhan Kaya
Iowa State University, okaya@iastate.edu

Navneet Garg
Federal Aviation Administration

Halil Ceylan
Iowa State University, hceylan@iastate.edu

Sunghwan Kim
Iowa State University, sunghwan@iastate.edu

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Abstract

As part of asphalt mix design for flexible airfield pavements, the Federal Aviation Administration (FAA) collects asphalt volumetric mixture properties and aggregate gradations. Binder properties as well as laboratory dynamic modulus |E*| measurements for asphalt mixes are performed for flexible airfield pavements research. An artificial neural networks (ANN) model was developed using collected volumetric properties, aggregate gradation, and binder properties as well as laboratory |E*| measurements from seven hot-mix asphalt (HMA) and warm mix asphalt (WMA) mixtures. ANN model predictions were compared with the modified Witczak predictive model calculations for the same mixtures, and it was found that the developed ANN model successfully predicted |E*| for airfield pavement asphalt mixtures.

Disciplines

Civil and Environmental Engineering | Structural Engineering | Structural Materials | Transportation Engineering

Comments

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Development of Artificial Neural Networks Based Predictive Models for Dynamic Modulus of Airfield Pavement Asphalt Mixtures

Orhan Kaya[1]; Navneet Garg[2]; Halil Ceylan[3]; and Sunghwan Kim[4]

[1]Dept. of Civil, Construction and Environmental Engineering, Iowa State Univ., Ames, IA. E-mail: okaya@iastate.edu
[2]FAA Airport Technology R&D Branch, ANG-E262, William J. Hughes Technical Center, Atlantic City, NJ. E-mail: navneet.garg@faa.gov
[3]Dept. of Civil, Construction, and Environmental Engineering, Iowa State Univ., Ames, IA. E-mail: hceylan@iastate.edu
[4]Dept. of Civil, Construction, and Environmental Engineering, Iowa State Univ., Ames, IA. E-mail: sunghwan@iastate.edu

ABSTRACT

As part of asphalt mix design for flexible airfield pavements, the Federal Aviation Administration (FAA) collects asphalt volumetric mixture properties and aggregate gradations. Binder properties as well as laboratory dynamic modulus |E*| measurements for asphalt mixes are performed for flexible airfield pavements research. An artificial neural networks (ANN) model was developed using collected volumetric properties, aggregate gradation, and binder properties as well as laboratory |E*| measurements from seven hot-mix asphalt (HMA) and warm mix asphalt (WMA) mixtures. ANN model predictions were compared with the modified Witczak predictive model calculations for the same mixtures, and it was found that the developed ANN model successfully predicted |E*| for airfield pavement asphalt mixtures.

INTRODUCTION

The dynamic modulus (|E*|) of an asphalt mixture is a fundamental property defining the structural response of asphalt layers in flexible pavement systems. It is a complex number that relates stress to strain in the frequency domain for linear viscoelastic materials subjected to continuously-applied sinusoidal loading. The complex modulus test is relatively expensive and difficult to perform, and data analysis is fairly complicated, so several models have been developed for predicting dynamic modulus values from asphalt mixture volumetric properties, aggregate gradation, and binder properties. The most widely used models are the Witczak predictive models (Andrei et al. 1999; Bari and Witczak 2006) based on conventional multivariate regression analysis of laboratory test data. Another dynamic modulus prediction model is the Hirsh model (Christensen et al. 2003).

The input variables for the 1999 version |E*| model (original Witczak equation) (Andrei et al. 1999) include aggregate gradation, mixture volumetric properties, viscosity of the asphalt binder (η), and loading frequency (f). With the introduction of the Superpave Performance Graded (PG) binder specification to the asphalt community, the modified Witczak equation (Bari and Witczak 2006 that replaces binder viscosity (η) and loading frequency (f) in the original equation with the binder dynamic shear modulus (|Gb*|) and phase angle (δb) (Bari and Witczak 2006) was developed.

Concerns regarding Witczak |E*| models include: they show significant scatter at low and/or high |E*| modulus extremes, they are dominated by the influence of temperature and they understate the influence of other mixture parameters. (Pellinen, 2001; Schwartz 2005; Dongre et al. 2005; Bari and Witczak 2006; Al-Khateeb et al. 2006; Azari et al. 2007). Ceylan at al. (2009) developed Artificial Neural Network (ANN) based models to predict dynamic moduli of HMA in highway flexible pavement that used the same input parameters as the modified Witczak equation and produced |E*| predictions with significantly higher accuracy than those from the modified Witczak equation. Kim et al. (2011) also developed ANN based |E*| prediction models to be used as part of the Long-Term Pavement Performance (LTPP) database. That study also compared the ANN models with closed-form models (Witczak and Hirsch), and found that ANN models more successfully predicted |E*| than any of the closed-form solutions (Kim et al. 2011). They also stated that ANN models are more sensitive to input parameters and can consider effects and interactions of many variables in predicting |E*| values.

Table 1. Aggregate gradation variables and volumetric properties of seven mixes.

Mixes	Aggregate Gradation (% Passing)				Volumetric (%)	
	ρ19mm (0.75 in.)	ρ9.5mm (0.375 in.)	ρ#4	ρ#200	Va	Vbeff
CC7 64-22	95.2	74.1	48.1	5.3	3.4	12.2
CC7 76-22	95.2	74.1	48.1	5.3	3.4	12.2
NAPMRC HMA 64-22	94.8	73.7	51.2	4.7	3.1	12.3
NAPMRC HMA 76-22	94.8	73.7	51.2	4.7	3.5	11.9
NAPMRC WMA 64-22	94.8	73.7	51.2	4.7	3.1	12.3
NAPMRC WMA 76-22	94.8	73.7	51.2	4.7	3.5	11.9
BOSTON WMA	100	80	59	4.5	3.5	12.1

As part of asphalt mix design for flexible airfield pavements, the FAA collects mixture volumetric properties and aggregate gradations (FAA 2014). Measurements of binder properties and laboratory |E*| measurements for asphalt mixes have been performed for flexible airfield pavement research. In this study, an ANN model was developed using collected volumetric properties, aggregate gradation, and binder properties as well as laboratory |E*| measurements from seven airfield hot-mix asphalt (HMA) and warm mix asphalt (WMA) mixtures, and ANN model predictions were compared with modified Witczak predictive model calculations for the same mixtures. Detailed procedures on ANN model development and accuracy of the developed ANN model are also discussed.

ANN MODEL DEVELOPMENT

An ANN model was developed using the same input parameters as the modified Witczak equation used to predict |E*| values. The input variables for the 1999 version |E*| model (original Witczak equation) (Andrei et al. 1999) include aggregate gradation, mixture volumetric properties, viscosity of the asphalt binder (η), and loading frequency (f). The aggregate gradation variables are the percentage passing a #200 sieve (ρ#200), the percentage retained on a #4 sieve (ρ#4), the percentage retained on a 9.5 mm sieve (ρ9.5mm), and the percentage retained on a 19 mm sieve (ρ19mm). The mixture volumetric properties include the air void percentage (Va) and the effective binder percentage by volume (Vbeff). With the introduction of the Superpave Performance Graded (PG) binder specification into the asphalt community, the modified Witczak equation (Bari and Witczak 2006) was developed; it replaces binder viscosity (η) and loading frequency (f) in the original equation with the binder dynamic shear modulus (|Gb*|) and phase angle (δb) (Bari and Witczak 2006) (Equation 1). This equation is quite complex and was obtained through regression analysis using the Witczak database (Bari and Witczak 2006). ANNs have many advantages over regression because they do not have limitations such as normality, linearity, and variable independence. ANNs can capture complex linear and nonlinear relationships between dependent and independent variables in a small fraction of the time.

$$\log_{10}|E^*| = -0.349 + 0.754\left(\left|G_b^*\right|^{-0.0052}\right) \left(6.65 - 0.032(\rho\#200) + 0.0027(\rho\#200)^2 + 0.011(\rho\#4) - 0.0001(\rho\#4)^2 + 0.006(\rho 9.5) - 0.00014(\rho 9.5)^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_{beff}+V_a}\right)\right) + \frac{2.558 + 0.032V_a + 0.713\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + 0.0124(\rho 9.5) - 0.0001(\rho 9.5)^2 - 0.0098(\rho 9.5)}{1+\exp(-0.7814 - 0.5785\log\left|G_b^*\right| + 0.8834\log\delta b)} \quad \text{(Equation 1)}$$

An ANN model was developed using collected volumetric properties, aggregate gradation, and binder properties as well as laboratory |E*| measurements from seven HMA and WMA mixtures. Mixes used in the model development were as follows:

- CC7 HMA 64-22: FAA's National Airport Pavement Test Facility (NAPTF) Construction Cycle 7 (CC7) HMA mix with Superpave binder grade of PG 64-22
- CC7 HMA 76-22: NAPTF CC7 HMA mix Superpave binder grade of PG76-22
- NAPMRC HMA 64-22: FAA's National Airport Pavement and Materials Research Center (NAPMRC) HMA mix with Superpave binder grade of PG 64-22
- NAPMRC HMA 76-22: NAPMRC HMA mix with Superpave binder grade of PG 76-22
- NAPMRC WMA 64-22: NAPMRC WMA mix with Superpave binder grade of PG 64-22
- NAPMRC WMA 76-22: NAPMRC WMA mix with Superpave binder grade of PG 76-22
- BOSTON WMA: Class 1 SBR Latex-Modified Dense Bituminous Concrete (P-401 3/4" nominal maximum size of aggregate (NMSA) WMA, 20% recycled asphalt (RAP))

Volumetric properties, aggregate gradation, binder properties as well as laboratory |E*| measurements of these seven mixes were used in ANN model development. The same particular input parameters used in the modified Witczak equation were also used in the model development. Details of model inputs and outputs used in the model development were as follows:

Model Inputs

- Volumetric properties of asphalt mixtures (air void percentage (Va) and effective binder percentage by volume (Vbeff)

- Aggregate gradation variables (percentage passing a #200 sieve (ρ#200), percentage retained on a #4 sieve (ρ#4), percentage retained on a 9.5 mm sieve (ρ9.5mm), and percentage retained on a 19 mm sieve (ρ19mm)
- Binder variables (dynamic shear modulus (|Gb*|) and phase angle (δb))

Model Outputs

- Measured |E*| values

Table 1 summarizes aggregate gradation variables and volumetric properties of seven mixes used in the model development.

ANN model development has three stages:

1. An excel spreadsheet was prepared that includes aggregate gradation variables, volumetric properties, binder properties and laboratory |E*| measurements from seven HMA and WMA mixtures.
2. Aggregate gradation variables, volumetric properties, binder properties of the mixes were categorized as inputs, while laboratory |E*| measurements of the mixes were categorized as outputs.
3. ANN model relates these inputs to outputs through learning algorithms. In the ANN model development, a two-layer feed-forward network was trained using a Levenberg-Marquardt algorithm (LMA) in the MATLAB environment.

Figure 1 shows the ANN architecture used in the model development. As can be seen in Figure 1, seven input parameters were used to predict an output parameter using fifteen hidden neurons, with this number chosen because in similar earlier problems, this number of neurons produced successful ANN models (Ceylan at al. 2009).

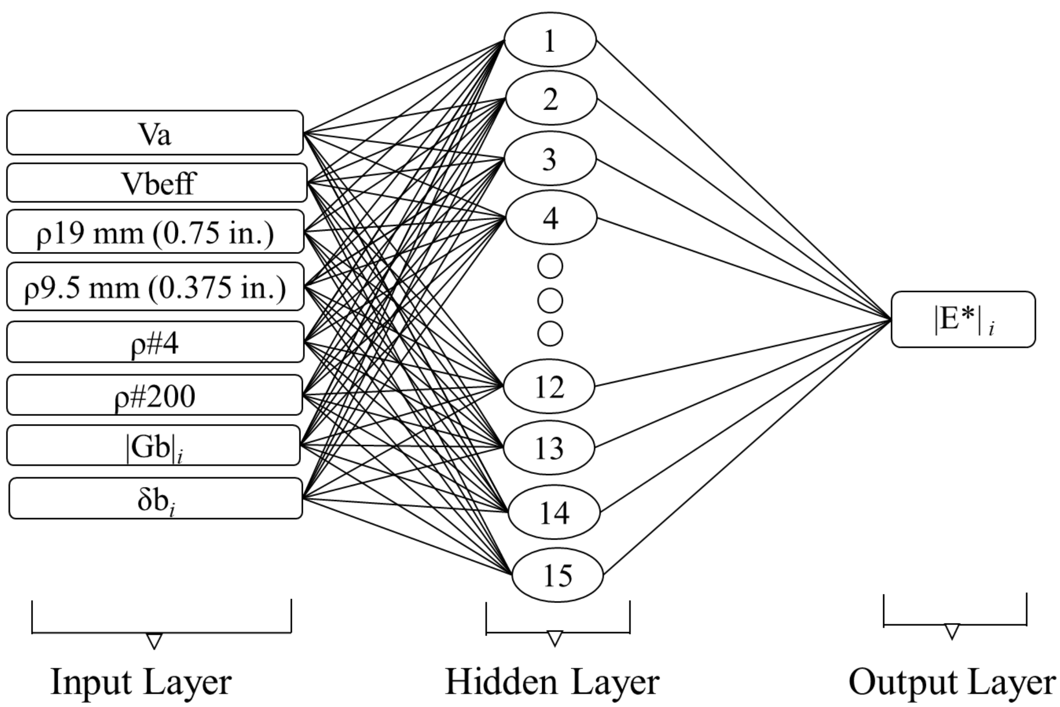

Figure 1. ANN architecture used in the model development.

RESULTS

Initially, ANN model E* predictions were compared with measured E* values to evaluate success of ANN model in predicting E* values. Figure 2 compares ANN predictions for |E*| compared to laboratory measurements. As can be seen in Figure 2, very successful correlation between measured E* values and ANN predictions was achieved.

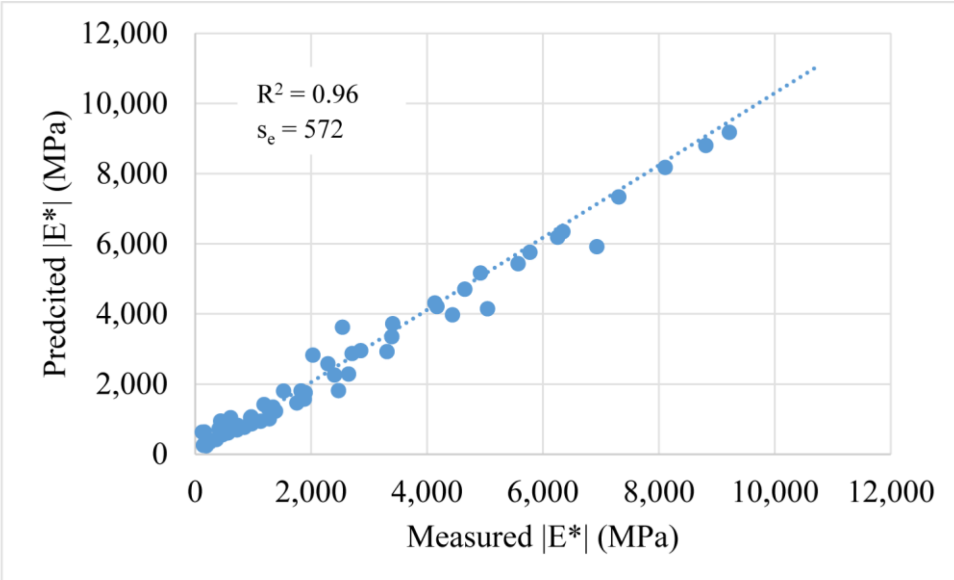

Figure 2. ANN model predictions vs. measured |E*|.

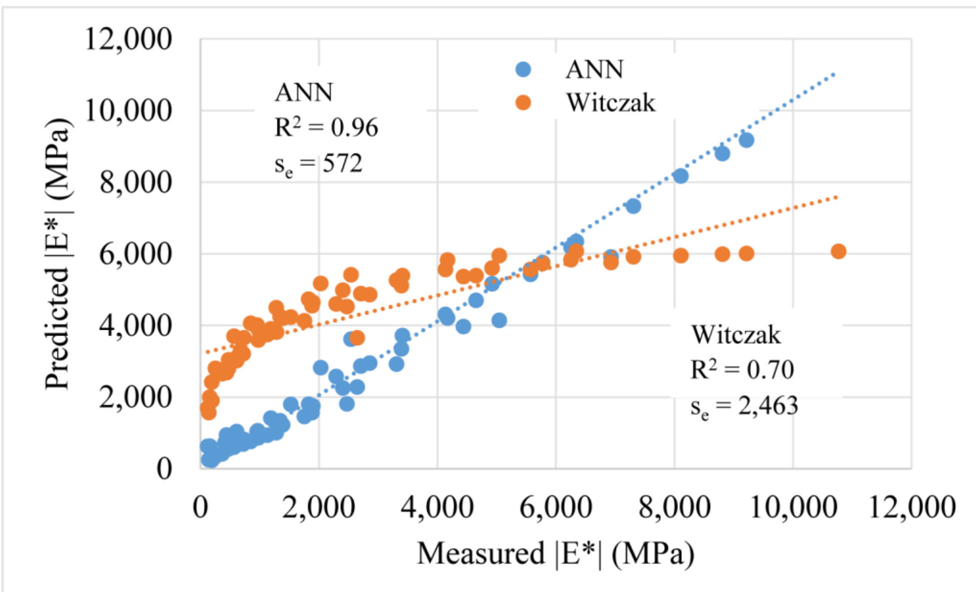

Figure 3. Comparison of ANN model and Witczak equation.

The model accuracies were expressed with the statistical terms; correlation coefficient (R^2) and standard error (Equation 2).

$$s_e = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n-p}} \quad \text{(Equation 2)}$$

$$e_i = E_{pi}^* - E_{mi}^* \quad \text{(Equation 3)}$$

Where,
se = standard error (i.e., standard deviation of errors);
E_{mi} = measured dynamic modulus;
E_{pi} = predicted dynamic modulus;
n = sample size;
p = number of model parameters

Figure 3 presents comparisons between ANN model predictions versus measured |E*| values and Witczak equation calculations versus measured |E*| values. As can be seen in the figure, the ANN model predicted E* values more accurately than the modified Witczak equation.

CONCLUSIONS AND DISCUSSION

In this study, an ANN model was developed to predict dynamic moduli of airfield pavement asphalt mixtures. In the model development, volumetric properties, aggregate gradation, and binder properties as well as laboratory |E*| measurements from seven HMA and WMA mixtures were used. ANN model predictions were compared with modified Witczak predictive model calculations for the same mixtures, and it was found that the developed ANN model successfully predicted |E*| for airfield pavement asphalt mixtures. Using this model, the dynamic modulus of similar airfield pavement asphalt mixtures could be predicted by inputting required input parameters to the model. The developed ANN model could also be further revised and validated using more mixes.

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