Prediction of the complex modulus of asphalt mixture containing RAP materials from the rheological properties of mortars

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ABSTRACT

In this paper, the properties of mortars that proportionally contain the same amount of fresh and RAP binder which can be found in the asphalt mixture, with respect to the specific material phase, are modeled with the objective of predicting the rheological behavior of the corresponding recycled mixture. For this purpose, Dynamic Shear Rheometer (DSR) tests are performed to determine the complex moduli of asphalt binders and mortars, which are then used as input in the empirical Hirsch and Witczak models. Based on the better predictions obtained from the latter, a modified formulation of the Witczak model was successfully derived to predict the mixture complex modulus directly from the experimental data of the corresponding asphalt mortar. The predictions obtained with the newly proposed expression of the Witczak model, closely match the laboratory measured complex modulus of asphalt mixtures. This can be used as input in the Mechanistic-Empirical Pavement Design Guide to analyze stress, strain, and deflection of asphalt pavements.

Keywords: Asphalt mixture; mortar; RAP; Hirsch model; Witczak model.

1. INTRODUCTION

The performance of flexible pavements is strictly associated with the modulus of asphalt mixture layers [1]. It is well known that the modulus depends on mixture volumetric properties, on the specific mix design, on loading rate and temperature [2]. Therefore, the complex modulus, E* can be used to characterize the asphalt mixture and represents a critical input in different design methods, such as the Mechanistic-Empirical Pavement Design (MPEDG) [3] in the US or in similar procedure available in Europe [4].

The MEPDG is a pavement design and performance predicting method, developed by the National Cooperative Highway Research Program (NCHRP) in 2002 [2], that using detailed traffic loading, material properties, and environmental data, allows to compute the pavement response and to predict the incremental damage over time. The MEPDG was adopted as a pavement design guide by the American Association of State Highway and Transportation Officials (AASHTO). For this purpose, pavement engineers need a quick, easy and accurate method to obtain the complex modulus avoiding complicated and time demanding laboratory tests on mixtures. In fact, these methods require a series of expensive sampling and testing equipment, experienced laboratory personnel, and a relatively long and complex analysis. For these reasons, empirical models, such as the Hirsch [5] and Witczak [6] models were developed.

These two models are capable of predicting the complex modulus of the mixture knowing the volumetric composition and the rheological properties of the binder. However, when Reclaimed Asphalt Pavement (RAP) materials are used, the characterization of the binder present in the mixture is associated with a number of limitations. This is because the binder consists of a mix of fresh and aged RAP binder with a certain degree of blending [7]. Extraction and recovery methods are commonly used to obtain and, then, characterize the binder contained in the recycled mixture [8]. Nevertheless, several studies have demonstrated that this method is not entirely accurate since it may alter the binder properties [9,10,11], as well as, results in a complete blending of fresh and RAP binder, which may not occur in the mixture [12].

Recently, investigation and modeling of asphalt mortar were proposed to provide a less test-demanding and time-consuming solution for addressing the use of RAP, in comparison to the complex characterization methods required by asphalt mixture [13]. If the experimental results obtained on asphalt mortar can be used as input in predictive models to determine the rheological properties of asphalt mixture, this would provide the possibility of obtaining critical information on mixture properties also when RAP is included in the mix design, simply relying on mortar testing. Such an approach would be more practical and easier to be implemented on a routine basis, especially for laboratories in road authorities and department of transportations.

In this paper, the possibility of using the rheological properties of asphalt mortars, prepared with RAP, to predict the corresponding properties of mixtures containing RAP is investigated. Asphalt mortars, consisting of fresh binder and different proportion of fine RAP particles, and RAP binder, were produced in order to recreate the same amount of fresh and RAP binder in the corresponding mixture. Then, the Hirsch and Witczak models were used to predict the complex modulus of the mixture. Next, a modified expression of the Witczak model was derived so that the rheological properties (G^* and δ) of asphalt mortar could be used in place of the binder data for predicting the corresponding E^* for the mixture.

2. MATERIALS AND TESTS

In the present work, four different asphalt mixtures were produced by mixing different proportion (0%, 20%, 35% and 50%) of a German RAP source with virgin aggregates and a traditional 50/70 fresh binder. All mixes have the following common characteristics: same gradation curve (Figure 1) commonly used in Germany for binder layer; Gabbro virgin aggregates size (11/16, 8/11, 5/8, 2/5, 0/2) and RAP material obtained from a single batch; 5% total binder content by weight of the dry mix; void content target at 4%±1.5%.

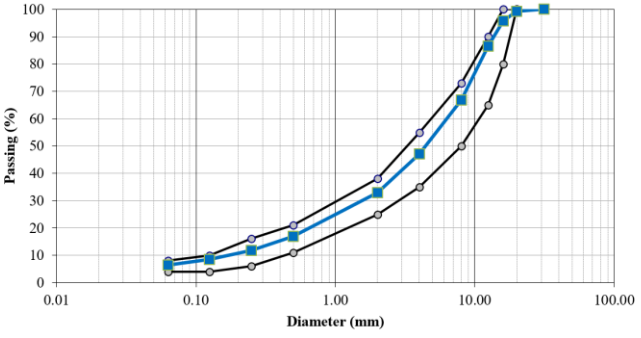

Figure 1 Gradation Curve used for Mixtures

The RAP content, 0%, 20%, 35% and 50%, was calculated in percentage by volume of the dry mixture; this corresponds to 0%, 19.6%, 34.2% and 48.5% by weight of the total mixture. All mixtures were mixed at 160°C and compacted at 150°C using a German sector compactor [14] producing slab with dimensions of 320 x 200 mm. From each slab, three cylindrical samples were cut with a diameter of 60 mm and a height of 180 mm.

All these mixture samples were tested in tension-compression mode (DTC-CY) according to EN 12697-26 - Annex D [15] in order to measure the complex modulus and the phase angle. In order to remain in the linear visco-elastic (LVE) domain and to avoid damage in the samples, a sinusoidal strain having a maximum amplitude of 50 microstrains was imposed to the specimens. The tested temperatures were -20, -10, 0, 10, 20, 30, 40°C and the frequencies were 0.1, 0.3, 1.59, 3, 5, 10 Hz. The specimen was conditioned for 5 hours at lower testing temperatures (-20, -10, 0°C) and for 4 hours at the remaining temperatures (10, 20, 30, 40°C).

Asphalt binders were extracted and recovered from the mixtures using the Rotatory Evaporator in accordance to EN 12697-3 [16]. Considering the volumetric composition of the mixtures, the blends of fresh and RAP binder obtained from extraction are shown in Table 1.

TABLE 1 Asphalt Binder Blends Composition

Bituminous Blends	Fresh binder	RAP binder
50/70+20%RAP	80.5%	19.5%
50/70+35%RAP	65.8%	34.2%
50/70+50%RAP	51.1%	48.9%

In addition, SRAP mortars composed by mixing the same fresh 50/70 binder previously used for mixtures with RAP material, passing sieve with an opening size of 0.15 mm, in different proportions, were produced to recreate the same amount of fresh and RAP binder in the blend and therefore, in the mixtures. Considering that the fine fraction of RAP contains 14.95% of RAP binder with respect to the aggregate and that the fine aggregate of the RAP has a density of 2.751 g/cm^3, the composition of the different mortars was obtained (Table 2). It must be noted that a percentage of RAP of 20%, 35% and 50% in the mixture correspond to a volume percentage of RAP particles in the mortar of 29%, 42% and 51%, respectively.

TABLE 2 Composition of SRAP Mortars

SRAP mortars	*Vp*	Fine particles of RAP	Fresh binder	RAP binder in the mortar	Total binder
SRAP 20%RAP	29	61.8%	38.2%	9.24%	47.4%
SRAP 35%RAP	42	77.7%	22.3%	11.61%	33.9%
SRAP 50%RAP	51	86.5%	13.5%	12.93%	26.5%

Frequency and temperature sweep tests were performed on both binders and mortars with the Dynamic Shear Rheometer (DSR) [17]. The plate-plate geometry with three different dimensions were used: the 4 mm plate was used for temperatures between -30°C and +10°C; the 8 mm for -10°C to +40°C; and the 25 mm for +30°C to +80°C. The tests were performed in stress-control mode for low temperatures and in strain-control mode for high temperatures. This mixed-mode approach was successfully used also in previous studies [18, 19].

3. EXPERIMENTAL RESULTS

Complex modulus and phase angle were calculated from the test results and the master curves of the different mixtures were plotted considering the Christensen Andersen Marasteanu (CAM) model [20]. The average value of the three samples tested for each type of mixtures was used to plot the master curves. The master curves are reported in Figures 2.

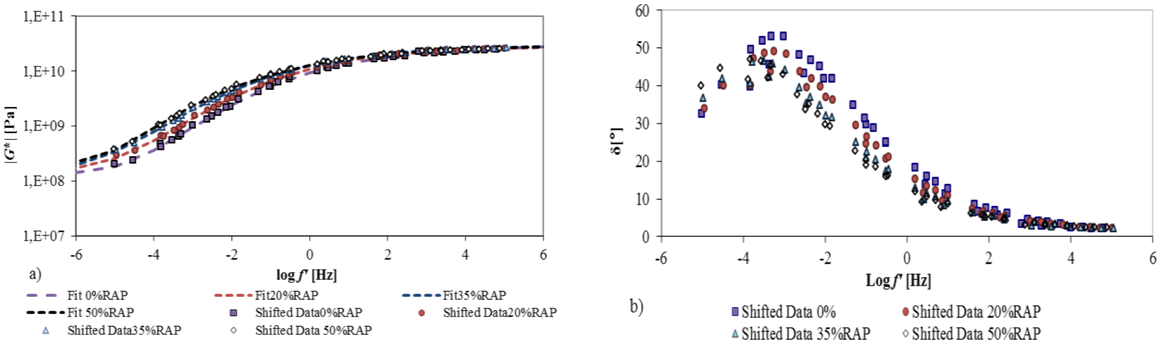

Figure 2 Master Curves of the Different Mixtures: a) Complex Modulus, b) Phase Angle

The complex modulus increases with the RAP content, while the phase angle decreases. Such a trend is not entirely surprising since the mixture becomes stiffer due to the RAP binder. The master curves of the complex modulus and of the phase angle for blends and mortars are reported in Figure 3 and 4, respectively.

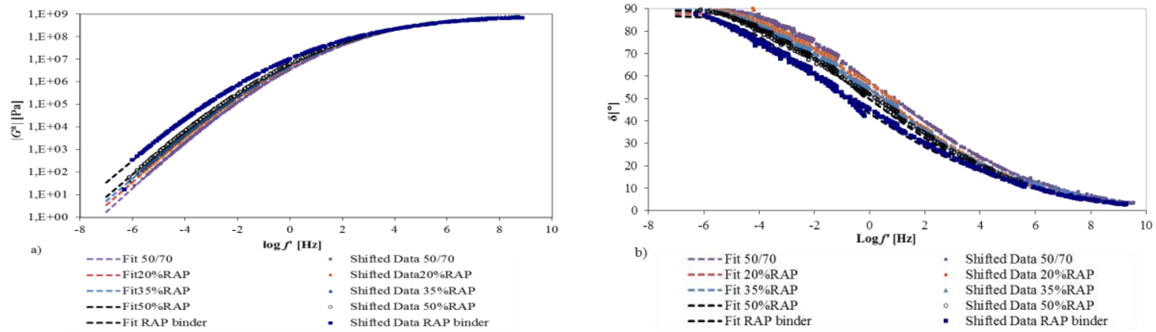

Figure 3 Master Curves of a) Complex Modulus and b) Phase Angle of the blends of Fresh and RAP Binder

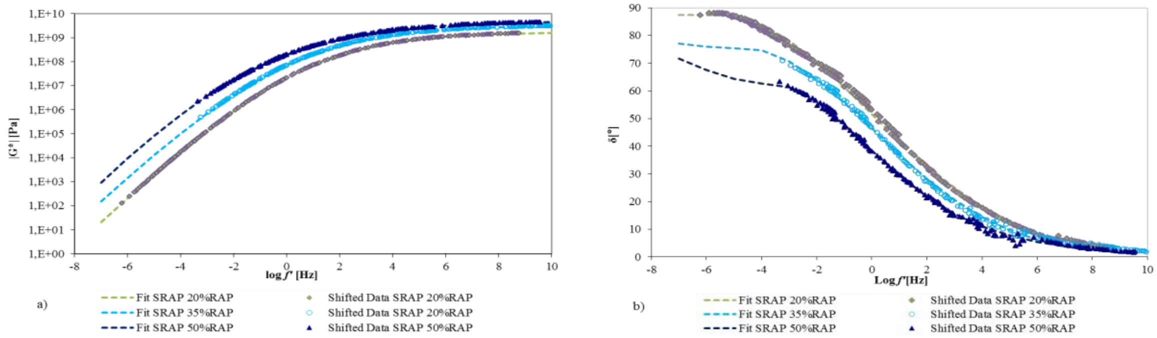

Figure 4 Master curves of a) Complex modulus and b) phase angle of SRAP mortars

As shown in the previous figures, the stiffening effect due to the presence of the aged binder and to the addition of particles is very significant. The mortar prepared with 50%RAP presents significantly larger complex modulus and lower phase angle with respect to other mortars; this is due to the stiffening effect of the aged binder contained in the RAP material.

5. MODELING AND ANALYSES

A number of empirical models were developed to predict the complex modulus of asphalt mixture from the corresponding asphalt binder. Two of the most widely commonly used models are those developed by Christensen et al. [21], based on the original Hirsch model [5]; and by Bari and Witczak [6] under the NCHRP 1-40D project (Witczak 1-40D model).

5.1 Empirical models' results

The Hirsch model [5] and the Witczak model [6] were used to predict the modulus |*E**| of the mixture starting from the rheological properties of the extracted binders. In Figure 5, the Hirsch and Witczak predictions are plotted against the experimentally measured modulus for all the mixtures. As shown, the Hirsch model underestimates the measured value by 23%, while the Witczak overestimates the measured value by 4%.

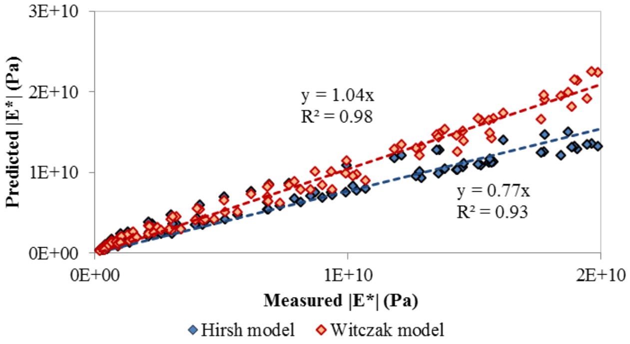

Figure 5 Predicted versus Measured Value of the Mixture Modulus |E*| with the Hirsch and Witczak Model from the Rheological Properties of Extracted Binders

Figure 5 suggests that the Witczak model provides a better prediction of experimental results in comparison to the Hirsch model for the material used in the present research. It is important to note that both empirical models were originally derived relying on a database of a specific set of mixtures [6, 21], therefore, their performance varies with the type of mixtures and volumetric properties.

On the other hand, the Hirsch model cannot closely predict the measured |*E**| since the formulation proposed by Christensen et al. [21] provides only a very simple assembly of the materials' phases, which cannot capture the number of interactions occurring in a complex mixture system. This is exemplified by the contact volume parameter, P_c, which empirically combines the contribution of the volumetric properties into a single value, disregarding, for example, shape and distribution of a critical material phase, such as air voids. This is also confirmed by the attempt of other authors [22] to propose alternative expression of P_c, which is, however, tailored to the specific material investigated.

5.3 Calibration of the Witczak model

Since the Witczak model shows better predictions compared to the Hirsch model for the mixture investigated in this study, the parameters of the Witczak model, reported in Equation 1, were fitted to directly link mortar and mixture properties.

$$\begin{aligned}\log E^* = {} & -a + b\,|G^*_{mortar}|(6.65 - 0.032\rho_{200} + 0.0027\,(\rho_{200})^2 + 0.011\rho_4 - 0.0001(\rho_4)^2 + \\ & +0.006\,\rho_{38} - 0.00014(\rho_{38})^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \\ & + \frac{2.56 + 0.03V_a + 0.71\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + 0.012\rho_{38} - 0.0001(\rho_{38})^2 - 0.01\rho_{34}}{1 + e^{\left(-c-d\ \log\left(\left|G_{bmortar}{}^*\right|\right)+e\ \log(\delta_{mortar})\right)}}\end{aligned} \tag{1}$$

where |*E**| is the complex modulus of mixture (psi), $|G^*_{mortar}|$ is the complex shear modulus of mortar (psi), ρ_{200} is the percentage passing #200 sieve, ρ_4 is the cumulative percentage retained on #4 sieve, ρ_{38} is the cumulative percentage retained on 3/8 in sieve, ρ_{34} is the cumulative percentage retained on 3/4 in sieve, V_a are the air voids (% by volume), V_{beff} is the effective binder content, δ_{mortar} is the mortar phase angle.

Based on nonlinear optimization, the initial parameters of the Witczak model, associated with the complex modulus and phase angle of the mortar (*a*, *b*, *c*, *d*, *e*) were estimated. For this purpose, all the mixtures composed with different percentage of RAP were analyzed. The parameters obtained from the optimization process are: a=4.215, b=1.493, c=10.111, d=0.327 and e=5.876.

Figure 6 presents a comparison between the Witczak model predicted complex modulus (using the rheological data of the mortar) and the measured experimental data. A strong linear trend can be observed as demonstrated by the very high regression coefficient R^2=0.95. Given a slope of 0.98, the model underpredicts the measured value by only 2%. In Figure 7, the residual plot (residuals versus predicted values) is presented. Residuals are considered to have a horizontal band pattern. Therefore, the calibrated model seems to reasonably predict $|E^*|$ of the asphalt mixtures investigated, starting from tests results on asphalt mortars.

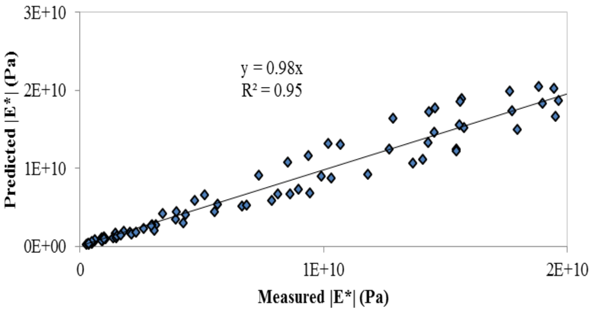

Figure 6 Witczak Predicted versus Measured Complex Modulus of the Mixture from Rheological Properties of Mortars

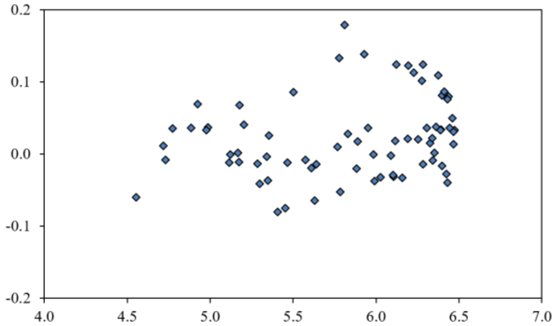

Figure 7 Residual Plots of the Calibrated Witczak Model

6. CONCLUSIONS

In this work, the empirical Hirsch and Witczak models were used to determine the complex modulus of asphalt mixture, starting from the rheological properties of the corresponding binder extracted and recovered from mixtures composed with different percentage of RAP materials (0, 20, 35, 50%). The Hirsch model was found to underpredict the measured value, while the Witczak model leads to slightly higher values of the complex modulus. In addition, it was found that the Witczak model better predicts the experimental values. Based on this initial analysis, the Witczak model parameters associated with the behavior of bituminous component were successfully calibrated to determine the complex modulus of the mixture knowing its volumetric properties and the rheological response of the corresponding mortar.

The new formulation showed a very close matching between experimental and Witczak's predicted complex modulus. In addition, the mixture behavior is directly obtained from tests on asphalt mortar, without relying on the extraction and recovery of RAP binder. Such an approach reduces the amount of time-consuming and costly tests of asphalt mixtures and will allow testing the RAP binder as is after the milling process avoiding any treatments and manipulations which may alter the recycled material properties. The predicted values of the mixture complex modulus can be used as input in the MEPDG [3] in order to evaluate the response asphalt pavement in terms of stress, strain, and deflection.

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