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Statistical Evaluation of Hot Mix Asphalt Resilient Modulus Using a Central Composite Design

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Abstract: An experimental study was performed to determine the effects of bitumen content, specimen diameter, test temperature, and load duration on resilient modulus of hot mix asphalt. Also, to develop a mathematical relation between these parameters, response surface methodology (RSM) was employed. Using this methodology, the polynomial model was successfully fitted to the results. The results revealed that within the range of the tested variables, increasing the temperature from 25℃ to 32.5℃ had the greatest effect on resilient modulus decrease, compared with the effects of other three parameters. In contrast, the influence of bitumen content on increasing resilient modulus was much greater than the effects of specimen diameter, test temperature, and load duration when the bitumen content changed from 4 to 5%.

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***Key words**: Bitumen content; Load duration; Resilient modulus; Response surface methodology; Specimen diameter; Test temperature.*

Introduction

Elastic behavior of pavement materials under dynamic load is commonly characterized by its resilient modulus (MR). This fundamental property of the bound and un-bound materials is a momentous criterion for flexible pavement thickness design as it is used to estimate the layer coefficients, and hence layer thicknesses [1, 2]. MR is defined as the ratio of applied axial deviator stress to axial recoverable strain [2, 3]. In addition, MR is used to evaluate material quality, and it is measured under application of cyclic axial load.

The indirect tension test is commonly used to measure the resilient modulus of bituminous paving mixtures. This test is standardized under ASTM D4123 [4]. According to the ASTM, the resilient modulus is measured by applying stresses with a magnitude in the range of 10 to 50% of the indirect tensile strength of the specimens. The vertical load is applied in the vertical diametric plane of cylindrical specimen through a loading strip, and the resulting horizontal recoverable deformation is measured [2, 4].

There are numerous factors affecting resilient modulus of bituminous paving mixes when subjected to the indirect tension test. 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 [2, 5-13].

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Ghaffarpour and Khodaii (2009) attempted to investigate the effect of different parameters, each at two different levels, on the resilient modulus of hot mix asphalt. According to fractional factorial analysis utilized in this study, they reported that the maximum nominal aggregate size is the most significant factor influencing the resilient modulus, followed by the load duration, specimen thickness, and specimen diameter [10]. Babr Khan et al. (2012) evaluated the influence of four factors, namely bitumen content, specimen diameter, test temperature, and load duration on resilient modulus using indirect tension test. The analysis of two-level full-factorial designed experiments revealed that all four factors have a negative effect on resilient modulus of asphalt mixtures. Also, they found that temperature is the most significant factor affecting the resilient modulus of bituminous paving mixes, followed by load duration and specimen diameter [2].

A literature review on the effective parameters on resilience modulus revealed that researchers had widely utilized full factorial design in their experimental works. Although this type of design can provide information about the interaction between parameters, if the number of parameters and their levels are high, the total number of experiments will increase excessively. This is one the most critical disadvantages of this type of design and may lead to consumption of more time and inevitably more expense. In addition, higher order interactions, obtained in full factorial, are usually statistically insignificant and, hence the information about them is not very useful [14-19]. On the other hand, fractional factorial designs (FFD)—such as central composite design (CCD) or Box-Behnken—can provide insight regarding interactions between variables with far smaller number of experiments. It should however be emphasized that reliable information about first order interactions can only be obtained from the results of Design of Experiments (DOE) which are not highly fractionated [14-19]. To overcome this shortcoming, factorial DOE, which can simultaneously consider many variables at different levels, may be used. This methodology employs techniques such as Response

Surface Methodology (RSM) to derive a suitable model between many variables and their response. However, RSM has not been used to investigate the interactive effects of Bitumen Content (BC), Specimen Diameter (SD), Test Temperature (TT), and Load Duration (LD) on Resilient Modulus (MR). A similar technique has been employed by Khodaii et al. to study the interactive effect of lime content and grading on the stripping potential of stone matrix asphalt (SMA) [14] and hot mix asphalt (HMA) [15]. Haghshenas et al. have also evaluated the effects of frequency and temperature on permanent deformation of HMA [16]. Besides, Kavussi et al., have investigated effect of hydrated lime and Zycosoil on stripping potential of warm mix asphalt (WMA) using RSM [17, 18].

Objective

Recognizing BC, SD, TT, and LD as the effective parameters that influence Resilient Modulus (MR) of HMA, the following objectives were selected for this study:

1. To develop a statistical/mathematical model relating BC, SD, TT, and LD,
2. To examine the interactive effect of BC, SD, TT, and LD on MR,
3. To identify of the most significant parameter affecting MR,

To achieve these purposes, RSM was employed and a half fractional factorial, namely Central Composite Design (CCD), was selected as the design matrix. This technique allowed a reliable identification of first order interaction between factors.

Materials and Methods

Materials

The Hot Mix Asphalt was made with coarse grading aggregate and asphalt binder. The aggregate had a maximum size of 12.5 mm and a specific gravity of 2.58. The fine aggregate had a specific gravity of 2.54. The coarse and fine aggregate gradations met the British Standard 882 [19]. Bitumen AC 60-70 (that corresponds to PG 64-16)—most widely used locally—was used as binder for mixture preparation.

Sample Preparation

To prepare uniform asphalt samples, it was necessary to measure several parameters such as the maximum theoretical specific gravity, the optimum compaction temperature, and the bulk specific gravity of the compacted mix. The percentage of air voids was maintained at 5% ± 0.5% for all specimens.

According to ASTM D4402 binder should have a viscosity of 170 ± 20 centistokes (cSt) to be sufficiently fluid for mixing and compaction. To determine the temperature at which binder has such viscosities, a rotational viscometer was used following ASTM D4402. It was found that the optimum temperature to achieve the required viscosity is between 140 and 145 ℃. This temperature was used for mixing and compacting the samples in the laboratory.

Experimental Method

Resilient modulus tests were conducted on these specimens using repeated-load indirect test setup in a 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. In the servo hydraulic UTM25 machine, the stress/load applied to the specimen is feedback controlled allowing the operator to select a loading wave shape (haversine or square pulse), pulse width duration, and rest period. A contact stress/load can also be applied so that the vertical loading shaft does not lift off the test specimen during the rest period. This constant contact stress can be programmed in the testing sequence.

To control the ambient temperature of testing samples, loading mechanism of UTM25 machine is placed within an environmental chamber [2, 20, 21]. The tests were carried out at 25℃, 32.5℃ and 40℃ temperature. Haversine-shaped wave load pulse was used in the tests to simulate the traffic wheel loading for 100, 200, and 300 ms load duration.

Design of Experiment

In order to explore the effect of four factors at different levels using RSM, Central Composite Design (CCD) was chosen and 28 experimental runs (design matrix) were selected by the MINITAB software [22]. Table 1 lists the combinations of different levels of the factors.

To predict the response variable in terms of the four independent variables, a quadratic polynomial regression model as proposed by Montgomery [23] was chosen for this study as follows:

$$Y = b_0 + \sum_{i=1}^{4} b_i X_i + \sum_{i=1}^{4} b_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{4} b_{ij} X_i X_j \qquad (1)$$

In the above equation, Y is the response variable (i.e. Resilient Modulus) and b_0, b_i, b_{ii} , and b_{ij} are constant coefficients of intercept, linear, quadratic and interaction terms, respectively, and X_i and X_j represent the four independent variables (i.e. BC, SD, TT, and LD).

Each experiment was repeated three times and the averages have been presented in Table 1. The experiments were conducted in a randomized order to avoid systematic error.

The statistical significance of the full quadratic model predicted was evaluated using analysis of variance (ANOVA). The quantity and significance of the effects estimate of BC, SD, TT, and LD as well as all their possible linear and quadratic interactions on the MR were also determined.

Results and Discussion

Model fitting

The values of response at each of the 28 combinations of factorial levels generated by the principles of RSM are listed in Table 1. The results of the ANOVA are presented in Table 2; the low P values for the regression (P < 0.1), and the fact that the lack of fit of the model is not significant (P > 0.1), indicate the suitability of the model.

Table 1. Central Composite Design Arrangement and Response.

Run	Factors				Response
	Bitumen Content (%)	Specimen Diameter (mm)	Test Temperature (℃)	Load Duration (ms)	Resilient Modulus (MPa)
1	3.0	101.6	25.0	100	7992
2	5.0	101.6	25.0	100	7890
3	3.0	152.4	25.0	100	7200
4	5.0	152.4	25.0	100	6657
5	4.0	101.6	40.0	100	5593
6	5.0	101.6	40.0	100	5588
7	3.0	152.4	40.0	100	3600
8	5.0	152.4	40.0	100	3708
9	3.0	101.6	25.0	300	5375
10	5.0	101.6	25.0	300	5550
11	3.0	152.4	25.0	300	5990
12	5.0	152.4	25.0	300	5349
13	3.0	101.6	40.0	300	3900
14	5.0	101.6	40.0	300	3880
15	3.0	152.4	40.0	300	3513
16	5.0	152.4	40.0	300	3049
17	3.0	127.0	32.5	200	3938
18	5.0	127.0	32.5	200	3674
19	4	101.6	32.5	200	4008
20	4	152.4	32.5	200	3420
21	4	127.0	25.0	200	4191
22	4	127.0	40.0	200	1795
23	4	127.0	32.5	100	3850
24	4	127.0	32.5	300	2388
25	4	127.0	32.5	200	2700
26	4	127.0	32.5	200	2900
27	4	127.0	32.5	200	2830
28	4	127.0	32.5	200	3000

Aside from the interactive term of BC-TT and BC-LD, all the first order, second order, and interactive terms of the independent parameters are significant at 95% confidence level, as presented in Table 3. Based on the regression coefficients calculated for the response shown in Table 3, a polynomial regression model equation is proposed and presented in Eq. (2):

$$MR\ (\text{MPa}) = 54875.8 - 7756X_1 - 353.4X_2 - 308.8X_3 \\ -45.5X_4 + 1019X_1^2 + 1.4X_2^2 + 3.7X_3^2 + 0.01\,X_4^2 - 3.9X_1X_2 \\ -1.1X_2X_3 + 0.1X_2X_4 + 0.3X_3X_4 \qquad R^2 = 99.61 \tag{2}$$

In the above equation, X_1, X_2, X_3 and X_4 are BC, SD, TT, and LD respectively.

Effects of Parameters: Analysis of Response Surface

If the interaction between factors is statistically significant, surface plot gives a complete picture regarding the effect of a factor on the response [14, 15, 23]. For instance, in a constant level of BC (i.e., 4%), when SD moves from low level (101.6 mm) to mid-level (127 mm), the values of MR decrease. However, with rising specimen diameter from mid to high level, the values of MR increase (Fig. 1a). A similar trend can be observed in values of MR versus SD and TT (Fig. 1b) and MR versus LD and ST (Fig. 1c).

It can be observed that in a constant level of LD (i.e., 200 ms) with increasing TT from low level to high level, the values of MR drop down (Fig. 1d). This obviously is in line with the common understanding of viscoelastic materials such as HMA.

Table 2. ANOVA Table for MR.

	DF	SS	MS	F-values	P-values
Total	27	73457604	-	-	-
Regression	14	73215712	5229694	281.06	0.000
Residual Error	13	241892	18607	-	-
Lack of Fit(Model Error)	10	194217	19422	1.22	0.48
Pure Error(Replicate Error)	3	47675	15892	-	-
R^2	99.67				

Abbreviations: DF, degrees of freedom; SS, sum of squares; MS, mean square.

Table 3. Values of Regression Coefficients Calculated for MR.

Independent Factor	P-value	T-value	Standard Error	Regression Coefficient
Constant	0.000	25.443	2180.39	55475.3
Linear				
BC (%)	0.000	-10.982	719.91	-7905.9
SD (mm)	0.000	-10.248	34.49	-353.4
TT (℃)	0.006	-3.241	102.86	-333.4
LD (ms)	0.000	-10.326	4.31	-44.5
Quadratic				
BC (%)	0.000	34.7	113.2	1019.0
SD (mm)	0.000	10.914	0.13	1.4
TT (℃)	0.031	2.425	1.51	3.7
LD (ms)	0.002	3.909	0.01	0.01
Interactive				
BC(%)*SD (mm)	0.013	-2.896	1.34	-3.9
BC(%)*TT (℃)	0.199	1.353	4.55	6.1
BC(%)*LD (ms)	0.477	-0.733	0.34	-0.3
SD (mm)*TT (℃)	0.000	-6.363	0.18	-1.1
SD (mm)*LD (ms)	0.000	9.351	0.01	0.1
TT (℃)*LD (ms)	0.000	6.114	0.05	0.3

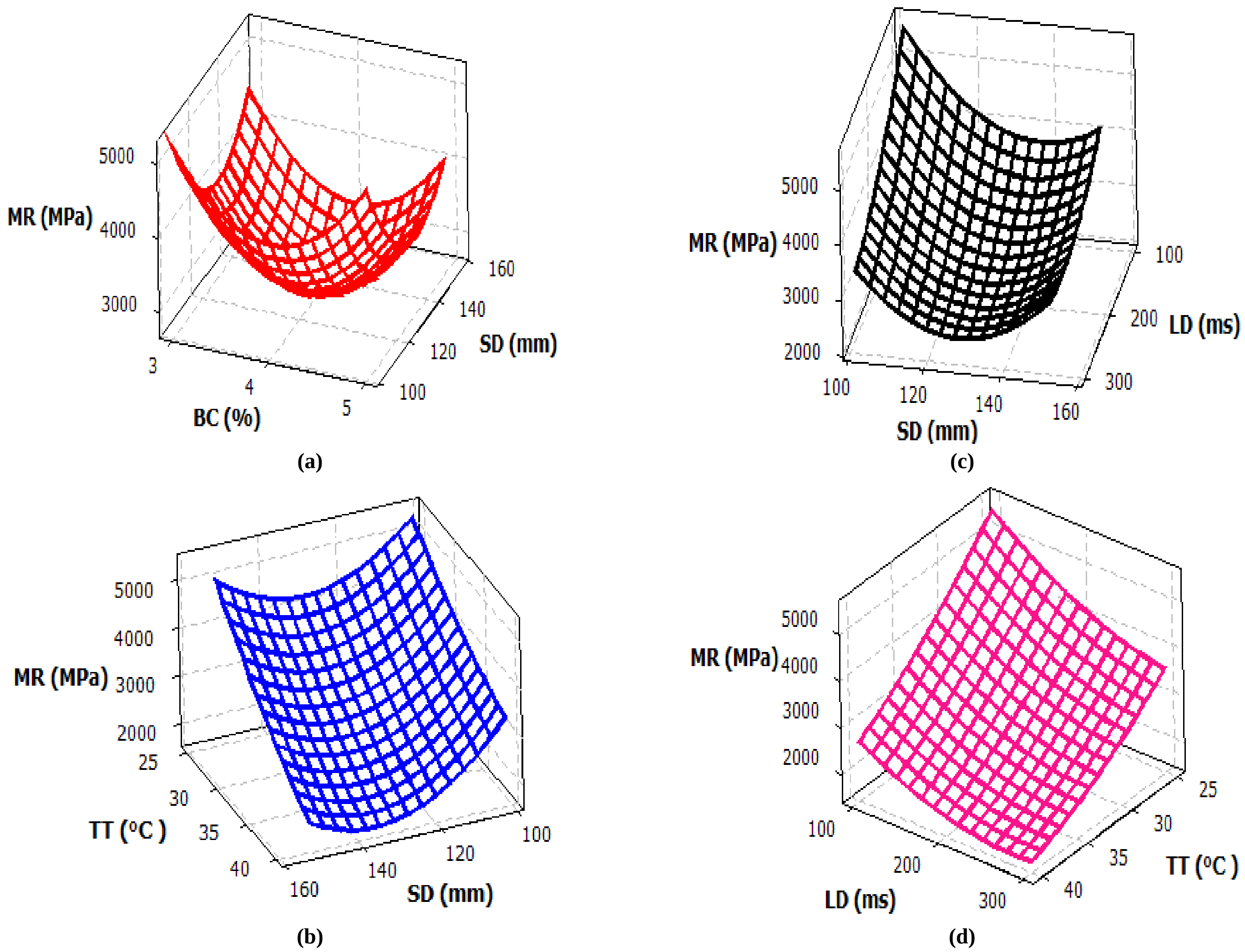

Fig. 1. Surface Plot of MR Versus (a) BC and SD, (b) TT and SD, (c) LD and SD, (d) TT and LD.

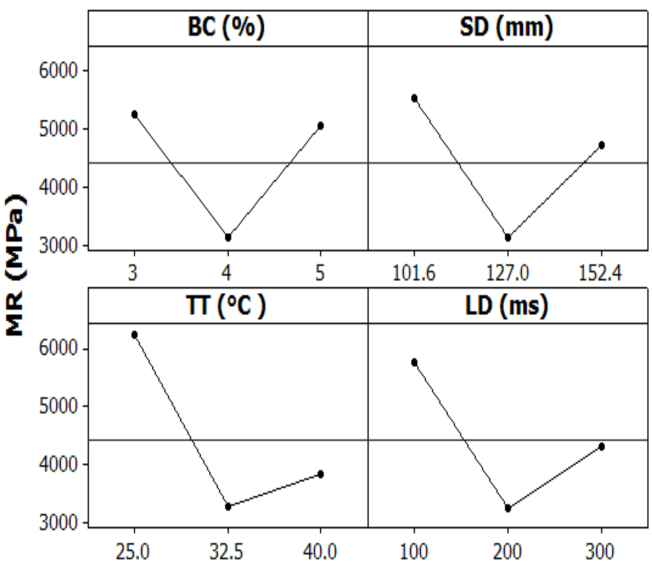

Fig. 2 Main effect plot of MR versus BC, SD, TT and LD.

Main Effect Plot

The main effect plots indicate the effect of an independent variable on a dependent variable when the other independent variables are set at their mid-levels. The “main effect” term is frequently used in conjunction with regression models to distinguish the main effects from the interaction effects [24, 25]. Fig. 3 elucidates the effects of each parameter on MR.

It can be seen that the effect of test temperature on decreasing MR is more pronounced than the effects of other parameters (i.e., when each factor changes from its low level to its mid-level). In addition, Fig. 2 shows that when a factor moves from its mid-level to its high level, the effect of test temperature in increasing MR is less than the effects of load duration, bitumen content, and specimen diameter. Finally, the impact of bitumen content on increasing MR is more than the effects of the other three factors.

Residual Analyses

Normal Test Plots (also called Normal Probability Plots) are used to see whether process data exhibit the standard normal "bell curve" or

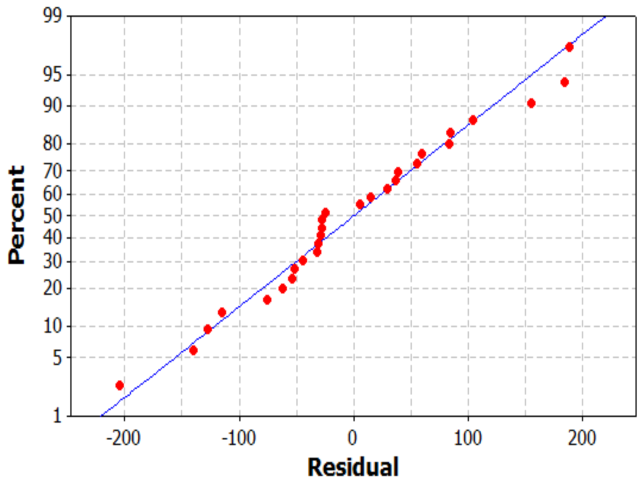

Fig. 3. Normal Probability Plot – Response is MR (MPa).

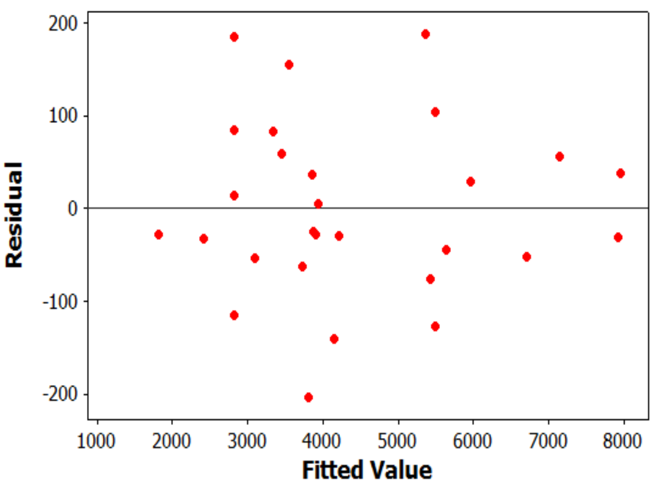

Fig. 4. Residual Plot - Response is MR (MPa).

Gaussian distribution.

It is worthwhile to note that the normal probability plot is a graphical technique for assessing whether or not a data set is approximately normally distributed. In this technique, the data are plotted against a theoretical normal distribution in such a way that the points form an approximate straight line if normally distributed. Departures from this straight line indicate departures from normality. As shown in Fig. 3, the points are very close to the line indicating the normal distribution of the data.

A residual plot is a graph that shows the residuals on the vertical axis and the fitted independent variable (i.e., MR) on the horizontal axis. If the points in a residual plot are randomly dispersed around the horizontal axis, as is the case in Fig. 4, the regression model is appropriate for the data. The main criterion in presenting such a plot is to show the random pattern of errors; it should be noted that this is a qualitative/comparative analysis and the quantitative analysis (ANOVA table) is already presented in the paper.

Conclusion

From the experimental works and the statistical analysis, which resulted in development of a second order polynomial model, the following conclusions could be drawn:

- A mathematical model was successfully developed to predict the resilient modulus, considering four factors each at three different levels.
- With MR parameter taken as the main response, all the first order, second order and interactive terms of the independent parameters were significant at 95% confidence level except for the interactive term of BC-TT and BC-LD.
- Within the range of the tested variables, comparing the effects of increase from their low level to mid-level in bitumen content, specimen diameter, load duration, and test temperature on MR, the test temperature had the greatest effect on MR decrease.
- Within the range of the tested variables, the influence of bitumen content on increasing MR was much greater than the effects of specimen diameter, test temperature, and load duration when parameters changed from mid-level to a high level value.

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