Prediction of HMA Mixture Performance from Rheological and Rutting Evaluation of Nanopolymer Asphalt Binder

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Abstract Recently, the interest among researchers in nanopolymers used in modified binders has increased in order to achieve high performance of the bituminous mixture. This work presents a study on HMA with different nanopolymer proportions and different mix gradation types conducted to evaluate the rheological performance of asphalt binder and HMA mixtures. The design method of the Marshall mix was used to achieve an optimal asphalt binder content with a different proportion of nanopolymer polymer modificers. The resilient modulus test was conducted to measure the stiffness of the HMA mixtures, while the dynamic shear rheometer test with a short-term aging technique was used to evaluate the rutting of the asphalt binder. The regression analysis was used to test the performance of the nanopolymer rheological asphalt binder and HMA asphalt mixture. Empirical and predicted data from experimental research have been used to construct and validate regression models. The rheological asphalt binder has been shown to have a significant effect on the performance of the HMA asphalt mixture. This result has shown that the finding provides guidance for predicting the performance of HMA asphalt mixtures with

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respect to the performance of the rutting asphalt binder and, as a result, nanopolymer can be used as an asphalt modifier in road construction.

Keywords Nanopolymer · Asphalt binder · Rheological properties · Hot mix asphalt · Rutting · Resilient modulus

1 Introduction

Through the years, conventional HMA mixtures have had a strong impact on the road pavement. Nevertheless, the demand for bitumen has increased rapidly in the last few years, with the increase in pavement failures due to permanent deformation or pavement surface rutting. Therefore, it is important for the Malaysian authority to provide good quality of asphalt binder to reduce cost of maintenance and improve pavement performance. Polymer-modified asphalt binder has been found to enhance several asphalt mix properties, such as fatigue life, susceptibility to temperature, and resistance to permanent deformation [1–3]. The polymer in the modified binder (PMB) should not be too viscous at mixing temperature or too brittle at low temperatures. In addition, PMB must have good stability during storage and transportation to ensure better mechanical strength performance than conventional asphalt. Styrene-butadiene-sty-rene (SBS), styrene-butadiene rubber (SBR), Elvaloy, rubber, ethylene vinyl acetate (EVA), polyethylene, and others are polymers that are commonly used for asphalt modification [3–5]. It is evident from previous studies that polymers are the appropriate material for the modification of asphalt, which in turn increases (a) the high temperature stiffness, (b) reduces the low temperature stiffness, (c) improves fatigue resistance, (d) improves age hardening resistance, (e) facilitates the preparation of stiffer hot-mixes as compared to conventional asphalt. The associated benefits of improving these properties are: (a) resistance to rutting, bleeding and flushing, (b) prevention of thermal cracking, (c) prevention of ravelling and cripping, (d) increase in durability and (e) possibility of thinner lifts [2–4]. Analytical methods to better characterize a PMB are not well established yet and many of them have been employed by several authors [6]. In addition to the reviewed advantages, researchers have also faced various challenges, including high costs, high temperature sensitivity of some PMBs, low aging resistance, poor storage stability and limited improvement in elasticity. The poor storage stability of some PMBs is usually due to the poor compatibility of polymer modifiers and bitumen controlled by the various properties of polymers and bitumen, such as density, molecular weight, polarity and solubility [5]. Some bitumen polymer modification issues are still not well understood. More efforts are expected to be made to encourage further development [6].

Although a common technique used for pavement improvement is the polymer modified asphalt binder, it will be of interest to experts and engineers to investigate the efficiency of pavement performances ranging from macro and meso scales to nanoscales. Nanomaterials for asphalt mixtures are becoming particularly interesting in the field of pavement engineering. Several studies have reported that nanomaterials have an excellent potential to improve the quality of asphalt binders and mixtures. This may improve the properties of the asphalt pavement. The most common materials used were several good asphalt modifiers, such as carbon nanofiber, carbon nanotube, nanoclay, and nanosilica, based on previous research and development [7–9]. Yusoff's study of the potential benefits of nanosilica particles in asphalt mixtures concluded that asphalt mixture modified by 4% nanosilica increased fatigue and rutting resistance and appears to have the greatest potential for beneficial binder modification [10]. Yao reported that the addition of nanoclay and carbon microfiber improves the stripping performance of mixtures or reduces the potential for moisture damage [11]. Research conducted by Li et al. [12] indicated that the addition of SBR/nanoclay improves the viscoelastic properties, resulting in enhancing its resistance to rutting at high temperature. On the other hand, the addition of carbon nanotubes contributes to the improvement of rutting resistance at higher performance temperatures and increases the failure temperature, viscosity and elastic modulus when modified with any supplied virgin binders [12]. Although nanomaterial binders have been studied by several researchers, conclusive results have yet to be established; however, there is a broad agreement on the use of nanomaterials as a potential modifier in asphalt binders [13]. The need to evaluate nanopolymer asphalt binders has therefore been explored to enhance rutting and permanent deformation resistance. In this study, nanopolyacrylate (NP) and composite nanopolyacrylate with natural rubber latex (NC) were used.

An important phenomenon for determining the overall performance of the modified asphalt binder is the study of the rheological properties of the asphalt binder. In the Superpave performance grade asphalt binder specification, the rolling thin film oven, pressure ageing vessel and dynamic shear rheometer are used to characterise the viscous and elastic behaviour of asphalt binders at high and intermediate service temperatures. The rheological testing such as dynamic shear rheometer (DSR) measures the complex shear modulus (G*) and phase angle (δ) of the binder which is used to determine the relationship between asphalt binder stiffness and the type of deformation. The G*/sinδ relationship is used to determine the asphalt binder's rutting at high-performance temperature as an indicator [14, 15]. It is important to understand this relationship to ensure stable and durable asphalt pavement. The regression analysis was conducted to evaluate the nanopolymer rheological asphalt binder and the performance of HMA mixture. Alternatively, predicting the rutting performance of the HMA mixture based on the rheological properties of the asphalt binder is very useful in describing the performance of the HMA. Several published works have applied regression analysis in pavement material modeling for its excellent ability to describe the correlation between dependent variables and a particular response. Recently, the use of regression analysis in pavement engineering has been increasingly recognized [16, 17]. Regression analysis is a statistical and mathematical technique that uses numerical and graphical representations to develop models between responses and one or more independent variables [18]. Regression analysis is mainly used for experimental design, modeling and optimization in a few experimental runs [16]. Regression analysis has been applied in various areas, such as mechanical engineering, biomass science and concrete materials. The present study aims to develop models for predicting the performance of HMA mixtures from rheological and rutting evaluation of nanopolymer asphalt binder.

1.1 Materials

In this study, granite aggregates from Blacktop Quarry, penetration grade bitumen (PEN) 80/100 and performance grade (PG 76) were used to produce AC14 and SMA14 HMA mix designs. Both types of asphalt binders were supplied by SHELL, Malaysia. In this study, two modifiers were used: nanopolyacrylate (NP) and a composite polymer of natural rubber latex (NC) nanopolyacrylate. Nanopolyacrylate has been obtained from the Nan Pao Resins Chemical CO., Taiwan. While the ACP-DMT, Klang supplied the natural rubber latex.

1.2 Preparation of Modified Asphalt Binders

Nanopolymer modified asphalt binders were prepared by adding a different proportion of nanopolyacrylate and natural rubber latex. The Penetration Grade 80/100 asphalt binder was heated to 160 °C in the oven. Nanopolyacrylate and natural rubber latex were slowly added to the liquid asphalt binder and sheared using a mechanical stirrer attached to the propeller mixer. When the mixing temperature of 160 °C was reached, the mixing cycle began at an increased speed of up to 1000 rpm for 60 min [19]. The modified asphalt mixtures were carefully stored prior to further testing.

1.3 Dynamic Shear Rheometer (DSR) Test

Dynamic Shear Rheometer (DSR) test was performed in accordance with ASTM D7175. This test is used in the Superpave performance grade asphalt binder specification to characterize the viscous and elastic behaviour of asphalt binders at high and intermediate service temperatures. At the desired temperature and frequency of loading, the DSR evaluates the complex shear modulus (G*) and phase angle (δ) of asphalt binders. The complex modulus (G*) can be considered to be the total resistance of the deformation of the sample when sheared repeatedly and the phase angle (δ) is the lag between the shear stress applied and the resulting shear strain. The results of G* andδ are generally used as indicators of HMA rutting and fatigue cracking [16]. Rutting and fatigue cracking are the greatest concern in the early and later stage of a pavement life. The rutting of the asphalt binder can be measured by the G*/sinδ ratio at a high-performance temperature. This relationship was used as an indicator to determine the performance of the asphalt binder [20]. An asphalt

Fig. 1 The RTFO machine

binder with a high G* value is considered to be stiffer, which increases its deformation resistance, and an asphalt binder with a low sinδ value is considered to be more elastic, and the ability to recover part of the deformation is increased [21]. The asphalt binder sample was aged through a rolling thin film oven (RTFO) to simulate the short-term aging of bitumen during the asphalt mixture mixing and compaction process. The RTFO test is conducted using RTFO Model N759, SEM, Pty. Ltd., Australia as shown in Fig. 1. The asphalt binder samples were poured into glass containers for this process and placed in the RTFO carriage with the opening of the glass containers in the chamber facing the jet air. With a carriage rotation speed of 15 rpm, the ageing process continues for 85 min at 163 °C. While the pressure aging vessel (PAV) as sown in Fig. 2 is used to simulate the aging of the asphalt binder that occurs during 5–10 years of HMA pavement service. There are few advantages to the pressure ageing of the asphalt binder, such as: limited loss of volatiles, accelerated oxidation without high temperatures, an adequate amount of asphalt binder may be aged for further testing at one time, and the test is practical for routine laboratory testing. The PAV is used to age RTFO residues which provide simulated long-term aging of the asphalt binder in the HMA pavement.

1.4 Resilient Modulus Test

Resilient modulus of HMA mixture is used to evaluate the elastic properties. This test shall be carried out in accordance with ASTM D 4123 [22]. It is measured in indirect tensile mode using the Universal Testing Machine (UTM-5P) at controlled

Fig. 2 The PAV machine

temperatures of 25 and 40 °C (±1 °C) as shown in Fig. 3. The pulse repetition period of 1000, 2000 and 3000 ms was used to distinguish between different modes of loading of samples. The standard peak load of 900 N was selected and applied vertically to the diametrical plane of the cylindrical specimen and the horizontal

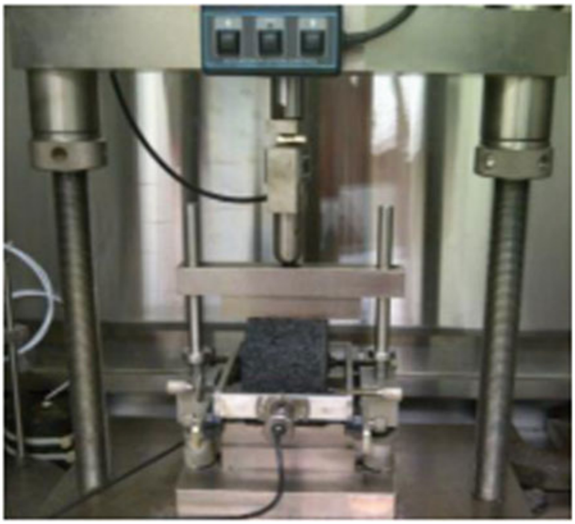

Fig. 3 Resilient modulus test (UTM-5P machine)

deformation was measured. The result is presented through a graph and the average resilient modulus is calculated.

1.5 Development of Resilient Modulus Model from Rutting, G*/sinδ of Asphalt Binder (M_R − G*/sinδ)

Resilient Modulus Model was predicted using Rutting, G*/sinδ of Asphalt Binder. Several processes such as data collection and screening outliers, descriptive statistics, correlation analysis, modeling of selected variables and model validation are required to develop a regression model. To provide a meaningful model for a better understanding of the strength of the relationship between dependent and independent variables, multi-regression was performed with a confidence level of 95%. In this study, the resilient modulus, M_R (40 °C) was assigned as dependent variables while temperature, mix design, asphalt binder type, percent asphalt binder, modifier and viscosity were assigned as independent variables. Model validation begins for all model variables with basic descriptive statistics. The relationship between actual or empirical values with the predicted values is then examined using a scatter plot. The scatter plots will show how the value of the scatter point is closer to a straight line of 45° between the empirical values and the values predicted. To check and compare the discrepancies or variations of the developed models, Root Mean Squared Error (RMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) are then used. In addition, to check the validity of the models, a paired t-test is performed. A multiple regression model was finally developed.

2 Results and Discussions

2.1 Statistical and ANOVA Analysis

Table 1 shows the statistical and ANOVA values between asphalt binders (independent variables, X-Rutting, G*/sinδ) and HMA mixtures (independent variables, Y-M_R (40 °C)). Correlation findings show a fair coefficient of determination (R^2) which indicates a close relationship between the 40 °C resilient modulus and the

Table 1 Statistical and ANOVA analysis between asphalt binders and HMA mixtures

Mixture types	Equation	R^2
AC-NP	$Y = 0.3672X - 1254.3$	0.9
SMA-NP	$Y = 0.1017X + 211.92$	0.7
AC-NC	$y = 0.0501x + 320.45$	0.9
SMA-NC	$y = 0.0271x + 588.55$	0.7

40 °C G*/sinδ asphalt binder for each asphalt binder type and HMA mixture type. The NP and NC modified asphalt binders and HMA mixtures, AC14 and SMA14 are clearly affected by the resilient modulus. Effective prediction models of resilient modulus from rutting, G*/sinδ asphalt binder (MR − G*/sinδ) have therefore been developed.

2.2 Prediction Resilient Modulus Model

The resilient modulus model was predicted using the 95% confidence level of multi-regression to provide a significant model. Resilient modulus factor, M_R (40 °C) was assigned as dependent variables while temperature, mix design, asphalt binder type, percent asphalt binder type, modifier and viscosity were assigned as independent variables. Table 2 provided a statistical analysis summarizing the value of the standard error mean, the standard deviation, the minimum value, the median value, the maximum value, skewness and kurtosis of screening.

Potential relationships between dependent and independent variables for regression models have been established through a correlation analysis. Based on the results obtained in Table 3, the temperature has a high correlation with the Resilient Modulus (r-value = 0.902). While the other variables, such as mix design, binder type, percent

Table 2 Descriptive statistic for resilient modulus model

Variable	Mean	StDev	Minimum	Median	Maximum	Skewness	Kurtosis
Resilient modulus	1418.3	758.9	467.0	977.0	3207.0	−0.42	−1.36
Temperature	1.5000	0.5007	1.0000	1.5000	2.0000	−0.00	−2.01
Mix design	1.5000	0.5007	1.0000	1.5000	2.0000	0.00	−2.01
Asphalt binder type	2.2857	0.7009	1.0000	2.0000	3.0000	−0.46	−0.89
% Asphalt binder type	2.7143	1.0317	1.0000	3.0000	4.0000	−0.19	−1.14
Modifier	7.500	4.037	1.0000	7.5000	14.000	0.00	−1.21
Rutting, G*/sinδ	6622	1896	4849	5343	9899	0.75	−1.14

Table 3 The correlation matrix among variables

Variable	Resilient modulus	
	R value	P value
Temperature	0.902	0.000
Mix design	0.156	0.004
Binder type	0.204	0.000
% Binder type	0.256	0.000
Modifier	0.264	0.000
G*/sinδ	0.219	0.000

Table 4 Multi linear regression for the $M_R - G^*/\sin\delta$ model

Predictor	Coef	P
Constant	480.49	0.000
Binder type	0.04	0.005
% Binder type	52.067	0.000
Rutting	0.011904	0.003
log mixdes × modifier	19.955	0.000
S = 63.4 R-Sq = 62.6%		

Table 5 Analysis of variance for $M_R - G^*/\sin\delta$ model

C	DF	SS	MS	F	P
Regression	4	718,599	179,650	44.76	0.000
Error	107	429,501	4014		
Total	111	1,148,100			

binder type and rutting $G^*/\sin\delta$, display a weak correlation with the resilient modulus (r-value < 0.4). Nevertheless, because the p-value was less than 0.05 (p-value < 0.05), both variables were significant.

The second model of multiple linear regressions was used to classify the predictor potential in the $G^*/\sin\delta$ model. Based on the result obtained in Table 4, all variables were significant where the p-value for multiple linear regression was less than 0.05 (p-value < 0.05). As a result, these predictors can be used in the model to predict the resilient modulus of the $G^*/\sin\delta$ asphalt binder. The R^2 value for the model was 62.6% of the variations, which indicates that the linear relationship between the response and the predictor fits well with the data.

The potential M_R model to be used for prediction was then analyzed using further variance analysis (ANOVA). The outcome of ANOVA in Table 5 indicates that the p-value was less than the 0.05 suggesting that the regression model was significant. This could be used to predict the resilient modulus of the $G^*/\sin\delta$ of asphalt binder. As a consequence, the resilient modulus equation ($M_R - G^*/\sin\delta$) for predicting this model was developed as shown in Eq. 1. This finding showed that the coefficient of the type of binder for this model had a positive indication that an increase in the percentage of the type of binder would lead to an increase in the rutting, i.e. $G^*/\sin\delta$. In addition, the positive sign for the percent of binder type also indicates that an increase in this factor will lead to an increase in the rutting $G^*/\sin\delta$.

$$\text{Resilient Modulus} = 480 + 0.01\ \text{Binder Type} + 52.1\%\ \text{Binder Type} + 0.0119\ \text{Rutting} + 20.0\ \log\ \text{mix design} \times \text{modifier} \quad (1)$$

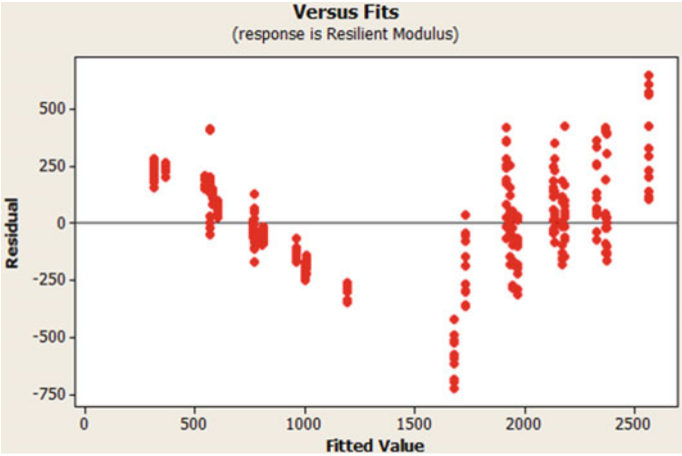

Fig. 4 Graph of residual versus fitted values for $M_R - G^*/\sin\delta$ model

2.3 Justification of the Regression Model Assumptions

Justifications for regression model assumptions are evaluated using a regression analysis. The regression analysis was used to model and determine the relationship between the response variable and one or more predictors. Figure 4 shows the residuals versus the fitted values plot for the resilient modulus with the $M_R - G^*/\sin\delta$ of asphalt binder. The results show a rather random scatter along the horizontal line with zero residual. Therefore, the model was adequate and the regression assumptions were met.

2.4 Normality Test for Residuals

Normality test used to determine if the data set is modelled for normal distribution using the Kolmogorov–smirnov test. The P-value of the Kolmogorov–smirnov test must be greater than 0.150, suggesting that the model was normally distributed. The result obtained in Fig. 5 did not satisfy the criterion, which indicates that the p-value was less than 0.01. The initial data for model development was transformed (Fig. 6) and the result of the P-value for the transformed data was greater than 0.150. Accordingly, this finding implies that the data was normally distributed after transformation and can therefore be accepted for model development.

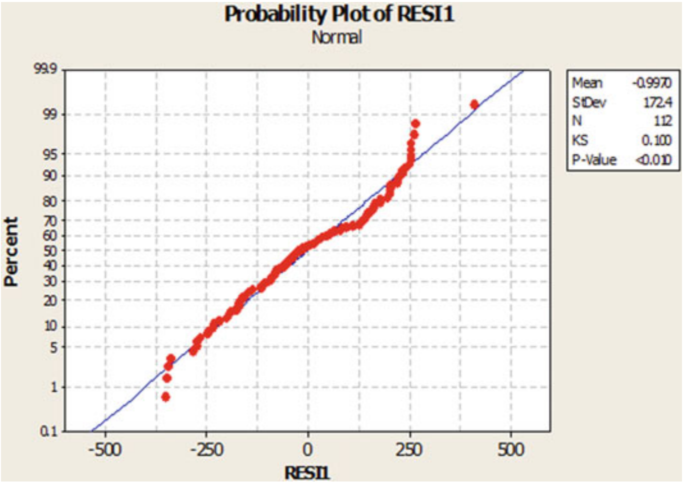

Fig. 5 Probability plot before data transform

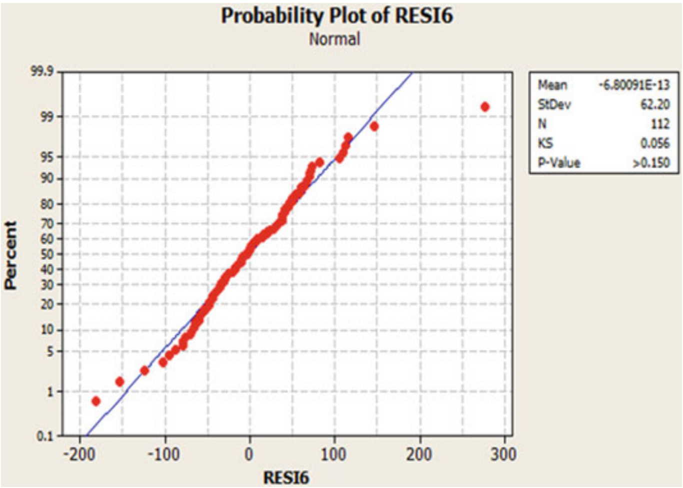

Fig. 6 Probability plot after data transform

2.5 Model Validation of M_R – G/sinδ*

Validation of the model is carried out to assess the accuracy of the models developed against the independent data set. Figure 7 shows the scatter plot of the $M_R - G^*/\sin\delta$ model which represents the relationship between the empirical $M_R - G^*/\sin\delta$ and predicted $M_R - G^*/\sin\delta$. The point plots are scattered closely to the line of linearity

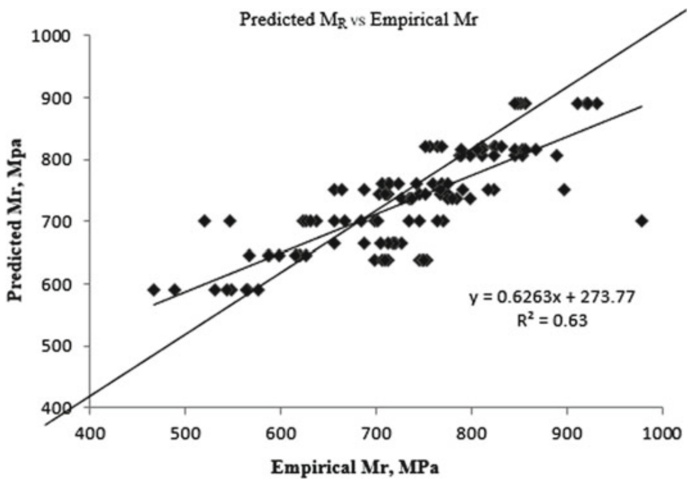

Fig. 7 Predicted $M_R - G^*/\sin\delta$ versus empirical $M_R - G^*/\sin\delta$

Table 6 MSE, MAE, and MAPE for $M_R - G^*/\sin\delta$ model

Model	RMSE (MPa)	MAE (MPa)	MAPE (%)
$M_R - G^*/\sin\delta$	16.93	7.01	6.71

for both models with the coefficient of determination, $R^2 = 0.63$. Therefore, the observed model can be successfully used to predict the independent dataset.

Model validation shall be performed to evaluate the accuracy of the models developed against an independent data set. Figure 5 displays the scatter plot of the $M_R - G^*/\sin\delta$, model, which represents the relationship between the empirical MR − G*/sin-pop and the predicted $M_R - G^*/\sin\delta$. Point plots are scattered closely to the linearity line for both models with a coefficient of determination, $R_2 = 0.63$. The observed model can therefore be used successfully to predict an independent dataset.

For the accuracy of the results, the findings obtained (Table 6) from the empirical value of the predicted $M_R - G^*/\sin\delta$ are 16.93 MPa for RMSE, 7.01 MPa for MAE and 6.71% for MAPE. The findings reveal a small discrepancy between the RMSE, MAE and MAPE values. This results indicate that the $M_R - G^*/\sin\delta$ model can be used and that it is acceptable to predict $G^*/\sin\delta$.

A comparison of the means was made for the paired t-Test between the predicted $M_R - G^*/\sin\delta$ and the measured $M_R - G^*/\sin\delta$. Table 7 shows the results of the validation analysis for $M_R - G^*/\sin\delta$ model. This result shows that the P-value

Table 7 Validation analysis result for $M_R - G^*/\sin\delta$ model

Test	Value
t-statistic	−0.07
p-value	0.944

is 0.944, which is greater than 0.05. It therefore indicates that the predicted $M_R - G^*/\sin\delta$ predicted model did not differ significantly from the $M_R - G^*/\sin\delta$ empirical values. Model was validated and the model predicted almost fit with the empirical data obtained. In conclusion, the model was successfully developed and validated.

3 Conclusions

From the study, on the basis of the results and analyses, the following conclusions can be highlighted:

1. Resilient Module at 40 °C showed a significant relationship with viscosity and $G^*/\sin\delta$ asphalt mixtures made with both mixtures and the modified type of binder.
2. The proposed ($M_R - G^*/\sin\delta$) model is.
3. Resilient Modulus = 480 + 0.01 Binder Type + 52.1% Binder Type + 0.0119 Rutting + 20.0 log mix design X modifier.
4. Based on the empirical data and the predicted data, this model has been successfully developed and validated, showing that the findings of the dependent and independent variables selected can affect each other in terms of pavement performance.
5. It could therefore be concluded that the use of NP and NC polymers as an asphalt modifier is feasible and the findings are expected to provide a starting point for the development of a national standard for the prediction of the performance of the HMA mixture with regard to the asphalt binder performance.

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