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RECALIBRATION AND DEVELOPMENT OF PREDICTION MODELS FOR DYNAMIC MODULUS OF BITUMINOUS MIXTURES

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Abstract

This study was conducted to predict the dynamic modulus of Pakistan's regionally prevalent bituminous mixtures using a wide range of material properties, mix design parameters, and testing conditions. A total of twenty-four bituminous mixes, characterized by sixteen distinct gradations and four different types of bitumen, were tested for dynamic modulus at various temperatures and frequencies. Three different types of models were used on the experimental data, namely, the traditional Witczak 1-37 model, recalibrated Witczak 1-37 model, and the recalibrated Witczak 1-37 model with dummy variables. Recalibration was done using 75% of the data, while the remaining 25% was used for testing. In each case, the model's accuracy was reported using R-squared values and two error parameters. The comparison of the models clearly demonstrated that the traditional Witczak model had the lowest accuracy in terms of the error parameters with error terms exceeding 3. Recalibrated models with and without the dummy variables, on the other hand, produced comparable results, with errors less than 0.5. The recalibration revealed an insignificant impact of fine material on stiffness. It also showed that 60/70 asphalt from a specific source has a significant impact on the model, while other types had an insignificant effect. The study findings are expected to be equally beneficial to both researchers and practitioners working on pavements mechanistic-empirical design. Future study might include incorporating other parameters and the most recent machine learning techniques to build models for the prediction of locally utilized bituminous mixes in Pakistan.

Keywords:

Local bituminous mixtures;
Dynamic modulus;
Regression models;
Dummy variables.

1 Introduction

The dynamic modulus of bituminous mixtures is a key element in the structural design of asphalt pavements and is closely related to several other parameters [1, 2]. To meet the demands of optimal performance, asphalt mix designers usually address three variables: bitumen, aggregates, and the proportion of bitumen to aggregates. In recent years, both the newly constructed and rehabilitated asphalt pavements in Pakistan have experienced an upsurge in premature failure due to rutting and fatigue cracking. Such premature failure is attributed to the existing design procedures, which are primarily based on the 1993 AASHTO design guide and fail to produce adequate and valid designs for heavy loads in diverse weather and climatic conditions. This highlights the need for the development of a new and more comprehensive design approach that integrates both mechanistic and empirical design features. The mechanistic and empirical design features address not only the factual characterization of pavement materials, but also the pavement response prediction models and transfer functions. Although accurate characterization of bituminous mixtures based on material properties is quite challenging, the material's dynamic modulus property stipulates insights into the time-temperature dependency of the bituminous mixtures. The dynamic modulus of bituminous mixtures is a stiffness parameter that partially describes its viscoelastic properties. This parameter indicates the bituminous mixture's ability to resist deformation when subjected to sinusoidal loading. It is defined by the absolute value of the complex modulus [3, 4]. This importance stems from its selection as a crucial factor in the assessment of bituminous mixtures for pavement design, as outlined in the AASHTO pavement design guide. Additionally, it has been proposed as a potential tool for evaluating the performance of bituminous mixtures, supplementing the existing Superpave mix design techniques.

The dynamic modulus of bituminous mixtures is influenced by several parameters, including variations in asphalt mix characteristics, climatic conditions, load dependent behavior of bitumen, and varying service conditions [5-7]. Many studies have been conducted to better understand the parameters that influence the dynamic modulus. In addition to aggregate type, bitumen content, and reclaimed asphalt pavement (RAP) proportions, the job mix formula has been shown to have a considerable influence on the dynamic modulus of bituminous mixtures at high temperatures and low frequencies [8-10]. Aggregate morphology also has a considerable influence on the dynamic modulus of bituminous mixtures, which is closely associated with the distribution of aggregate morphology indices [11]. The dynamic modulus of bituminous mixtures is also considerably affected by bitumen grade. Softer bitumen exhibits a lower dynamic modulus, whereas harder bitumen demonstrates opposite effect [12-14]. The dynamic modulus of bituminous mixtures exhibits an increase in correlation with the nominal size of aggregate. Nevertheless, a reduction in aggregate's nominal size by one level results in a decrease of the dynamic modulus of bituminous mixtures by approximately 16 to 21% under the conditions of a frequency of 10 Hz and a temperature of 21°C [15].

In addition to material properties, some studies have also investigated the influence of mix design parameters on the dynamic modulus of bituminous mixtures. Regarding this, a recent study [16] built a multiple linear regression prediction model and revealed that the subsequent parameters, arranged in descending order of importance, greatly influence the dynamic of asphalt mixtures: viscosity and complex modulus of the bitumen, voids filled with asphalt (VFA), air voids (AV), bitumen penetration, and softening point. Furthermore, the relationship between the dynamic modulus and bitumen viscosity and complex modulus showed a high degree of agreement. Conversely, another study [17] concluded that the dynamic modulus of asphalt mixtures is mostly influenced by the softening point (13.3%), followed by the air void volume (12.5%), and the voids in mineral aggregates (VMA) (12%). The bitumen viscosity and complex modulus were found to have relatively minimal influence on the dynamic modulus of asphalt mixtures. A study of typical mixtures used in Colorado, USA reported a direct relation between the dynamic modulus and amount of effective bitumen (Vbe), Va, and VFA, and an inverse relation between the dynamic modulus, bitumen content, and VMA. However, compared with Vbe, Va, and VFA, the influence of VMA and bitumen content on the dynamic modulus was found less sensitive [18,19].
Several studies [20-22] have concluded that the testing conditions, especially temperature and frequency, are the most critical parameters influencing the stiffness values of bituminous mixtures. The asphalt mixture performance tester (AMPT) was utilized to characterize bituminous mixtures, and the findings indicated that the dynamic modulus of the bituminous mixtures reaches its peak at 30°C. Subsequently, a gradual decline in the dynamic modulus was observed at 35, 40, 45, and 50°C, respectively. The results also revealed that low-phase angle values correspond to low viscosity of the bitumen due to increased temperature [12]. The performance evaluation of recycled asphalt mixtures indicated that RAP content affects the dynamic modulus such that it increases with increasing loading frequency and lower temperature [23]. Similarly, research on cold recycled emulsified asphalt mixtures revealed a rise in the dynamic modulus as the loading frequency increases. The increase was noted in the beginning, but when frequency reached 10 Hz, the rise in the dynamic modulus became consistent, and its rate steadily decreased [24].

The Witczak model is widely regarded as the most extensively utilized and acknowledged model for predicting the dynamic modulus of bituminous mixtures. Currently, there exist two versions of the model: the original 1999 model (Witczak 1-37A) and the revised 2006 model (Witczak 1-40D) [25, 26]. Both models use multivariate regression techniques and are available in the ongoing versions of the mechanistic-empirical pavement design software [27, 28]. Despite the Witczak models demonstrating efficacy in universal applications like the mechanistic-empirical pavement design guide, limitations may occur in more localized or project-specific scenarios. It has been reported that the Witczak model exhibits noticeable bias at both the lower and higher extremes of dynamic modulus [29, 30].

This research study employed the Witczak model to predict the dynamic modulus of locally used asphalt mixtures in Pakistan, a subject matter that has not been comprehensively explored, particularly using such a large-scale dataset. In brief, this study examines the impact of material properties, mix design parameters, and testing conditions on the dynamic modulus of bituminous mixtures locally used in Pakistan. A total of twenty-four bituminous mixtures, comprising sixteen distinct gradations and four types of bitumen, commonly used to build pavements in Pakistan, were investigated. The dynamic modulus of these bituminous mixtures was determined using AMPT at four distinct temperatures and six varying frequencies. The traditional Witczak model was employed to validate its predictive capability for the dynamic modulus of available dataset, and the obtained results were statistically analyzed to ascertain its accuracy. In addition, recalibration of the existing model was also carried out to explore the potential increase in its prediction accuracies. The results of this study are expected to be equally beneficial for researchers and practitioners involved in the mechanistic-empirical design of pavements.

2 Materials and methods

The subsequent sections provide a brief overview of the materials and methods employed in this research study. Initially, the aggregate and bitumen were evaluated in accordance with their standard specifications. The optimum bitumen contents (OBC), AV, VMA, VFA, and strength parameters of bituminous mixes were then determined following the specifications of the Marshall mix design method. Based on the calculated OBC, Superpave gyratory compacted samples were prepared and sliced using core cutting and saw cutting machines. Following the standard specifications, the dynamic modulus test was conducted at varying temperatures and frequencies. Ultimately, statistical analysis was carried out on the laboratory test data using the traditional Witczak 1-37 model, uncalibrated Witczak 1-37 model, and calibrated Witczak 1-37 model. Finally, conclusions were drawn and suggestions for future research were provided as described in the following sections.

2.1 Aggregates

In this study, limestone aggregates, acquired from a local source were selected to be used. The mineral composition of the aggregates was determined through petrographic analysis in accordance with ASTM C295 standards. This method involves a microscopic examination of the aggregate samples to ascertain their mineralogical and textural characteristics. Such analysis yields important information regarding the composition and appropriateness of the aggregates for various construction applications. The results concerning the mineral composition of the aggregates are illustrated in Fig. 1. Several laboratory tests were performed to ascertain the basic characteristics of the aggregates, which were found to fall within the specified ranges of the test standards. These properties are summarized in Table 1. Sixteen different gradation blends were developed and named G-1 to G-16. The sieve analysis of the classified gradation blends is described in Table 2.

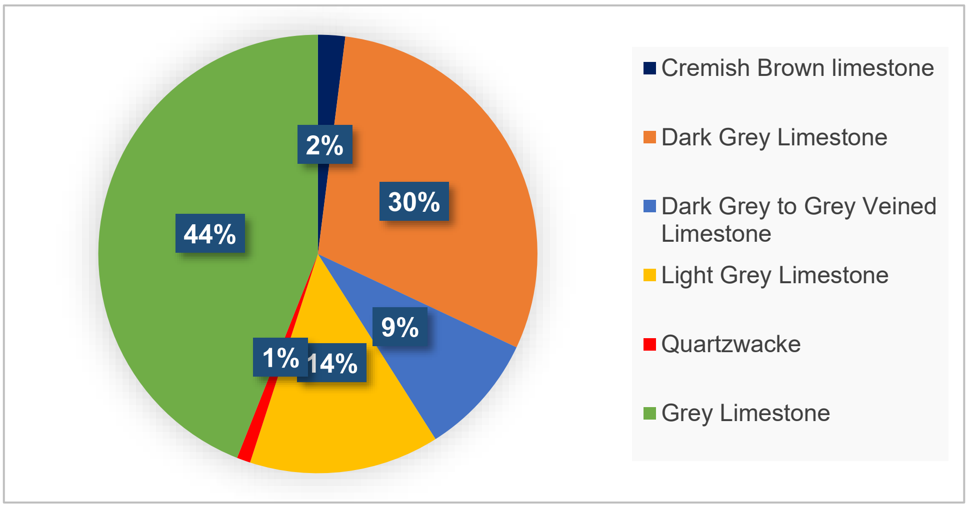

Fig. 1: Mineral composition of aggregates.

Table 1: Properties of mineral aggregates.

Property/Test	Standard	Average Value	Range
LA Abrasion [%]	AASHTO T96	26	≤ 30
Elongation Index [%]	ASTM D 4791	7	≤ 10
Flakiness Index [%]	ASTM D 4791	5	≤ 10
Sand equivalent value [%]	AASHTO T 176	72	≥ 45
Soundness [%]	AASHTO T104	3.38	≤12

Table 2. Details of gradation blends.

Gradation Type	Sieve Sizes (mm) and Percent Passing								
	37.5	25.0	19.0	12.5	9.5	4.75	2.36	0.30	0.075
G-1	-	-	-	82.5	68.7	49.3	30.8	10.5	5.2
G-2	-	-	99.9	79.5	69.4	48.7	35.3	11.8	5.2
G-3	-	-	99.7	84.5	63.4	46.0	30.5	10.3	5.0
G-4	-	-	-	80.0	67.0	48.0	33.0	11.0	4.7
G-5	-	82.6	69.7	59.2	52.2	41.6	24.5	9.4	5.0
G-6	-	85.4	71.0	59.9	53.4	35.5	26.4	10.8	4.7
G-7	98.8	82.7	67.4	56.2	43.5	35.0	25.1	7.6	4.2
G-8	-	-	95.0	76.0	63.0	42.5	29.0	8.5	5.0
G-9	-	-	-	82.0	70.0	50.0	30.0	10.0	5.0
G-10	-	-	-	94.0	87.0	65.0	37.0	9.0	5.0
G-11	-	-	-	95.0	82.0	59.0	43.0	13.0	6.0
G-12	95.0	77.0	65.5	52.5	44.0	31.5	22.5	7.0	4.5
G-13	-	82.5	72.5	62.5	52.5	37.5	25.0	10.0	4.5
G-14	-	95.0	85.0	60.0	47.0	30.0	20.0	8.0	4.0
G-15	-	95.0	83.0	70.0	63.0	52.0	39.0	14.0	5.5
G-16	-	-	95.0	83.0	65.0	46.0	30.0	9.0	5.0

2.2 Bitumen

In Pakistan, the two largest bitumen manufacturing sources are Attack refinery limited (ARL) and national refinery limited (NRL). Based on prevalent construction procedures in Pakistan, four types of bitumen were obtained from ARL and NRL for the development of bituminous mixtures. The tests for penetration (AASHTO T49), softening point (AASHTO T53), flash and fire point (AASHTO T48), and viscosity (AASHTO T316) properties of the selected bitumen were performed, and the results are summarized herein Table 3. From the properties of bitumen's, it can be observed that ARL's 40/50 bitumen is the harder grade bitumen as evident by the low value obtained in the penetration test, followed by NRL 60/70, ARL 60/70, and ARL 80/100, respectively. Moreover, from the results of the viscosity test, it can be inferred that ARL 40/50 exhibits the highest viscosity, and consequently offers more resistance to flow. While ARL 80/100 possesses the lowest viscosity and thus offers the least resistance to flow, making it the easiest to work with at the specified temperature.

Table 3: Properties of bitumen.

Bitumen Tests	Standard	ARL 40/50	ARL 80/100	ARL 60/70	NRL 60/70
Penetration [0.1 mm]	AASHTO T49	43	84	66	64
Softening Point [°C]	AASHTO T53	52	46	48.8	49.2
Flash and Fire Point [°C]	AASHTO T48	335 & 359	233 & 275	304 & 334	310 & 343
Viscosity [Pa.s] @ 135°C	AASHTO T316	0.486	0.226	0.241	0.292

2.3 Marshall mix desing

The Marshall method was used to develop bituminous mixtures and determine the mix design parameters for the selected gradations and bitumen [31]. For this, bituminous mixes were developed at varying bitumen contents as shown in Fig. 2. Fabrication of the specimens was carried out by delivering seventy-five blows to each side of the specimens to ensure adequate compaction. During the compaction process, care was taken to keep the temperature at 145 ± 5°C. The specifics of the mix design are summarized in Table 4. After the determination of OBC, gyratory compacted samples were prepared for dynamic modulus test. Following the cooling period, each of the compacted samples was cored and sawed to the required dimeter of 100 mm and height of 150 mm to comply with the specimen requirements of the dynamic modulus test, as shown in Fig. 3 [1].

Fig. 2: Samples for optimum bitumen content (OBC).

Fig. 3: Samples for dynamic modulus test.

Table 4: Summary of Marshall mix design results.

Bitumen source/type	Gradation type	AV [%]	OBC [%]	VMA [%]	VFA [%]	Stability [KN]	Flow [mm]
ARL 40/50	G-8	4.0	3.9	13.09	69.44	1198	2.29
	G-10	4.0	5.5	15.22	73.71	1447	2.63
	G-14	4.0	3.4	13.16	69.62	2243	3.40
	G-15	4.0	4.4	13.55	70.48	3114	9.00
ARL 80/100	G-8	4.0	3.7	11.32	64.66	790	2.68
	G-10	4.0	4.6	15.04	73.40	934	2.58
	G-14	4.0	3.3	11.45	65.07	2526	8.81
	G-15	4.0	4.3	12.30	67.50	610	7.52
ARL 60/70	G-3	4.0	4.2	14.20	66.50	1343	3.10
	G-4	4.0	4.2	13.40	59.50	1298	2.99
	G-7	4.0	3.5	12.80	58.00	2632	5.02
	G-8	4.0	4.0	12.15	66.08	1362	3.00
	G-9	4.0	4.1	12.95	65.16	1291	3.16
	G-10	4.0	5.0	14.70	69.18	1424	3.38
	G-11	4.0	4.8	14.52	67.73	1544	3.28
	G-12	4.0	3.3	11.38	62.19	2650	4.81
	G-13	4.0	3.7	11.87	63.33	2905	4.66
	G-14	4.0	3.6	12.17	61.93	2295	5.38
	G-15	4.0	3.9	12.40	61.33	3496	4.53
	G-16	4.0	4.36	14.43	74.53	3235	9.12
NRL 60/70	G-1	4.0	4	14.8	66.9	1290	2.88
	G-2	4.0	4.4	15.3	63.5	1330	3.052
	G-5	4.0	3.3	13.7	58.1	2890	4.302
	G-6	4.0	3.4	13.2	59.2	2620	4.981

2.4 Performance tests

The dynamic modulus describes the stress-strain relationship of linear viscoelastic substances subjected to a continuous sinusoidal load. It represents the ratio of the maximum dynamic stress to the maximum recoverable axial strain. The phase angle, denoting the degree of lag between the maximum recoverable axial strain and the maximum dynamic stress, indicates the viscous nature of the asphalt mixes. It is important to note that materials with lower viscosity have a phase angle close to 0°, while materials with high viscosity have a phase angle close to 90° [32, 33].

The dynamic modulus test can be executed with AMPT, which applies a repeated cyclic axial load of constant magnitude and duration to the test specimen as shown in Fig. 4 [32-37]. Additionally, the device includes a conditioning chamber that can regulate temperatures up to 60°C and pressures up to 210 kPa. In this study, replicate specimens of the classified bituminous mixtures were subjected to dynamic modulus testing at temperatures of 4.4, 21.1, 37.8, and 54.4°C, utilizing loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. The specimens were conditioned before the test to attain the requisite equilibrium and test temperatures. The dynamic modulus and phase angle data were recorded for each temperature and frequency at the end of the test, which were then used for developing prediction models.

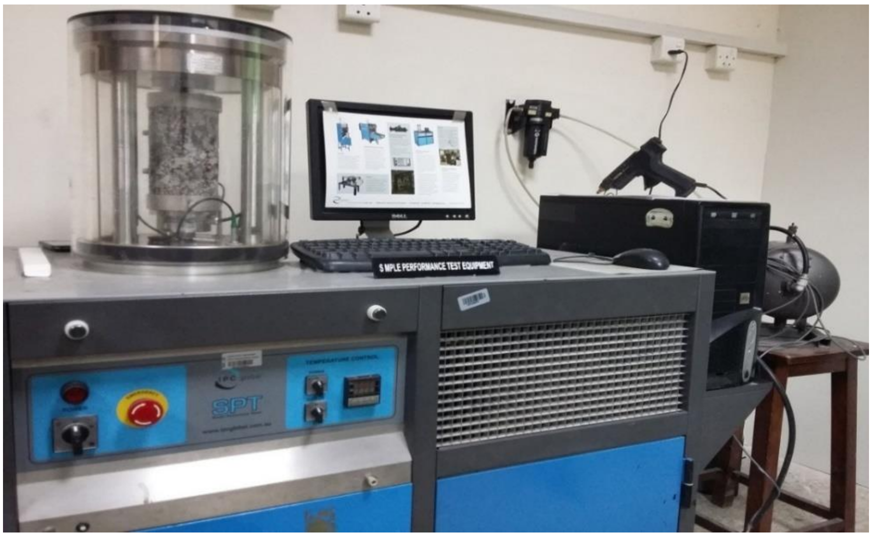

Fig. 4: Execution of simple performance test on cored sample.

Fig. 5 represents the comparison of dynamic modulus for different types of bitumen in the form of a box plot. It can be observed that ARL 80/100 has lower moduli compared to other types of bitumen. This could be linked to higher flow/softness of this type of bitumen resulting in lower stiffness modulus. Consequently, the highest moduli are observed for 40/50 bitumen type. Among the 60/70 bitumen types, samples with bitumen from NRL show higher moduli and less variation while those with bitumen from ARL exhibit lower moduli and more variation. In fact, the variation in the latter is the highest among all other types of bitumen used in this study. These trends make the use of such bitumen in the pavement construction questionable.

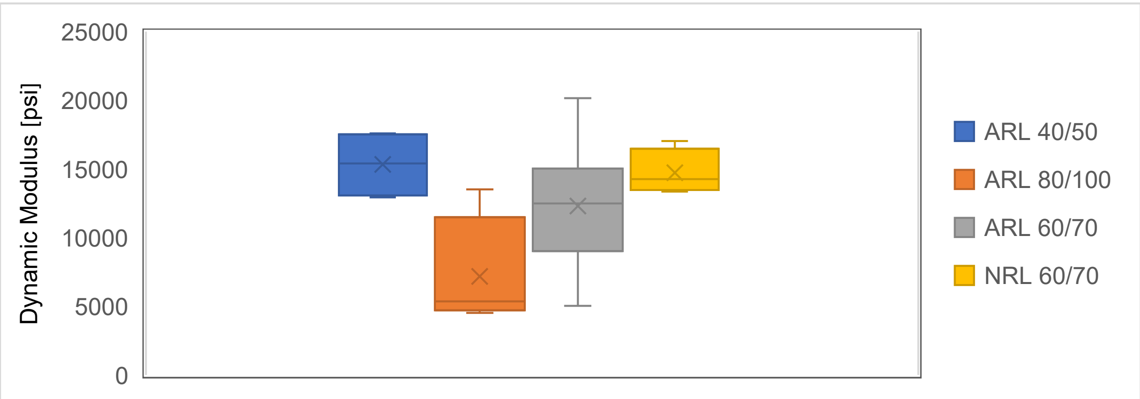

Fig. 5: Comparison of results for different types of bitumen.

2.5 Modeling parameters

As mentioned above, the modeling of the experimental parameters is done on the basis of Witczak 1-37 model. The model provides the log of dynamic modulus and its input variables include the proportions of aggregate retained on sieves of sizes #200 (0.075 mm), #4 (4.75 mm) and 3/8" (9.5 mm), respectively, the air voids ratio in the Marshall sample, the proportion of effective asphalt content in the sample, the loading frequency during the test (Hz), the bitumen viscosity at the test temperature in (105 pa.s). The same parameters were used at the recalibration stage of the model. At the third stage of the modeling task, dummy variables for each type of bitumen (as shown in Table 3) were used as additional input variables in the model while recalibrating it.

3 Results and discussion

The acquired data was modeled using three different approaches. First, the traditional Witczak 1-37 model was applied without any changes. Recalibration of the Witczak model is required when dealing with new materials, regional differences, and large datasets. This research focuses on the dynamic modulus of asphalt mixtures at a local level, hence the recalibration of the Witczak model was conducted to enhance its precision and applicability. The said model was therefore recalibrated using 75% of the data and the remaining 25% was utilized for testing its performance. The model was then recalibrated once more when dummy variables (0, 1) representing different bitumen types were included. This step used the same data distribution as the initial recalibration. In each case, two error parameters and R-squared values were used to report the accuracy of the model. The model's results are detailed in the following sub-sections.

3.1 Witczak 1-37 Model (Uncalibrated)

The uncalibrated Witczak 1-37 model was applied on the entire available dataset. Before doing so, several changes were made to the available dataset to match the units of the parameters used in the model. This model is represented by the equation (1).

$$\log E = -1.249937 + 0.02923P_{200} - 0.001767P_{200}^2 - 0.002841P_4 - 0.05809V_a - 0.082208[V_a/(V_a+V_{beff})] + [(3.871977-0.0021P_4+0.003958P_{3/8}-0.000017* P_{3/8}^2-0.00547P_{3/4})/\{1-EXP(-0.6033-0.313351LOG(f)-0.3935321*LOG(\eta*10^{-5})\}] \quad (1)$$

Where E is the dynamic modulus in psi, P200, P4 and P3/8 are the proportions of aggregate retaining of sieve of size #200 (0.075 mm), #4 (4.75 mm) and 3/8" (9.5 mm), respectively, Va is the air void ratio in the Marshall sample, Vbeff is the proportion of effective asphalt content in the sample, f is the loading frequency during the test (Hz), η is the bitumen viscosity at the test temperature in (105 pa.s) [38]. Since the available dataset was not utilized for calibration or development of this model, it was used completely (without any distinction of development and test datasets) for testing of the model. It was found that the mean absolute error for the model on the available dataset was 3.17 and its root mean square error was 3.21. Fig. 6 depicts the scatterplot between the predicted and observed values along with the R-square value for the plot.

Since the model predicts the log of the dynamic modulus, which limits the parameters to a restricted range, the error terms were found to be particularly large. Furthermore, the scatter plot's R-square value was discovered to be quite low. It is worth noting that the Witczak 1-37 model is empirical in nature and can only provide accurate estimations in conditions in which it was developed. Since a wide range of aggregates and bitumen are utilized in the development of bituminous mixtures, developing a universal relationship that can be applied to all bituminous mixtures is extremely difficult, if not impossible [39]. This prompted the researchers to initiate the process of recalibrating the Witczak 1-37 model for the available dataset, which is detailed in the next sub-section.

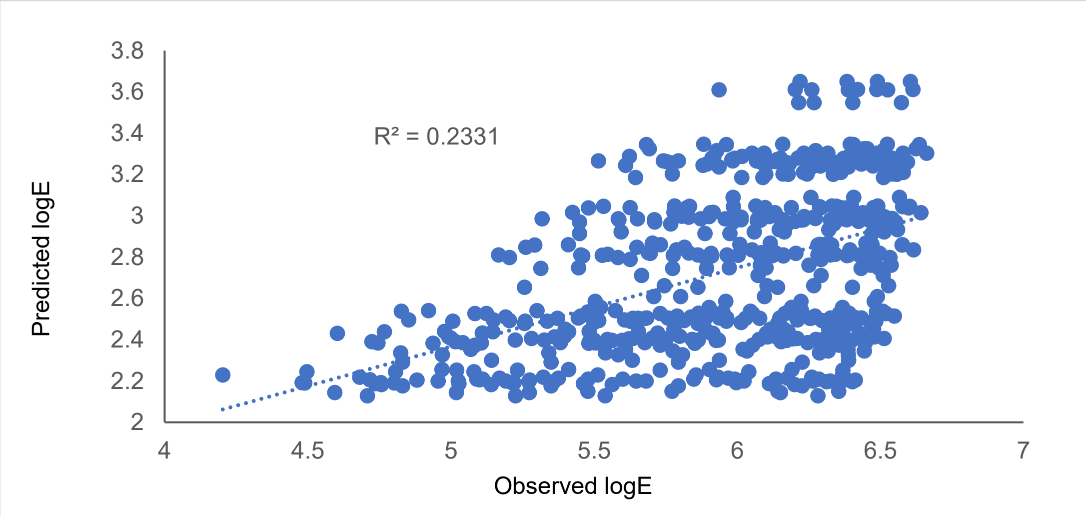

Fig. 6: Plot of the Witczak 1-37 Model.

3.2 Witczak 1-37 Model (Calibrated)

Ordinary least-square regression method was used for recalibrating the traditional Witczak 1-37 model. The terms utilized in this model were the same as those in the original model; however, some of those terms were either found to have a statistically insignificant effect on the model or had no variation on the available dataset. One such term was Va, which was used 4% in the standard procedure for Marshall method to obtain optimal performance [40], hence, being the same for all samples. The final equation is shown as (2).

$$log E = 5.86 – 1.32[V_a/(V_a+V_{beff})]– 0.64 [(3.871977-0.0021P_4+0.003958P_{3/8}-0.000017* P_{3/8}^2-0.00547P_{3/4})/\{1-EXP(-0.6033-0.313351LOG(f)-0.3935321*LOG (\eta*10^{-5})\}] \quad (2)$$

All the model's parameters were found to be the same as defined earlier. The significance of the model coefficient, in terms of t-statistic and its p-values are given in Table 5. It could be observed that the linear and quadratic terms for P200 were found to have no meaningful influence on the model, thus they were entirely removed from the model. Hence, it could be said that the proportion of fillers had an insignificant influence on the model. This can be accredited to the fact that fillers have no direct impact on the stiffness of the asphalt mixtures. Fillers mainly enhance the workability and durability of asphalt mixtures, linking their function more to the microstructure of the mixtures rather than the macroscopic properties assessed by the dynamic modulus. The mean absolute error for the recalibrated model is shown in Table 6, and the scatterplot of the predicted and observed values is shown in Fig. 7. As mentioned earlier, the data was divided into two sets for model building and testing, each consisting of 432 (75%) and 144(25%) of the total available samples. To assure equality, stratified sampling was employed to choose values for the development and test datasets [41].

Table 5: Significance of coefficients for Recalibrated Witczak 1-37 model.

Coefficient	t-statistic	p-value
5.86	18.67	2.24E-57
-1.32	-2.12	0.03
-0.64	-11.60	2.88E-27

Table 6: Error terms for Recalibrated Witczak 1-37 model.

Data	Mean absolute error	Root Mean square error	R-square
Development	0.33	0.41	0.25
Test	0.36	0.44	0.24

The model's performance was nearly the same for the development and test samples, which is an indicator of its robustness. However, in both situations, the R-squared value was still very low.

Fig. 7: Plot of Recalibrated Witczak 1-37 model.

3.3 Witczak 1-37 Model (calibrated with dummy)

The influence of bitumen on the dynamic modulus could be multidimensional, hence it might not be sufficient to include the viscosity of the bitumen in the model. As a result, many researchers updated the Witczak model and developed other models for the prediction of the dynamic modulus [42]. Thus, it made sense to attempt to add more bitumen-related variables to the model in this study. To do this, dummy variables were introduced for each type of bitumen in the available dataset. This would be a convenient method to comprehensively incorporate and differentiate the impacts of various bitumen types. Particularly, since one of the bitumen (NRL 60/70) had a different source than the others.

The recalibrated model using the dummy variable is given by equation (2). This model was recalibrated using the same procedure as the previous recalibration. ARL 60/70 was discovered as the only distinguishing bitumen type while the other bitumen types were found to have the same effect, as seen by their exclusion from the equation owing to their insignificant influence on the model. The unique characteristics of ARL 60/70 bitumen can be attributed to its chemical composition, which may differ among the different penetration grades bitumen. ARL 60/70 bitumen may possess a specific combination of chemical components, thereby impacting the Witczak model differently compared to other types of bitumen. The use of this approach is justified by the fact that one of the bitumen types had a significant impact on the model despite maintaining the same variables from the earlier recalibration.

$$logE=5.86-0.22(ARL60/70)-1.32[V_a/(V_a+V_{beff})]-0.64[(3.871977-0.0021P_4+0.003958P_{3/8}-0.000017*P_{3/8}^2-0.00547P_{3/4})/\{1-EXP(-0.6033-0.313351LOG(f)-0.3935321*LOG(\eta*10^{-5})\}] \quad (3)$$

Table 7 shows the significance of variables' coefficients for this model. Table 8 shows the error terms calculated for the recalibrated model with the dummy variable, whereas Fig. 8 illustrates the scatterplots of the predicted and observed values for the development and test datasets.

Table 7: Significance of coefficients for Recalibrated Witczak 1-37 model with dummy variable.

Coefficient	t-statistic	p-value
5.96	19.22	7.71E-60
-0.21	-3.86	0.00
-1.42	-2.32	0.02
-0.63	-11.55	4.54E-27

Table 8: Error terms for Recalibrated Witczak 1-37 model with dummy variable.

Data	Mean absolute error	Root Mean square error	R-square
Development	0.32	0.40	0.28
Test	0.35	0.43	0.27

Fig. 8: Plot of Recalibrated Witczak 1-37 model with dummy variable.

3.4 Comparison of the model performances

The model's ability to predict the dynamic modulus served as the initial benchmark for comparison. Fig. 9 shows a comparison between the models in terms of mean absolute error and root mean square error values. This clearly demonstrates that the original Witczak model had the lowest accuracy in terms of error parameters. Recalibrated models with and without the dummy variables, on the other hand, produced comparable results. In terms of error, the recalibrated models are providing better performances than some of the earlier studies [43].

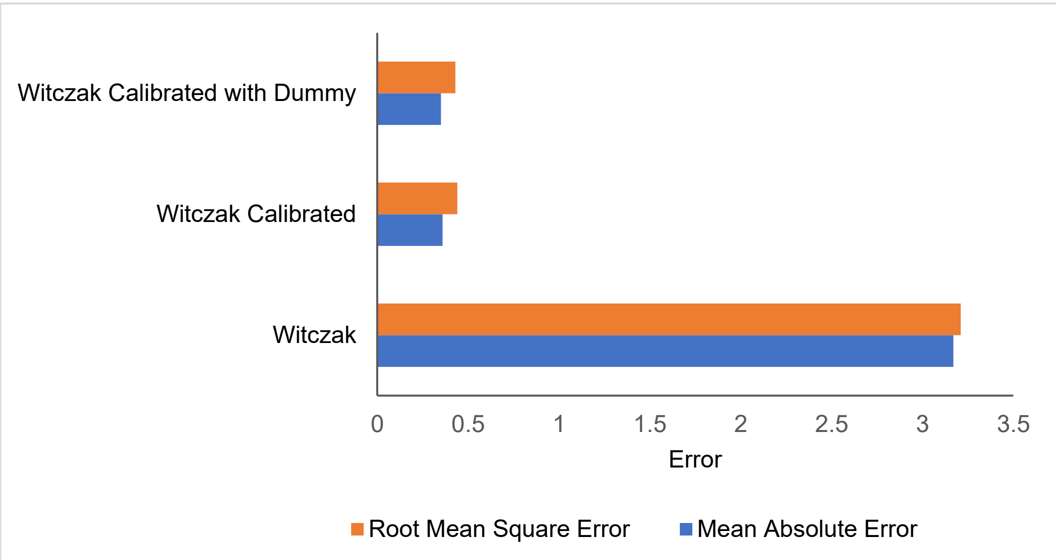

Fig. 9: Plot for the comparison of model performances.

The R-squared values for all models, however, were within standard deviations of one another and below the parameter's allowable bounds [44]. A concise review of literature showed that R-squared value is not always considered a valid parameter for evaluating the performance of non-linear models due to the variance distribution which does not add up in the equation [45]. The comparison of the traditional Witczak 1-37 model (Equation (3.1)) and the recalibrated models (Equations (3.2) and (3.3)) reveals a significant difference, which would account for the improvement in prediction performance of recalibrated models. To begin with, the parameters related to the proportion of fillers were discovered to be insignificant in the recalibrated models. This could be linked to the test conditions and/or the type of bitumen used because fillers do not affect the bituminous mixtures evenly; rather, the effects vary depending on the bitumen and gradation [46]. Similarly, another parallel study [47] revealed the inability of the quality-related specifications software (QRSS) distress predictive models to capture the influence of filler type on anticipated dynamic modulus. This is owing to the dynamic modulus prediction model's constraint of characterizing the filler simply by the P200, which was kept nearly constant across all the bituminous mixtures.

To study this influence, a more comprehensive investigation with additional samples and parameters would be required. Second, the influence of some of the parameters changed in terms of the sign of their coefficients. Those parameters were combinations of various independent variables; hence it was not possible to discern the influence of individual parameters on the dynamic modulus. The recalibrated model, on the other hand, consistently generated positive predictions for all ranges of available data.

The introduction of dummy variables for bitumen type did not significantly change the variables and their impacts compared to those found in the previous recalibration. However, the usage of ARL 60/70 was found to have a significant negative influence on the model. Hence, it could be argued that the use of this bitumen type is less preferable for durable asphalt mixes. The available bitumen properties (penetration, softening point, flash and fire point, viscosity, and stiffness) did not show any reason for the distinctive effect of this type. To ascertain the cause, a more detailed experimental program concentrating on this bitumen type and its characteristics would be required.

4 Conclusions

• The aim of this study was to determine the effectiveness of Witczak 1-37 model for predicting the dynamic modulus of asphalt concrete using a wide range of material properties and mix proportions. In addition, the Witczak model was recalibrated using two distinct ways to improve its accuracy on the available dataset. The recalibration efforts proved to be beneficial in reducing the average error from 3 to less than 0.5.

• It was found that the recalibrated models outperformed the traditional Witczak model significantly. Furthermore, the recalibrated models filtered the terms related to the proportions of fine materials in the asphalt mix. The significance of the variables at the recalibration stage was tested using a t-statistic with a confidence level of 5%. Finally, the use of ARL 60/70 bitumen showed a significantly distinct influence on the prediction of the model. The graphical analysis of the results showed that ARL 60/70 had a negative impact on the dynamic modulus and increases the variation in the data with values ranging from 20000 to 5000 psi.

• One of the limitations of the current study was the exclusion of other models for predicting dynamic modulus due to a lack of relevant parameters for those models. The results of the study were found to be encouraging, and it is recommended that recalibrated models be tested on other datasets. The performance of the models on the test dataset indicates that they are robust.

• Future directions of research could include incorporating other parameters and cutting-edge machine learning techniques to build models for the prediction of dynamic modulus of asphalt concrete. However, the application of these techniques to other datasets and their explanatory power is a challenge that should be considered in such cases. Another direction of research is a more detailed experimental program focusing on the study of variables found to influence the recalibrated models in this study.

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