Construction and Building Materials 102 (2016) 65–75

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Calibration of dynamic modulus predictive model

Konstantina Georgouli [a,*], Andreas Loizos [b], Christina Plati [a]

[a] National Technical University of Athens, Laboratory of Pavement Engineering, 5 Iroon Polytechniou St, Zografou Campus GR 157 73, Athens, Greece
[b] National Technical University of Athens, Department of Transportation Planning and Engineering, 5 Iroon Polytechniou St, Zografou Campus GR 157 73, Athens, Greece

HIGHLIGHTS

- Need for calibration of the Witczak 1-37A model emerged from the evaluation process.
- Calibrated algorithms were developed for asphalt base and wearing course mixes.
- No calibration was needed for wearing course mixes with air voids lower than 16%.
- The sigmoidal function form may be appropriate for representing E^* of all mixes.

ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form 23 October 2015
Accepted 24 October 2015

Keywords:
Asphalt mixtures
Dynamic modulus
Predictive equations
Calibration

ABSTRACT

The aim of the present study is the evaluation of the Witczak 1-37A, Bari & Witczak, NCHRP 1-40D and Hirsch models for the estimation of dynamic modulus (E^*) and the subsequent calibration of the model to best fit with laboratory reference data of the material under investigation. For this purpose asphalt mixture specimens for both asphalt base and wearing courses were prepared in the laboratory. E^* was determined in the lab and estimated through the aforementioned prediction algorithms. According to the evaluation process results, the Witczak 1-37A model was selected for calibration. The developed model was verified and further validated with a high degree of statistical certainty.

1. Background and objectives

The performance of a flexible pavement is significantly influenced by the modulus of the asphalt mix layers. In general, the modulus is affected by mix characteristics, loading rate and temperature.

Complex modulus, which is a way to determine creep compliance in the frequency domain, can be determined from oscillating loading at different frequencies. For a given frequency ω, if the input is an oscillatory stress $\sigma_o e^{i\omega t}$ then the strain response is $\varepsilon_o e^{i\omega t}$ will be an oscillation at the same frequency as the stress, but lagging behind by a phase angle δ [1]. From the complex modulus test, complex E^*, dynamic $|E^*|$, storage E' and loss E'' moduli can be determined as follows:

$$E^* = \frac{\sigma_o}{\varepsilon_o} e^{i\delta} = \frac{\sigma_o}{\varepsilon_o}(\cos(\delta) + i\sin(\delta)) = |E^*| \times (\cos(\delta) + i\sin(\delta)) = E' + iE'' \quad (1)$$

Therefore, dynamic modulus $|E^*|$, which for simplicity reasons will be referred to as E^* hereafter, is a fundamental property of a viscoelastic material in the frequency domain. It can be determined from sinusoidal load applied at different frequencies to capture the linear viscoelastic properties of the Hot Mix Asphalt (HMA) mixture. Mathematically, the dynamic modulus is defined as the absolute value of the complex modulus [2].

The dynamic modulus which can be utilized for mixture ranking and characterization purposes and mix design, is a primary stiffness property used as an input parameter in mechanistic-empirical pavement design (MEPDG) and analysis processes [3].

The dynamic modulus is used to predict pavement response parameters that determine the strains and displacements of layered pavement structures under different temperatures and loading conditions [4,5]. It is also a key input for the prediction of fatigue and rutting damage in MEPDG [4]. The master curve generated at a reference temperature based on dynamic modulus test results is utilized to calculate the dynamic modulus over a wide range of temperatures and frequencies.

For pavement design purposes the MEPDG program has three distinct levels of inputs for the traffic and material characterization depending on the information available to the pavement designer.

* Corresponding author.
E-mail addresses: kongeor@central.ntua.gr (K. Georgouli), aloizos@central.ntua.gr (A. Loizos), cplati@central.ntua.gr (C. Plati).

http://dx.doi.org/10.1016/j.conbuildmat.2015.10.163
0950-0618/

Despite the level of input, the same computation methodology is used for performance prediction. For Level 1 analysis, dynamic modulus testing in the laboratory at various frequencies and temperatures is required. However, laboratory testing for the determination of the dynamic modulus is not always feasible, as it is a tedious and time consuming process and requires extended effort to develop a single master curve [4,6,7]. Level 2 and 3 analysis on the other hand do not require laboratory test data but instead, empirical models are utilized to estimate dynamic modulus, which are based on mix properties, including volumetric properties [8–11].

Numerous equations have been developed for the estimation of asphalt concrete stiffness, dating back to the Van der Poel model [12]. The most recent globally applicable models include the Witczak 1-37A [11], the Bari & Witczak [3], the NCHRP 1-40D [13] and the Hirsch [10] model.

According to a multitude of research studies [3–8,14–22] that investigated the evaluation of the available empirical models, the performance of a model varies with the type of mixtures and other volumetric properties. Obulareddy [6], Birgisson et al. [4], Tran and Hall [8], Kim et al. [15] investigated the performance of the Witczak 1-37A model for local mixes and concluded that dynamic modulus is over predicted. Moreover, Obulareddy [6] and Birgisson et al. [4] concluded that the modulus predictions of Witczak 1-37A model at higher temperatures (lower modulus values) generally were closer to the measured values than the predictions at lower temperatures. However, according to other studies [15,23,24] the Witczak 1-37A model underestimates the dynamic modulus while modulus predictions are closer to the measured values at low and intermediate temperatures. The Bari & Witczak and Hirsch model have been subject of many recent studies [25–27]. Overall, relevant studies have demonstrated that the performance of these models is not consistent and vary depending of the type of the Hot Mix Asphalt (HMA) mixture. It is therefore of significant importance to appreciate the relative ranges of dynamic modulus values from mixtures made from locally available materials [28]. On top of that, it is also important to understand how well the dynamic modulus for locally available materials compares with the predicted dynamic modulus.

Taking into consideration the above-mentioned, the accuracy of global E^* predictive equations must be evaluated for localized mixtures. The aim of the present research paper is the evaluation of a number of existing E^* algorithms on local pavement materials and the subsequent calibration of the model to best fit localized needs of the material under investigation. For the purposes of this research, laboratory testing was performed on laboratory compacted mixtures. Specimens include both mixtures utilized for asphalt base and wearing course layers, with varying volumetric properties and gradation. The accuracy of the algorithms was investigated and the results of the evaluation and calibration process are presented in the following sections.

2. Predictive models

2.1. Witczak 1-37A model

The Witczak 1-37A model (Eq. (2)) [11] is one of the most comprehensive mixture stiffness models currently available. The model is capable of predicting mixture stiffness over a range of temperatures, loading rates, and aging conditions from information that is readily available from material specifications or volumetric design of the mixture.

$$\log E^* = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \quad (2)$$

where E^*: dynamic modulus of mixture (psi), η: viscosity of binder (10^6poise), f: loading frequency (Hz), V_a: air voids (% by volume), V_{beff}: effective binder (% by volume), ρ_{34}: cumulative percentage retained on 3/4 inch (or 19 mm) sieve, ρ_{38}: cumulative percentage retained on 3/8 inch (or 9.5 mm) sieve, ρ_4: cumulative percentage retained on No. 4 (or 4,75 mm) sieve, ρ_{200}: percentage passing No. 200 (or 0.075 mm) sieve.

For use in this model, the viscosity of the binder is determined by a linear relationship between log–log viscosity and log temperature, as illustrated in Eq. (3).

$$loglog\eta = A + VTS \times \log T_R \quad (3)$$

where η: viscosity of binder (cP), A & VTS: regression parameters, T_R: temperature (° Rankine).

According to [29] the prediction model is accurate for all mixes (using either conventional or modified asphalt) and appears to be applicable for a wide range of asphalt types (including modifiers) and aggregate sizes. The percent of air voids of the mixes included in the database ranged from approximately 1.5%–16%. Specimens were compacted with kneading and mainly with gyratory compaction methods. Although the model proved to accurately predict the E^* values from the database, it is necessary to determine its ability to predict E^* for other gradation and binder variations not included within the database, before suggesting its use globally [29]. Several comparison studies have been completed to assess the quality of the model, with various and sometime conflicting results. According to Dongre et al. [14] the Witczak 1-37A model was found to overestimate E^* for the specimens tested at moduli values below 125,000 psi. Causes for over predictions of E^* were assumed to be associated with the A and VTS parameters. The overestimation of E^* at lower moduli values reported by Dongre and his associates [14], was echoed in later investigations. In a comparison study on Louisiana asphalt mixtures, the Witczak 1-37A model generally underestimated the measured values, except at high temperatures and/or low frequencies [30]. At these lower measured E^* values, the model was found to over predict dynamic moduli values for the thirteen Superpave mixtures tested [30]. Azari and colleagues observed over prediction across the board, with the over prediction more significant at 500,000 psi and lower [7]. In a comparison study, the Witczak 1-37A was found to overestimate measured values in some instances, with a predicted value reported nearly twice the measured value [5].

2.2. Bari & Witczak model

Bari and Witczak [3] in 2005 revised the Witczak 1-37A model, using 7400 data points from 346 HMA mixes. The revised model uses dynamic shear modulus ($|G_b^*|$) and phase angle (δ_b) of binder as input parameters as shown in Eq. (4).