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Factorial Design Approach to Investigate the Effect of Different Factors on the Resilient Modulus of Bituminous Paving Mixes

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ABSTRACT

Resilient modulus is an important property used in the mechanistic analysis of pavement response under moving loads as well as an input parameter for design of flexible pavements. The effectiveness and efficiency of pavement structural thickness design is contingent on the accuracy in measuring the resilient modulus (M_R). This research study investigates the effect of four factors namely bitumen content, specimen diameter, test temperature and load duration on resilient modulus of bituminous paving mixes. The specimens of dense graded hot mix asphalt (HMA) were prepared by Marshall Compaction method using 4% and 5% bitumen content and with 4 in and 6 in diameter. The resilient modulus tests were conducted on these specimens using repeated-load indirect test setup in Universal Testing Machine (UTM-25) at 25 $^\circ$C and 40 $^\circ$C temperature. Haversine-shaped wave load pulse was used to simulate the traffic wheel loading for 100 ms and 300 ms load duration. The analysis of two-level full-factorial designed experiments revealed that all four factors have a negative effect on resilient modulus of bituminous paving mixes. Temperature was the most significant factor affecting the resilient modulus followed by load duration and specimen diameter. In 2-way interaction, diameter–temperature, diameter-load duration, and load duration-temperature were significant. The most significant 3-way interaction was bitumen content-temperature-load duration. The results from the study suggest that in measuring the resilient modulus, an appropriate temperature and load duration should be selected to quantify the representative resilient modulus for in-situ conditions.

Keywords: *Resilient modulus, Factorial design, Bitumen content, Specimen diameter, Test temperature, Load duration*

1. INTRODUCTION

Resilient modulus is the property of bound and unbound pavement materials that characterize the elastic behavior under dynamic traffic loading conditions. It is an important parameter for flexible pavements thickness design as the resilient modulus of structural layers are used to estimate the layer coefficients hence layer thicknesses [1]. Therefore; the effectiveness of thickness design is directly related to the accuracy in measuring the resilient modulus. Resilient modulus can also be used in the evaluation of materials quality. The resilient modulus is elastic modulus which is based on the recoverable strain under repeated loads [2]. It is known that the materials for wearing course i.e. bituminous materials are not elastic, but experience some small amount of the permanent deformation after each application of load. If this application of load is small compared to strength of the material and repeated for large number of times, the deformation under each cycle of load is nearly recoverable. It can be considered as elastic and proportional to load. Under a cyclic load test, there is plastic strain at the initial stage of application of load and by increasing load repetition, the plastic strain decreases after each repetition of load. After about 100 to 200 cycles of repetitions, the strain is almost all recoverable as shown in Fig 1.

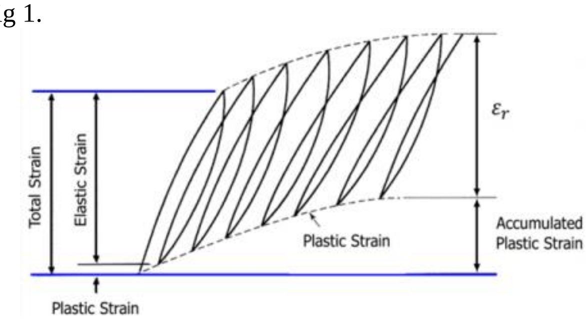

Fig 1: Elastic and plastic responses under repeated loads [2].

The indirect tension test is most common repeated load test to measure the resilient modulus of bituminous paving mixes due to its simplicity. It is standardized under the American society of Testing and Materials (ASTM D4123) [3]. The test involves preparing a compacted cylindrical bituminous mix specimen subjected to

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diametrical repeated loading. The test method recommends that the resilient modulus (M_R) be measured by applying stresses with magnitudes in the range of 10 to 50% of the indirect tensile strength of the specimens. In these tests, compressive load with haversine or any other suitable waveform is applied in the vertical diametric plane of cylindrical specimen through a loading strip, and the resulting horizontal recoverable deformation is measured. The resilient modulus is computed from following equation:

$$M_R = \frac{P(\nu + 0.27)}{Ht}$$

Where: M_R = Resilient Modulus, P= Peak load, H= recoverable horizontal deformation (mm),
t = thickness of specimen (mm), ν = Poisson's ratio.

This research paper first presents a brief introduction to the resilient modulus, its importance in the flexible pavement design and the test procedure for resilient modulus. The literature review section briefly highlights the findings of the previous studies related to resilient modulus and discussion on the input parameters for flexible pavement design is made, followed by the study methodology including selection of materials used in this research, specimen fabrication process and two-level full factorial analysis procedure for the data obtained from the resilient modulus tests. Then the test results are analyzed including two-level full factorial analysis and residual analysis. Finally, conclusions and recommendations are drawn from research findings.

2. LITERATURE REVIEW

There are a numerous factors affecting resilient modulus of bituminous paving mixes when subjected to resilient modulus test using indirect tension test setup. These include the thickness and diameter of specimens, nominal maximum aggregate size, test temperature, the load waveforms and pulse durations applied to the specimens, and the type of compaction.

The indirect tensile test on both 4 in. (101.6 mm) and 6 in. (152.4 mm) diameter specimens and revealed that the tensile strength of 6 in. (152.4 mm) specimens was lower than 4 in. (101.6 mm) specimen [4]. The resilient modulus tests and indirect tension testing (diametrical testing) on 4 in. (101.6 mm), 5 in. (127.0 mm) and 6 in. (152.4 mm) diameter specimens and concluded that resilient modulus decreased as the diameter of the specimen increased [5]. The measured resilient modulus value depends on the percentage of indirect tensile strength used as applied load. The tests with load magnitude ranged from 10 to 30% of indirect tensile strength of the specimen were conducted. They concluded that the load magnitude during resilient modulus test should be large because it gives a smaller resilient modulus value, which in turn results in a more conservative design. It was found that the difference in resilient modulus at load magnitude of 1000 and 2700 N was as great as 4 % for the specimens prepared with asphalt content of 4% [6]. The hot mix asphalt being a viscoelastic material, the loading time affects its properties and it is recommended that the loading time of HMA dynamic tests must be reduced to 300 ms (0.03 seconds) to better match loading times obtained from moving trucks at average speed and from falling weight deflectometer testing [7]. The influence of flaky aggregate content on the resilient modulus of asphalt concrete was studied. It was observed that the value of resilient modulus decreased with increasing the flaky aggregate content in the mix [8].

The past researchers also carried out comparison of different factor affecting the resilient modulus in asphalt mixes. The investigation revealed that the interaction of different factors affect the resilient modulus. The fractional factorial experimental design showed that the nominal maximum aggregate size was the most important factor affecting the resilient modulus, then the load duration, and the geometry of specimen [9]. The drastic reduction of about 85% in resilient modulus has been observed for an increase in temperature from 25 to 40º C. Similarly the resilient modulus decreased up to 30% with increase in time of loading from 150 to 450 ms (0.015 to 0.045 seconds) [10].

The laboratory tests were conducted to investigate the effect of material properties of aggregate on the resilient modulus of hot-mix asphalt and observed that the coarse aggregate morphology is the principal factor that influences the resilient modulus. Conducting resilient modulus test of bituminous mixture at 25 $^{\circ}$C with the coarse aggregate of irregular morphologies improved the resilient modulus of bituminous mixture. It was also observed that the different aggregate gradation did not significantly affect the relationship between the coarse aggregate morphology and the resilient modulus of bituminous mixture [11]. The temperature of asphalt layer influence the elastic modulus (resilient modulus) of material, the fatigue life of the asphalt, the plastic strains and the temperature is, therefore; very important for the performance of the pavement. At temperature above 20 $^{\circ}$C, the elastic modulus decreases rapidly and reaches to unrealistic low values at 40 $^{\circ}$C [12].

This research aims to consider the effects of Bitumen Content, Specimen Diameter, Test Temperature and Load Duration, their interactions on the resilient modulus of bituminous paving mixes through a two-level full- factorial design of experiment.

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3. STUDY METHODOLOGY

Two-level four factor full-factorial designed experiment was conducted to evaluate the effects of four different factors such as bitumen content, specimen diameter, test temperature and load duration on the resilient modulus of bituminous paving mixes. The specimens of dense graded hot mix asphalt were prepared by Marshall Compaction method. The gradation with ½ in. nominal maximum size aggregate according to ASTM D3515 was selected for this study [13]. Various engineering properties of aggregates are given in Table 1.

Table 1: Engineering Properties of used Aggregates

Test type	Test Designation		Test Results
Shape test	Flakiness Index Elongation Index	BS 812	14.62% 12.31%
Impact test	BS 812		16.68%
Los Angles abrasion test	ASTM C 131		31.15%
Bulk Specific gravity	Coarse aggregate	ASTM C 127	2.61
	Fine aggregate	ASTM C 128	2.69

The penetration grade of used bitumen was 60-70 in preparation of mixes which is the common bitumen grade used in Pakistan. Test results for bitumen are presented in Table 2.

Table 2: Results of Tests Performed on Bitumen

Test type	Designation	Test Results
Penetration @ 25°C, 0.1mm	ASTM D 5	62
Flash point (Cleveland), °C	ASTM D 92	242
Specific gravity @ 25°C (gm/cm^3)	ASTM D 70	1.022
Ductility Test (cm)	ASTM D113	100+

The bitumen content of 4 % and 5 % of the total weight of mix was selected for the preparation of all specimens in this study. Similarly, specimens were compacted by Marshall Hammer using the Marshall heavy traffic criteria for both 4 in. (101.6 mm) and 6 in. (152.4 mm) diameter specimens in this study. According to the test method ASTM D4123, the thickness of specimen is to be between 1.5 in. (38.1 mm) and 2.5 in. (63.5 mm). In this research, the thickness of all the specimens was kept 2.5 in. (63.5 mm). The resilient modulus tests were conducted on these specimens using repeated-load indirect test setup in temperature controlled Universal Testing Machine (UTM-25). Two linear variable differential transformers (LVDTs) were used to measure the horizontal deformation of specimens subjected to dynamic vertical loading. The load applied was measured by load cell. The tests were carried out at 25 °C and 40 °C temperature. Haversine-shaped wave load pulse was used in the tests to simulate the traffic wheel loading for 100 ms and 300 ms load duration. In this study the Poisson's ratio of 0.4 was assumed.

4. RESULTS AND DISCUSSION

A two-level four factor full-factorial design of experiment was carried out in this study to investigate the effects of four factors on the resilient modulus of bituminous paving mixes. The factors considered in this research with their abbreviation, low and high levels and units are shown in Table 3. The values in parentheses (-1 or +1) are meant for coded values at low (-1) and high (+1) levels of the factors studied, respectively. The full factorial runs with four variables, two replicates, their possible combinations and the observed resilient modulus are shown in Table 4.

Table 3: Levels of Factors Studied

Factors	Abb.	Units	Low Level	High Level
Bitumen content	A	%	4 (-1)	5 (+1)
Specimen diameter	B	Inch	4 (-1)	6 (+1)
Test temperature	C	˚C	25 (-1)	40 (+1)
Load duration	D	ms	100 (-1)	300 (+1)

The main effect estimates and the interaction effect estimates are represented in Table 5. The effect is defined as the difference between the average response of factor at high level and that of average response of the factor at low level. The interaction effect between two factors (say, C∗B) may be defined as the mean difference between the effects of "test temperature" at high level of "specimen diameter" and the effect of "test temperature" at low level of "specimen diameter". The full model regression coefficients were determined in terms of their coded values by MINITAB-15 software [14]. The effect estimates of the factors can be

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obtained by multiplying the regression coefficient by a factor of 2.

Table 4: Factor Combinations of Full-Factorial Runs

Runs	A	B	C	D	Resilient Modulus (MPa)
1	+1	+1	+1	-1	3503
2	-1	+1	+1	-1	3442
3	+1	-1	+1	-1	5673
4	+1	-1	-1	+1	5467
5	+1	-1	-1	-1	7799
6	+1	-1	+1	+1	3250
7	-1	+1	-1	+1	5992
8	+1	-1	+1	-1	4844
9	+1	+1	+1	+1	2736
10	-1	+1	+1	-1	3156
11	-1	-1	-1	+1	4962
12	+1	+1	-1	-1	6617
13	+1	+1	-1	+1	5185
14	+1	-1	-1	+1	5309
15	-1	-1	+1	+1	4029
16	-1	+1	-1	-1	7242
17	-1	-1	-1	+1	4978
18	-1	-1	+1	-1	5361
19	-1	+1	+1	+1	3062
20	-1	-1	+1	-1	4067
21	-1	+1	+1	+1	3262
22	+1	-1	-1	-1	7903
23	+1	+1	-1	+1	5077
24	+1	+1	-1	-1	5582
25	-1	-1	-1	-1	8292
26	+1	+1	+1	+1	2861
27	+1	+1	+1	-1	3331
28	-1	+1	-1	+1	5751
29	-1	+1	-1	-1	6951
30	+1	-1	+1	+1	3498
31	-1	-1	-1	-1	8446
32	-1	-1	+1	+1	3719

Table 6 shows the analysis of variance of observed data up to three factors interactions. Analysis of Variance with higher order interactions of four variables resulted ill model so is neglected. The sparsity of effect principle states that most of the processes are governed by some main factors and few low order interactions and most of the higher order interactions are negligible [15].

In the analysis of variance, four F-tests were made. To evaluate these four tests, probability values are given. The first three tests assess the significance of individual factors, 2-way interactions and 3-way interactions. The higher value of F or the lower value of p represents the significance of individual factors and interactions. The fourth test is the lack of fit test for errors. When low model error is obtained, the model shows a good fit to the data, i.e. the model has no lack of fit.

4.1 Effect of the Factors

From Table 5 it can be observed that effect estimates of all the main factors are negative which means that they have negative effect on the resilient modulus of bituminous paving mixes. It implies that if the levels of these factors increased, the resilient modulus will be decreased. A cumulative normal probability plot of main and interaction effect of full model parameters is shown in Fig 2

Table 5: Main and Interaction Effect Estimates

Factors	Effects	p-value
Main Effects		
A	-254	0.058
B	-865	0.000
C	-2610	0.000
D	-1442	0.000
Two Factors Interaction		
A*B	-241	0.071
A*C	205	0.119
A*D	-41	0.745
B*D	705	0.000
B*C	-270	0.045
C*D	572	0.000
Three Factors Interaction		
A*B*C	168	0.196
A*B*D	-15	0.905
A*C*D	-340	0.015
B*C*D	-212	0.108

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Table 6: Variance Analysis Showing up to Three-Factor Interactions

Source	DF	SS	MSS	F-test	Prob >F
Main Effects	4	77,659,431	19,414,858	151.52	0.00
2-way Interaction	6	7,992,358	1,332,060	10.40	0.00
3-way Interaction	4	1,510,385	377,596	2.95	0.051
Residual Error	17	2,178,063	128,121		
Lack of Fit	1	192,355	192,355	1.55	0.231
Pure Error	16	1,985,708	124,107		
Total	31	89,340,237			

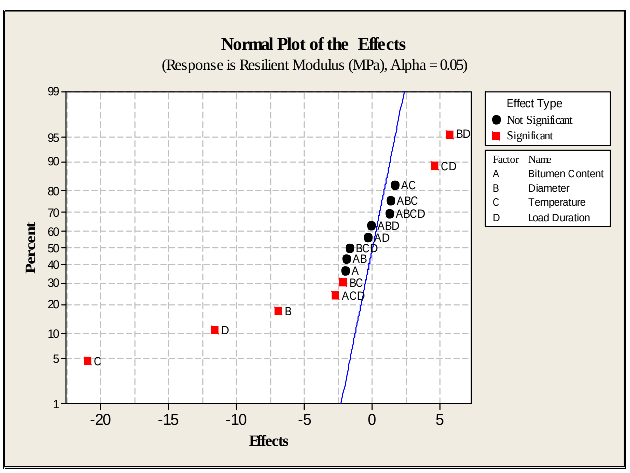

Fig 2: Cumulative normal probability of effect estimates

It is clear that all the factors are not lying along a straight line. The factor outliers (represented by red squares) are the most concerning in predicting the resilient modulus and are considered to be the most governing parameters. The effects that are insignificant are normally distributed with mean zero and variance $\pm^{2}$ and will tend to fall along a straight line on this plot, whereas significant main effects and interaction will have nonzero means and will not lie along the straight line [16]. It is clear from the Fig 2 that bitumen content is not a potential outlier; thus it can be concluded that the effect of bitumen content studied in this work is not significant compared to the test temperature which is a potential outlier. This may be attributed to the fact that the range of bitumen content (4 – 5%) evaluated in this study was very small.

Fig 3 is the plot of main factors effects. It can be easily seen from the figure that all the factors have negative slope. The Temperature plot has a very steep negative slope whereas; the bitumen content has mild negative slope. This may be due to the fact that with increase in temperature, softening of bitumen takes place. The softening of bitumen in the mix results in the permanent strains with application of loads and thus decrease in resilient modulus takes place. Specimen diameter plot has also shown the negative slopes. This may be due to the presence of more micro cracks in large diameter specimen compared to small diameter specimen. Similarly load duration plot has also shown the negative slope which indicate that higher strain result for a longer period of time and reduce the resilient modulus.

4.2 Interaction Effect

An interaction is failure of one factor to produce the same effect on the response at different levels of another factor [15]. The interaction between two variables is said to occur when change in the values of one variable alters the effect on other [17].

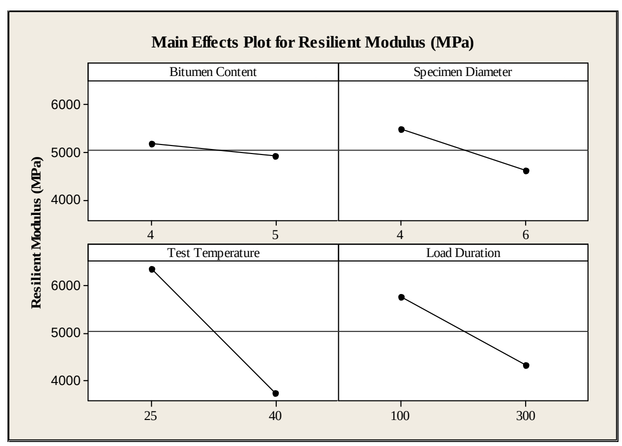

Fig 3: Main effect of factors on the resilient modulus.

It means that the factor interactions which are insignificant will produce the similar trends in the response at different levels of other factor. As an example for explanation of interaction effect as shown in Fig 4, an insignificant two factors interaction (A * D, p-value = 0.745) and one significant interaction (B *D, p-value = 0.000) are presented. It is clear that when load duration is increased keeping bitumen content at low percentage level, resilient modulus decreases. Similarly, when load duration is increased keeping bitumen content at high level, the resilient modulus again decreases. Thus, the two factors have similar effect on resilient modulus and shown to be parallel, which implies that there is no interaction between the factors. On the other hand it is also found that the effect of load duration is very prominent in the smaller specimen diameter, while it is less in the larger specimen diameter. Similarly, significant interaction (B*C, p-value = 0.045) is showing that the 6 in diameter specimens are more sensitive to change in temperature from 25 °C to 40 °C as compared to 4 in. diameter specimen. Therefore; resilient modulus rapidly decreases in 6 in. diameter specimen when temperature change occurs from 25 °C to 40 °C as compared to 4 in. diameter specimen. It might be due to the fact that accumulated strain in case of 6 in. diameter specimen was great as compared to 4 in. diameter specimen.

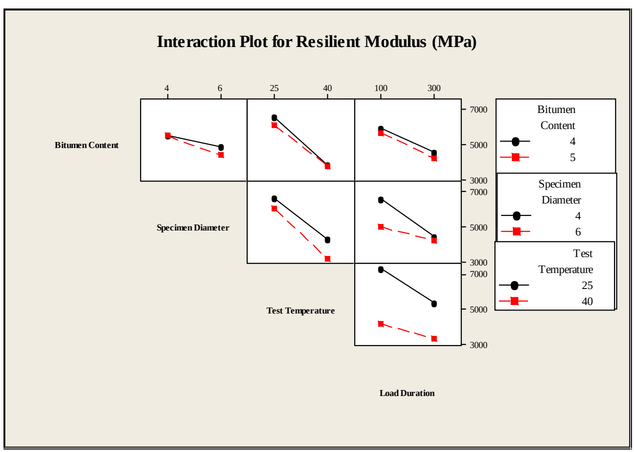

Fig 4: Interaction effect of factors on the resilient modulus.

4.3 Regression Analysis

The regression analysis illustrates statistical relationship between one or more independent variable and response variable to predict new observations. By considering only the significant main and interaction terms, the model is obtained in terms of actual values by least square regression method for the prediction of resilient modulus MR of bituminous paving mixes is given by following equation:

$$M_R(MPa) = 17379 - 160*C - 552*B - 37.2*D - 18.0*B*C + 0.521*C*D + 3.53*D*B - 0.0312*A*C*D$$

The coefficient of determination (R^2) of the model is 0.949 and adjusted R^2 (R^2_{adj}) is 0.934. The values of both R^2 and R^2_{adj} are close to each other which show that no insignificant terms are included in the model. The R^2 of model shows that more than 94% variability of response can be explained by the variables of model. This regression model is valid to the range of values for parameters that are specified in Table 3.

4.4 Checking of Model Adequacy

The residual plots are used to check the goodness of a fit in regression analysis. Typically, the residual plots are used to examine if the least squares assumptions are reasonable to produce unbiased coefficient estimates with minimum variance. One of the basic assumptions for the model development is that the errors must be normally distributed [18]. The normality assumption can be checked by normal probability plot of residuals. The residuals are the differences in resilient modulus value between experimental (observed) and predicted values. Figure 5(a) shows the normal probability plot of residuals of the values. It is clear that all the points are quite close to the straight line which supports that the residuals are normally distributed. The residuals (errors) and the predicted resilient modulus by the model are presented in Figure 5(b). It is evident that the residuals are structure less with no noticeable pattern which shows that the model is adequate [15].

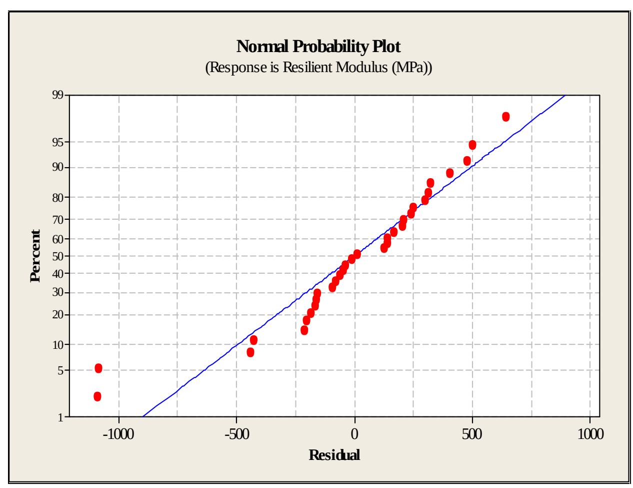

Fig 5(a): Normal probability plot of residuals

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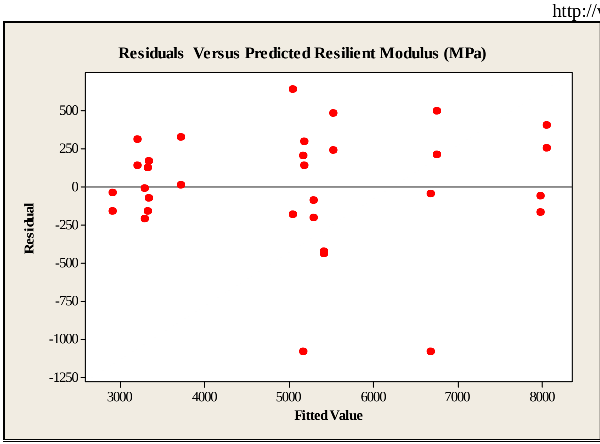

Fig 5(b): Plot of residual vs. predicted resilient modulus

5. CONCLUSIONS

In this study, full factorial design of experiment was carried out to evaluate the effect of various factors such as bitumen content, specimen diameter, test temperature and load duration on the resilient modulus of bituminous paving mixes. It was observed that all the four factors have negative effect on the resilient modulus of bituminous paving mixes. Temperature was found the most significant factor affecting the resilient modulus of bituminous paving mixes, followed by load duration and specimen diameter. Most high order interactions were negligible which corroborates sparsity of effect principle. In 2-way interaction, diameter–temperature, diameter-load duration, and load duration-temperature were significant. The most significant 3-way interaction was bitumen content-temperature-load duration. The bitumen content alone was an insignificant factor but it became significant in interaction with test temperature and load duration. A model to predict the resilient modulus was developed using two-level four-factor full-factorial design. The effects of four factors studied were within a selected range of values. Further studies are recommended with wider range at both high and low levels of the parameters used in the present study.

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The authors gratefully acknowledge the support from the laboratory staff in preparing the samples for the research study. The contents of this article reflect the views of the authors who are responsible for the facts and the accuracy of the data and results presented herein. This is merely a technical article for the experimental investigation of factors affecting the resilient modulus of bituminous paving mixes using Indirect Tension Test. This research study does not constitute a standard, specification, or a regulation.

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