Construction and Building Materials 170 (2018) 698–707

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Revisiting the relationship of dynamic and resilient modulus test for asphaltic concrete mixtures

Yasir Ali [a,*], Muhammad Irfan [b], Muhammad Zeeshan [a], Imran Hafeez [c], Shafeeq Ahmed [d]

[a] National Institute of Transportation, School of Civil and Environmental Engineering, National University of Sciences & Technology (NUST), Islamabad 44000, Pakistan
[b] Military College of Engineering, National University of Sciences & Technology (NUST), Risalpur 24080, Pakistan
[c] Department of Civil Engineering, University of Engineering & Technology, Taxila 47050, Pakistan
[d] Highway Research and Training Centre, Burhan Camp Jallo 14400, Pakistan

## HIGHLIGHTS

- A correlation of |E*| and $M_R$ is developed.
- Developed correlation is rigorously testing.
- Developed correlation is compared with an existing correlation.
- A statistical model for predicting |E*| as function of $M_R$, gradation and mix volumetric parameter is presented.

## ARTICLE INFO

*Article history:*
Received 10 January 2018
Received in revised form 9 March 2018
Accepted 12 March 2018

*Keywords:*
Asphalt mixtures
Resilient modulus
Dynamic modulus
Correlation
Statistical model

## ABSTRACT

Mechanistic-Empirical Pavement Design is considered relatively more effective than conventional empirical design for excessive tyre pressure exerted by axle load spectra and diverse environmental conditions. Many highway agencies are adopting a paradigm shift to Mechanistic-Empirical pavement design practices, obsoleting huge inventories of resilient modulus database used for empirical design. This paper attempts to develop an empirical correlation of dynamic modulus (|E*|) and resilient modulus ($M_R$) – two performance tests used to characterize the stiffness of asphaltic concrete mixtures, and proposes a statistical model for |E*| as a function of $M_R$, gradation parameter, and mix volumetric parameter. For the comparison purpose, a rigorous testing using bi-level testing protocol is offered for all the relationships (i.e., correlation and model). The comparison of |E*| with $M_R$ shows that at a temperature of 25 °C, |E*| at 5 Hz is strongly correlated with $M_R$ at a loading frequency of 300 ms. The developed statistical model captured 97% of the variability in the data in predicting |E*| from $M_R$ with an error of 6% and 23% for first and second level of bi-level testing protocol, respectively. It is envisaged that the findings of this study can help the highway agencies and practitioners in smooth transitioning to Mechanistic-emprical pavement design practices.



## 1. Introduction

Mechanistic-Empirical Pavement Design Guide (M-EPDG) for new and rehabilitated flexible pavement structures is considered more appropriate for improved pavement design practices with an enhanced capability for prediction of pavement performance and maintenance needs over the service life. Prior to M-EPDG, the American Association of State Highway and Transportation Officials (AASHTO) 1993 flexible pavement guide [1] was most widely used, which is inherently empirical and inadequate for heavy axle loads, tyre pressures, diverse environmental conditions, material variation, etc. This design guide uses resilient modulus ($M_R$) while M-EPDG uses |E*|. In order to shift smoothly from previous design guide to new M-EPDG and save time and expenditure involved in performing laborious tests, a relationship of |E*| and $M_R$ is needed which can predict |E*| from $M_R$. For this purpose, there exists a few correlation in the literature, however, these correlations are not rigorously tested. Therefore, this study revisits the relationship of |E*| and $M_R$ and attempts of improve the accuracy of this relationship so that it can used for prediction purpose.

For the design of flexible pavements using M-EPDG, one of the key input parameters is the dynamic modulus (|E*|)–a parameter

* Corresponding author.
*E-mail addresses:* yasirali@nit.nust.edu.pk (Y. Ali), mirfan@mce.nust.edu.pk (M. Irfan).

https://doi.org/10.1016/j.conbuildmat.2018.03.098
0950-0618/

that is globally used for material characterization. The use of |E*| in M-EPDG provides more accurate/rigorous measures of pavement structural design procedures and analyses of asphalt concrete (AC) mixtures. This is the first and most prominent change in M-EPDG compared to 1993 AASHTO design guide which uses $M_R$ as the material property of AC layers. Apart from |E*|, Flow Number and Flow Time were two other inclusions in M-EPDG. The FN, a repeated load test, applies a haversine loading with 0.1 s loading time followed by 0.9 s dwell time, while a static loading is applied in FT test; both tests measure visco-elastic response of materials and provide information about rutting behaviour of AC mixtures. For more details, readers are referred to [2].

|E*| is a basic design input parameter for AC mixtures obtained through laboratory testing and possesses highest precision level; |E*| test also correlates laboratory obtained results with field performance of AC mixtures that complements mix-design criteria in M-EPDG. On the contrary, $M_R$ has been used worldwide for the design of flexible pavements. $M_R$ is the elastic modulus to be used with the elastic theory and obtained through various data tests and reduction techniques [3,4]. The potential advantages of |E*| over $M_R$ could be: (a) |E*| provides full picture of asphalt mixtures by complete characterization (i.e., testing at various test temperatures and loading frequencies) while $M_R$ cannot be performed at various loading frequencies, (b) the effect of geometry is nullified in |E*| because height to diameter ratio is always constant while $M_R$ is performed at varying diameters which can significantly influence the stiffness parameter.

|E*| test, performed according to standard test procedure of AASHTO [5], was carried out for stiffness evaluation, measured in terms of |E*| and visco-elastic properties (i.e., phase angle, φ) of AC mixtures. In |E*| test, Superpave gyratory compacted specimens (100 mm diameter and 150 mm height) were subjected to a sinusoidal wave of compressive axial load (stress) under stress-controlled testing mode for a range of testing temperatures and loading frequencies. On the other hand, $M_R$ test was performed in accordance to ASTM [6] and a static repetitive haversine load of 0.1/0.3 s followed by 0.9/0.7 s rest period at a loading frequency of 1 Hz was applied on cylindrical specimen along a vertical diametral plane. However, different loading durations can be used to simulate actual vehicle speed on pavement.

Various research studies were conducted in past focusing on the characterization of AC mixtures using |E*| and $M_R$ test [2,7–12]. |E*|– which is as an input to M-EPDG in the form of master curves – was used to simulate axial stress–strain behaviour of an AC mix, characterized by testing conditions, e.g., testing temperature and loading frequency. The development of master curves required testing of a mix at multiple testing temperatures and loading frequencies typically encountered on pavements, which remained the objective of various studies [13–16]. However, $M_R$ has not received much attention recently due to its inability of evaluating pavement response analogous to |E*| master curves.

Witczak [17] carried out a study, which was summarized in NCHRP 1-37A project, that differentiated between |E*| and $M_R$ test for AC mixtures. The key differences like loading pattern, loading period, and specimen geometry as shown in Fig. 1 were reported. Several other research studies also pinpointed various differences between |E*| and $M_R$ [17–20], which are summarized in Table 1.

Apart from this, several researchers attempted to develop the correlation between these two test methods [21–23]. Birgisson et al. [21] determined the tensile dynamic complex modulus from indirect tensile strength (IDT) tests based on their developed testing and analysis protocols. This study found dynamic complex modulus to be in agreement with $M_R$ and testing frequency for a given range of testing temperatures and loading frequencies. Loulizi et al. [22] studied the relationship of |E*| and $M_R$ tests and confirm that there exists a correlation between these two tests methods. Similarly, Ping and Xiao [23] carried out a comparative study on |E*| and $M_R$ and report that |E*| performed at 4 and 5 Hz was strongly correlated with $M_R$ performed at a frequency of 1 Hz (0.1 s). These researches either used a single testing temperature and/or loading duration to determine the relationship between $M_R$ and |E*|. Building further upon this, the developed correlations in these studies were not rigorously tested e.g., using their own dataset as well as data acquired from already published literature. The rigorous testing of any developed correlations is essentially important consideration; and low predictive power of these correlations poses concerns for the pavement analysts and transport agencies to solely rely on the correlations for prediction of |E*| for design purposes. However, the literature is devoid of any evidence of rigorous testing of developed correlations and our understanding on this important aspect of |E*| and $M_R$ relationship remains elusive.

Given the differences between these two test methods and earlier work carried out by various researchers, this study aimed to derive a correlation between |E*| and $M_R$ in order to save the agencies' inventory and to ensure smooth transition from empirical to M-E design. Along this line, this study attempted to achieve following objectives: 1) to develop a correlation that can estimate |E*| using $M_R$ under similar testing conditions and test parameters; 2) to rigorously test the developed correlation using proposed bi-level testing protocol; and to compare the developed correlation with the one reported in literature; and 3) to develop a statistical model for prediction of |E*|.

Towards this end, the paper is organized as follows: Section 2 explains experimental plan including material section and bitumen content determination; Section 3 describes results obtained from performance testing; Section 4 presents correlation and rigorous testing, including model development; Section 5 discusses main findings and future work direction; and Section 6 summarizes study findings.

## 2. Experimental plan

The study design and experimental plan to achieve objectives is presented in Fig. 2. Firstly, material was selected and then the optimum bitumen content (OBC) of selected material was determined. Based on the OBC, specimens for performance testing were prepared. Two performance tests were carried out and results obtained from these tests were used for studying their relationship (i.e., by a correlation and statistical model). To verify the veracity and assess predictive power of the developed correlation, a bi-level testing protocol was proposed. At the first level, predictive capability of the correlation was assessed by validating the dataset from the current study, while at the second level, a cross-validation was carried out using the data acquired from the published literature. Further, a comparative analysis was performed for comparing the correlation developed in the current study with a correlation reported in literature using similar bi-level testing protocol. In addition, a statistical model was developed to improve the predictive capability, which was tested using proposed bi-level testing protocol.

### 2.1. Material selection and optimum bitumen content determination

This study used four wearing course mixtures of nominal maximum aggregate size 19 mm and 12.5 mm and an asphalt binder of penetration grade 60/70. The gradations included: Pakistan's National Highway Authority (NHA)'s Class A and B [24], Superpave mix (SP) [25] and Asphalt Institute Manual Series (MS)-2 mix [26]. The testing matrix presented in Table 2 explains the details of research study variables. The percent passing for each gradation