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Research Paper

Investigating the Marshall and Volumetric Properties of Asphalt Concrete Containing Reclaimed Asphalt Pavement and Waste Oils Using Response Surface Methodology

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ABSTRACT: This research aimed to use response surface methodology (RSM) for investigating the Marshall Stability (MS), flow and Voids in Mineral Aggregates (VMA) of asphalt concrete containing different percentages of Reclaimed Asphalt Pavement (RAP) and rejuvenated by different percentages of waste cooking and engine oil. Variables of RAP content in 3 different levels of 25, 50 and 75% (by the weight of total aggregates) and waste oils content in 3 different levels of 5, 10 and 15% (by the weight of total binder) were selected. Quadratic and linear two factor interaction models were well fitted to the experimental results. Analysis of variance showed that the models were capable to well predict the MS, flow and VMA of the mixtures, and the terms of oil and RAP content and type of oil are significant. MS, flow and VMA increased with increasing RAP content and decreased with increasing oil content. Results also reveal that higher MS, flow and VMA values are resulted by using WEO than using WCO. Some interaction effects were found between RAP content, oil content and type of oil on the responses. Optimization analysis showed that using 10.6% of WCO and 15% of WEO, allows a maximum RAP incorporation of 75 and 51.77%, respectively, by which the properties are similar to control mix. Use of the rejuvenators allows using high RAP content without sacrificing the properties of the mixtures.

Keywords: Marshall Test, Reclaimed Asphalt Pavement, Response Surface Methodology, Waste Cooking Oil, Waste Engine Oil.

INTRODUCTION

One of the major concerns of construction industry is the disposal of the generated wastes, which their inappropriate handling may cause adverse effects on the environment (Eghbali et al., 2018). One of the main construction waste is reclaimed asphalt pavement (RAP), generated by milling distressed asphaltic layers of flexible pavements. On the other hand, having asphalt mixture with a better performance is economically and environmentally beneficial (Taherkhani, 2016). Using RAP, in production of new asphalt mixtures is environmentally and economically beneficial. The mixtures containing RAP have higher stiffness and resistance against

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rutting (Peterson et al., 2000). However, due to the ageing process undergone by the binder in RAP, the asphaltic mixtures containing high amounts of RAP are prone to cracking and raveling (Al-Qadi et al., 2012; Mogawer et al., 2013). Therefore, many agencies have set limits on the RAP inclusion in production of new asphaltic mixtures (Zargar et al., 2012). The limits commonly range from 10-30% (Mazzoni et al., 2018). Therefore, solutions are sought to confront the adverse effects of increased aged binder in the mixture.

Using a softer virgin binder in the mixture and recycling agents allow using higher RAP inclusion in hot mix asphalt without sacrificing the performance (Mazzoni et al., 2018; García et al., 2011). Recycling agents are classified into two categories of softening agents and rejuvenators (Terrel and Epps, 1989). Softening agents lower the viscosity of aged binder and rejuvenators restore the chemical composition of aged binder to its original properties. Rejuvenators are classified into different categories, among which are paraffinic oils, aromatic extracts, naphthenic oils, triglycerides and fatty acids and tall oils (NCAT, 2014). Using waste materials as rejuvenator, in addition to environmental benefits reduces the construction cost.

A large amount of engine and cooking oil are wasted every day, which can adversely impact the environment if not appropriately disposed or recycled. The heavy metals and non-degradable components in WEO are harmful for environment (Dedene, 2011; Dominguez-Rosado et al., 2004). As engine oil and asphalt are both produced from crude oil, they have similarities in chemical composition; thus, WEO has been used as a rejuvenator for restoring the original properties of aged binder (Dedene, 2011, Jia et al., 2015). Studies have revealed that using WEO compensates the increased stiffness resulted from aged binder inclusion and allows using higher RAP content in asphalt mixtures (Dokandari et al., 2017, Jia et al., 2015).

Jia et al. (2015) found that addition of WEO into asphaltic mixtures containing RAP results in decrease of optimum asphalt content and resistance against deformation, while does not significantly affect the resistance against fatigue cracking. Waste cooking oil, has similar chemical composition to other rejuvenators and is able to restore the mechanical properties of aged binder (Zhang et al., 2017). Therefore, using WCO for rejuvenating aged binder has the benefits of saving cost and protecting environment, as conventional rejuvenators are expensive and elevate recycling cost. Effects of using WCO on aged binder has been studied by a number of researchers (Azahar et al., 2017; Chen et al., 2014; Eriskin et al., 2017; Su et al., 2015; Zargar et al., 2012). It has been revealed that using WCO increases the resistance against thermal cracking, while decreases the rutting resistance at elevated temperatures (Abdullah et al., 2016).

Zargar et al. (2012) restored the properties of a 40/50 aged binder to the original 80/100 binder by adding 3 to 4% of WCO. Addition of waste frying oil into aged binder by Eriskin et al. (2017) revealed that the softening point decreases and penetration grade increases with modification. The effects of WCO modification on the recycled asphalt mixtures have also been investigated and it has been found that the dynamic modulus decreases (Wen et al., 2012), resistance against thermal cracking increases (Bailey and Zoorob, 2012; Villanueva and Zanzotto, 2008) and resistance against rutting decreases (Abdullah et al., 2016; Bailey and Zoorob, 2012; Wen et al., 2012). Azahar et al. (2012) found that adding 5% of WCO into asphalt concrete containing RAP results in increase of indirect tensile strength, Marshall stability and stiffness.

Application of statistical analysis methods is useful for understanding the main and interaction effects of independent variables on some particular responses (Bala et al., 2017). Response Surface Methodology (RSM) is one of the statistical methods which can be used for design of experiments, establishing mathematical model between the dependent variables and one or more independent variables, investigating the main and interaction effects of independent variables and optimization of process (Kushwaha et al., 2010).

Using RSM methodology can reduce the required number of experiments for evaluation of the main and interaction effects of variables. Three main steps are followed in RSM method, including designing experiments, performing the tests, establishing a mathematical model for prediction of one or more dependent variables, and interpreting the main effects and interaction effects using 2 and 3D plots generated from the mathematical models. The optimized values of independent variables to achieve a maximum or minimum value for the desired response can be found using RSM. RSM has been used in experimental studies of various subjects such as concrete technology, material science as well as mechanical and geotechnical engineering. Recently, researchers have used RSM methodology for investigating asphaltic materials (Golchin and Manssorian, 2017; Hamzah et al., 2015; Haghshenas et al., 2015; Nassar et al., 2016; Hamzeh et al., 2016, Bala et al., 2017, 2018; Khodaii et al., 2013).

Exploring literature revealed that the properties of recycled asphalt mixtures containing a wide range of RAP and waste oil contents have not been investigated. Response surface methodology has been used for studying different aspects of asphalt mixtures. However, it has not been utilized for investigating rejuvenated recycled asphalt mixtures. Due to its capability, as mentioned earlier; RSM can be used to investigate the main and interaction effects of independent variables on particular responses. It can also be used for optimization. Therefore, the objective of this study was set to be evaluating the viability of using RSM to investigate the properties of recycled asphalt mixtures and the effects of different variables on the properties by developing mathematical models and generating 2D and 3D plots of variation of the desired properties and the independent variables. Three fundamental properties of asphalt mixtures including Marshall stability, flow and voids in mineral aggregates (VMA) were selected as the responses and the effects of RAP content, oil type and content on the responses were studied.

RESEARCH METHODOLOGY

Materials

Five types of material including virgin asphalt, virgin aggregates, waste cooking oil, waste engine oil and reclaimed asphalt pavement (RAP) have been used in this research for making the test samples. PG58-16 asphalt cement produced in Pasargad Oil Co. in Iran was used as virigin asphalt in the mixtures. The required specifications were met by the binder. The virign dolomite aggregates used in this study were collected from an asphalt plant in Zanjan city in Iran. Limestone filler has been used for making all the mixtures. The coarse, fine and filler fractions satisfied the requirements of national specification (IAPC, 2012).

For brevity, the properties of the asphalt and virgin aggregates are not provided in this paper, however, they can be found in the Taherkhani and Noorian (2018). The reclaimed asphalt pavement used in this study was obtained from the milled asphaltic layers of Zanjan-Myaneh road. RAP was graded first, after which, its binder content was determined following ASTM-D2172 standard method. After separating the binder, the aggregates were graded and angularity of coarse fraction was determined to be 91% in two faces. Gradation of RAP before and after extracting the binder was found to be within the limits of gradation No. 4 in Iranian asphalt pavement code (IAPC, 2012). The gradation of the mixtures used in this study was targeted to be the middle of lower and upper limits of gradation No. 4, as shown in Figure 1.

Waste engine oil and waste cooking oil have been used as rejuvenators in this study. The waste engine oil was collected from a local car service center in Zanjan city, and the waste cooking oil was collected from the central resturaunt in University of Zanjan. The oils were filtered using a sieve No. 30, before being used as rejuvenator to separate the impurities. The filtered oils are shown in Figure 2.

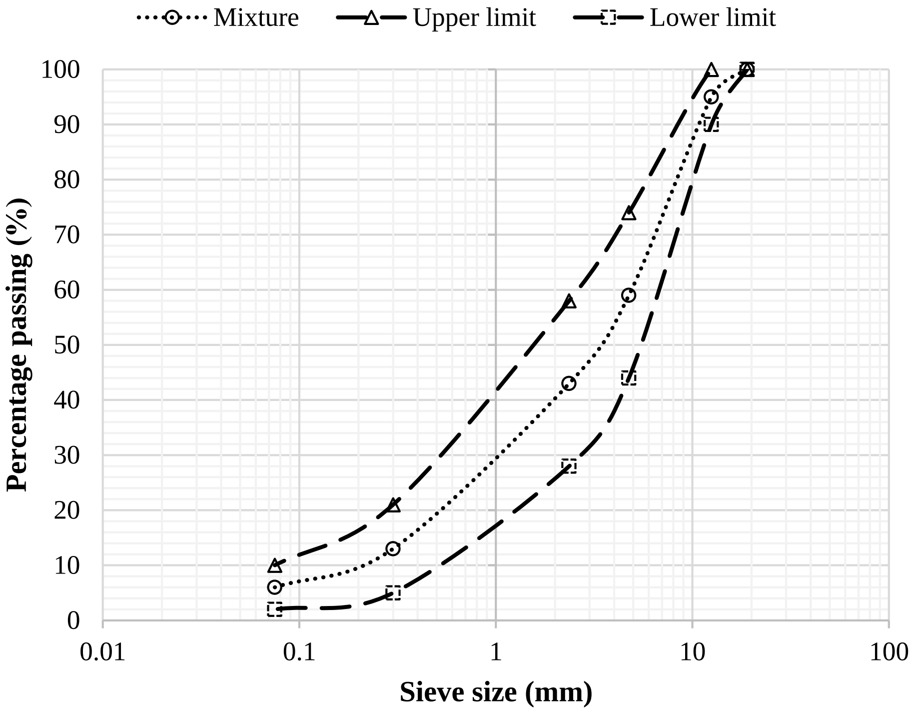


Fig. 1. Grading of mixtures

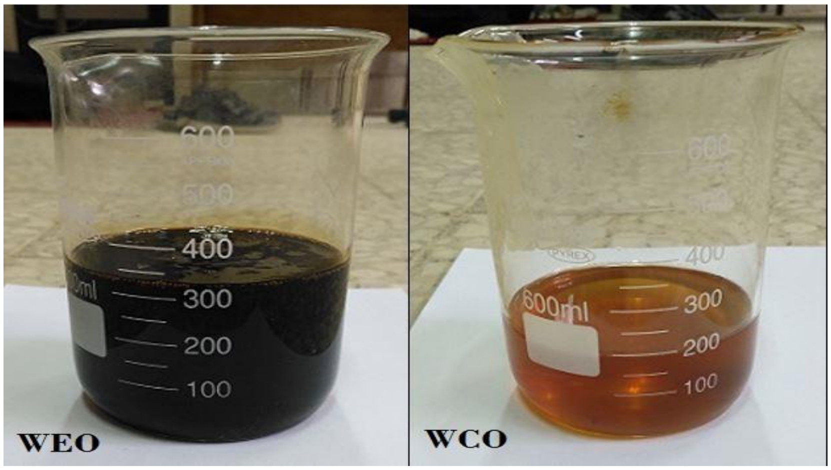


Fig. 2. Waste engine and cooking oil used in this research

Design of Experiments and Fabrication of Samples

Response surface methodology in Design Expert 10.0.7.0 was used for designing experiments. The faced center composite central design method in RSM was utilised, which is the most popular method for designing experiments. Two numerical and one categorical variables were chosen for this research. The numerical variables include RAP content in 3 levels of 25, 50 and 75% (by the weight of total aggregates in the mixture). These levles were chosen as the RAP content more than 25% is commonly considered as high RAP content recycled mixtures (Mogawer et al., 2013). Waste oil content in 3 different levels of 5, 10 and 15% (by the weight of total binder). These levels were selected according to the range of dosages used in previous studies (Zaumanis and Mallick, 2013; Eriskin et al., 2017; Azahar et al., 2017) and the RAP contents used in our research. The categorical variable was chosen to be type of waste oil in two levels of waste cooking and waste engine oil. Table 1 shows the runs in designed expriments provided by software, in which the actual values of the variables are provided. Using Eq. (1) the actual values of variables were transformed into coded form.

$$x_i = \frac{X_i - X_0}{\Delta X} \tag{1}$$

in which, x_i: is the coded value of variable i and is dimensionless, X_i: is the actual value of i^th^ factor and X_0: is the center actual value of the variable and ΔX: is the step change of i^th^ factor.

The mixtures were designed according to Marshall mix design method as per ASTM D1559 standard method. In order to make the samples, the required virgin aggregates were stored in oven set at 170 °C for 16 hours to be dried and attain the desired tempearture for mixing. The virgin binder was also heated in oven set at 150 °C. RAP was also heated at 150 °C for 1.5 hours. The waste oils were added to the RAP, and, after fully mixing, the heated virgin asphalt and aggregates were added and mixed until the aggregate particles were well coated with binder. Then, the mixtures were poured into the mold and compacted by applying 75 impacts on each side. The specimens were removed from the molds after 24 hours and stored to be tested. In total 54 specimens were made in this study (Figure 3a).

(a) **(b)**

Fig. 3. Marshall specimens and Marshall set-up

Table 1. Design of experiments and the actual and predicted response

Runs	RAP content (%) (A)	Oil content (%) (B)	Type of waste oil	Responses		
				Marshall stability (kN)	**Flow (mm)**	**VMA (%)**
1	75	5	WEO	16.15	3.365	14.97
2	50	15	WCO	12.5	2.61	13.34
3	50	5	WCO	14.74	3.1	14.22
4	25	10	WEO	13.08	2.81	13.41
5	50	10	WEO	15.49	3	13.71
6	25	5	WCO	14.07	2.87	13.33
7	75	5	WCO	15.18	3.29	14.48
8	25	15	WCO	12.35	2.5	13.02
9	75	10	WCO	13.85	3.24	14.34
10	25	5	WEO	14.09	2.812	13.63
11	50	5	WEO	15.23	3.125	14.25
12	75	15	WCO	14.02	3.025	13.75
13	75	10	WEO	16.16	3.37	14.27
14	75	15	WEO	14.81	2.975	14.2
15	50	10	WCO	12.95	2.8	13.61
16	25	10	WCO	12.43	2.75	13.1
17	25	15	WEO	12.98	2.835	13.27
18	50	15	WEO	14.11	2.86	13.51

Marshall Test and VMA Determination

Marshall test was conducted on the specimens according to ASTM D1559 standard method and the Marshall stability and flow were determined for each mixture.

The bulk density of the compacted mixtures was measured according to ASTM-D2726. Using Eq. (2) the voids in mineral aggregates (VMA) of the mixtures was determined.

$$\mathrm{VMA} = \left(1 - \frac{\mathrm{G_{mb}}}{\mathrm{G_{sb}}} \mathrm{P_s}\right) \times 100 \qquad (2)$$

where, G_{mb}: is the bulk density of the mixtures, P_s: is the percentage of the aggregate in the mixtures (based on total weight of the mixture), and G_{sb}: is the bulk density of the aggregates.

Method of Analyzing Results

In this study, response surface methodology (RSM) in Design Expert 10.0.7.0 software, has been used for modeling and analysis of results and determining the main and interaction effects of variables on the Marshall stability, flow and VMA. Design Expert uses mathematical and statistical methods for obtaining the best model to characterize the responses. 2D and 3D plots are provided for the responses, by which the optimum point can be obtained. The Marshall stability, flow and VMA of asphalt concrete were chosen as the responses to obtain the prediction model. The general form of response function is as Eq. (3) (Can et al., 2006; Aksu and Gonen, 2006).

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} x_i x_j + \varepsilon \qquad (3)$$

in which, Y: is the computed response, β_0: is constant, x_i: and x_j: are independent coded variables, β_i and β_{ii}: are the coefficients of the linear and second order terms, β_{ij}: is the coefficient of interaction term, ε: is random error and n is the number of variables.

The fitted polynomial equation is presented as 2 and 3 dimensional plots to visualize the relation between the response and variables and determine their optimum value. Based on the analysis of variance, the effect and the regression coefficients of linear, second order and interaction terms were determined. The ANOVA analysis in

Design Expert was used to evaluate the adequacy of model.

RESULTS AND DISCUSSION

Analysis of Variance of Models

As mentioned earlier, the MS and flow were measured by performaing Marshall test on the samples of asphalt concrete containing different percentages of RAP and waste cooking and engine oil. VMA was also determined using Eq. (2). The resutls of MS, flow and VMA are given in Table 1. Using Design Expert software, response surface methodolgy was utilised to study the effects of RAP, WEO and WCO content and their interaction effects on the responses and generate approperiate models to be able to accurately predict the repsonses using independent variables. The highest degree of polynomial function which has statisticaly significant terms was selected.

Table 2 shows the statistical summary of the models evaluated by the software for the responses of MS, flow and VMA. According to the results for F-value, p-value, R^2, adjusted R^2 and adequate precision, which should be more than 4, all models are significant and valid for prediction of the responses. However, for the Marshall stability and flow, the difference between adjusted R^2 and predicted R^2 is more than 0.2 for the quadratic and cubic model, which is not desirable. Also, for VMA, the cubic model has a difference more than 0.2 between adjusted and predicted R^2. Therefore, 2FI model is used for MS and flow and quadratic model is used for VMA. To check the adequacy of sugested model, the results of ANOVA in Design Expert software were used (Myer and Montgomery, 2002; Korbahti and Rauf, 2008).

The results of ANOVA analysis are provided in Tables 3-5 for MS flow and VMA, respectively. In these tables the p-values for the models and terms are provided. The models and terms with p-value less than 0.05 imply that they are significant for 95% intervals. As can be seen, the p-value of models is less than 0.0001 indicating that the models are significant and adequate to predict the responses. In addition, the terms A (RAP content), B (oil content) and C (type of oil) have p-values less than 0.05 for all responses and are significant factors and the interaction and quadratic terms are not significant. According to the F-values, the terms in order of effect on MS, flow and VMA can be ranked as A, B and C. The selected models, in terms of coded factors, for prediction of MS, flow and VMA are shown in Eqs. (4-6), respectively.

Table 2. Comparison of the models

Response	**Source**	**SS[a]**	**MS[b]**	**Df[c]**	**F-value**	**p-Value**	**R^2**	**Adjusted-R^2**	**Predicted R^2**	**Adequate precision**
Marshall stability	Linear	22.26	7.42	3	28.71	< 0.0001	0.86	0.83	0.7819	18.45
	2FI	23.13	3.85	6	15.38	< 0.0001	0.8935	0.8354	0.7039	14.168
	Quadratic	23.31	2.97	8	10.17	0.0011	0.9	0.8119	0.6016	11.688
	Qubic	25.31	1.96	13	13.54	0.011	0.9739	0.9054	0.3733	11.588
Flow	Linear	0.91	0.3	3	29.8	< 0.0001	0.8646	0.8356	0.6634	17.87
	2FI	0.95	0.16	6	16.08	< 0.0001	0.8977	0.8419	0.7692	13.81
	Quadratic	0.98	0.12	8	13.97	0.0003	0.9255	0.8592	0.6052	12.19
	Cubic	1.04	0.08	13	17.3	0.007	0.9825	0.9257	0.5652	14.377
VMA	Linear	4.53	1/51	3	59.26	< 0.0001	0.9270	0.9114	0.8747	24.76
	2FI	4.63	0.77	6	33.65	< 0.0001	0.9483	0.9202	0.8428	19.721
	Quadratic	4.68	0.59	8	25.63	< 0.0001	0.9580	0.9206	0.8085	17.44
	Cubic	4.79	0.37	13	15.69	0.0084	0.98	0.91	0.6482	13.64

[a] Sum of squares; [b] Degree of freedom; [c] Mean squares

Table 3. ANOVA results for Marshall stability

Source	SS[a]	DF[b]	MS[c]	F-value	p-Value	Significance
Model	23.13	6	3.85	15.38	< 0.0001	Significant
A	10.36	1	10.36	41.34	< 0.0001	Significant
B	6.29	1	6.29	25.11	0.0004	Significant
C	5.61	1	5.61	22.39	0.0006	significant
AB	0.014	1	0.014	0.054	0.82	insignificant
AC	0.65	1	0.65	2.59	0.136	insignificant
BC	0.2	1	0.25	0.8	0.3906	insignificant

[a] Sum of squares; [b] Degree of freedom; [c] Mean squares

Table 4. ANOVA results for Marshall flow

Source	SS	DF	MS	F-value	p-Value	Significance
Model	0.95	6	0.16	16.08	< 0.0001	Significant
A	0.6	1	0.6	61.41	< 0.0001	Significant
B	0.26	1	0.26	26.24	0.0003	Significant
C	0.052	1	0.052	5.3	0.0419	Significant
AB	0.012	1	0.012	1.21	0.2915	Insignificant
AC	2.76E-003	1	2.76E-003	0.28	0.6063	Insignificant
BC	0.02	1	0.02	2.07	0.1785	insignificant

Table 5. ANOVA results for VMA

Source	SS	DF	MS	F-value	p-Value	Significance
Model	4.68	8	0.59	25.63	< 0.0001	Significant
A	3.17	1	3.17	138.96	< 0.0001	Significant
B	1.15	1	1.15	50.24	< 0.0001	Significant
C	0.21	1	0.21	9.25	0.014	Significant
A^2	9.025E-004	1	9.025E-004	0.4	0.5451	Insignificant
B^2	0.038	1	0.038	1.67	0.2290	Insignificant
AB	0.1	1	0.1	4.53	0.0621	Insignificant
AC	6.75E-004	1	6.75E-004	0.03	0.8673	Insignificant
BC	7.5E-005	1	7.5E-005	7.5E-005	0.9555	insignificant

$$\begin{aligned} MS &= 14.12 + 0.93A - 0.072B \\ &-0.56C + 0.041AB \\ &-0.23AC - 0.13BC \end{aligned} \tag{4}$$

$$\begin{aligned} Flow &= 2.96 + 0.22A - 0.15B \\ &-0.054C - 0.038AB \\ &+0.015AC - 0.041BC \end{aligned} \tag{5}$$

$$\begin{aligned} VMA &= 13.71 + 0.51A - 0.31B \\ &-0.11C - 0.11AB - 0.0075AC + \\ &0.0025BC + 0.048A^2 + 0.098B^2 \end{aligned} \tag{6}$$

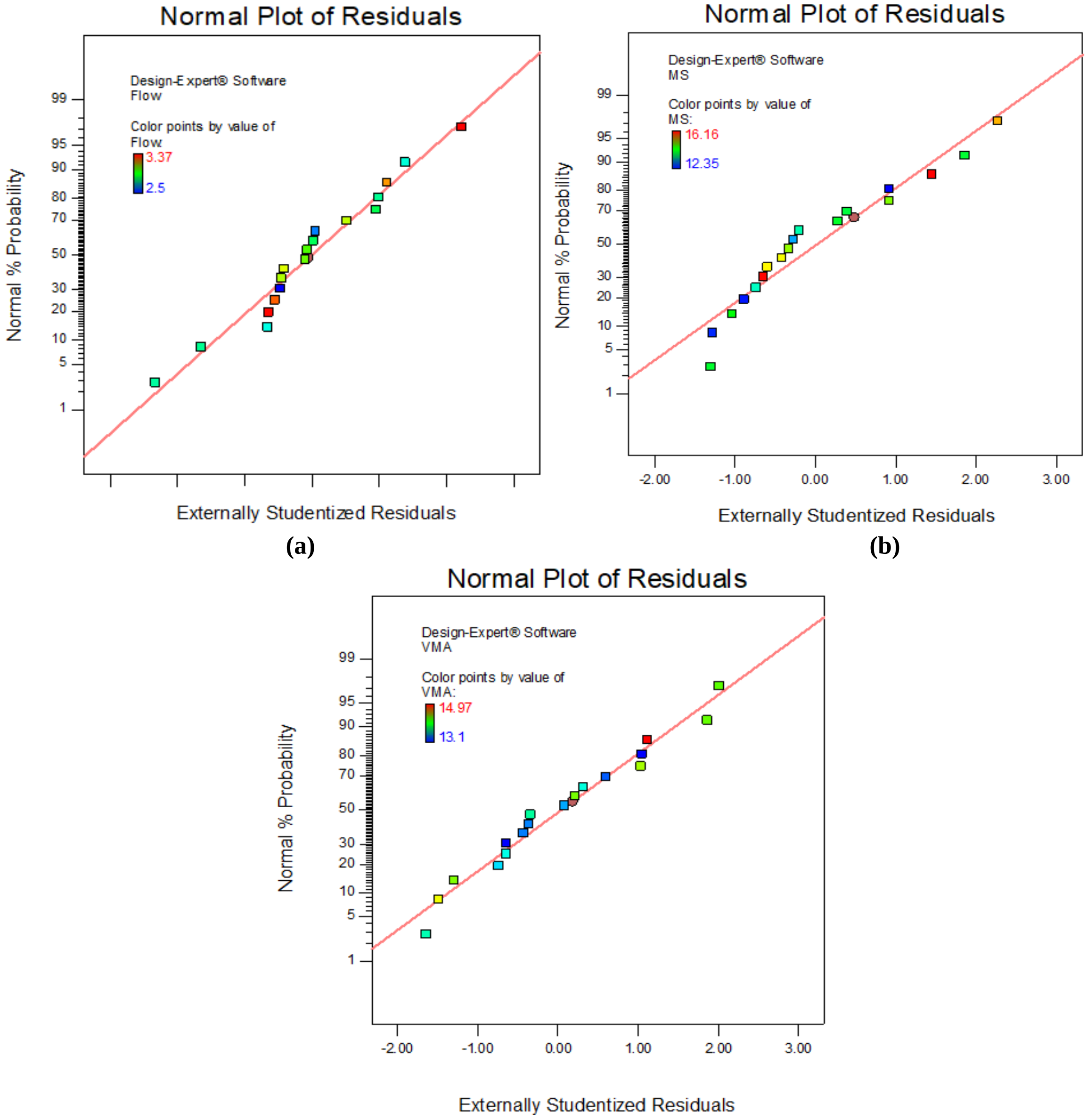
in which the terms *A*, *B* and *C*: are the RAP and waste oils content, and type of oil, respectively.

In order to check the adequacy of the developed models and the regression coefficients, the determination coefficient (R^2), adjusted R^2, predicted R^2 and adequate precision from ANOVA analysis in Design Expert are used, which are shown in Table 6 for the models for prediction of MS, flow and VMA. Value of R^2 is an indication of the goodness of fit (Korbahti and Rauf, 2009). R^2 values of 0.899, 0.897 and 0.958 for the model for predicting MS, flow and VMA, respectively, indicate that only less than, approximately, 10, 11 and 4% of the total variations are not explained by suggested models.

The adjusted determination coefficient values of 0.8294, 0.841 and 0.92 are high, indicating that the models are significant. The high values of R^2 and adjusted R^2 shows that there is a good agreement between the predicted and actual responses (Baghaee Moghaddam et al., 2015). The adequate precision values of 13.07, 13.81 and 17.44 for the models for MS, flow and VMA, respectively, are much higher than 4, implying that the models are highly accurate (Olmez, 2009). Moreover, the low difference between the adjusted and predicted R^2 indicates that the models are suitable for prediction of the MS, flow and VMA.

Analysis of Residuals and Diagnostic Plots

Figure 4 shows the normal probability of residuals for MS, flow and VMA models. Normal probability plot is used to check the normality of data. Following a linear trend indicates that the plot is good and the data are normal. As can be seen, in all plots, the residuals fall on the straight line, indicating the normal distribution of the errors and goodness of model for prediction of MS, flow and VMA. Figure 5 shows the predicted versus actual responses. As can be seen, there is a good agreement between the values predicted by the developed model and the actual MS, flow and VMA values measured in laboratory.



(a) (b)

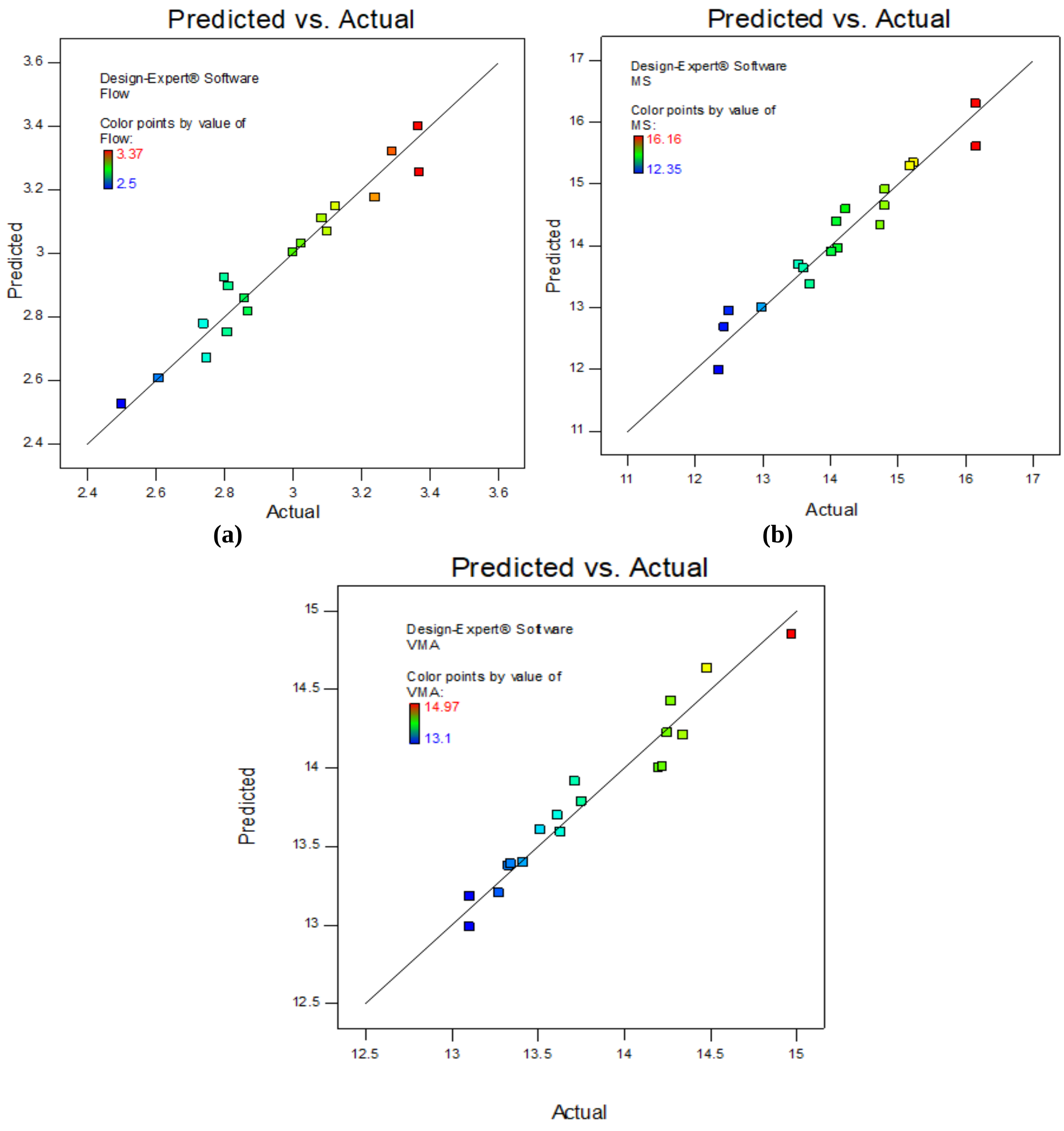
(c)

Fig. 4. Residual normal probability plot: a) flow; b) Marshall stability; c) VMA

Table 6. Indices of model adequacy

	Index	SD^a	Mean	CV^b	R^2	Adjusted R^2	Predicted R^2	Adequacy precision
Response	Marshall stability	0.51	14.12	3.61	0.8996	0.8354	0.7039	14.68
	Flow	0.099	2.96	3.34	0.8977	0.8413	0.6634	13.819
	VMA	0.15	13.81	1.09	0.9580	0.9206	0.8085	17.44

^{a} Standard deviation; ^{b} Coefficient of variation



(a) (b)

(c)

Fig. 5. Predicted versus actual values: a) flow; b) Marshall stability; c) VMA

Perturbation Plot

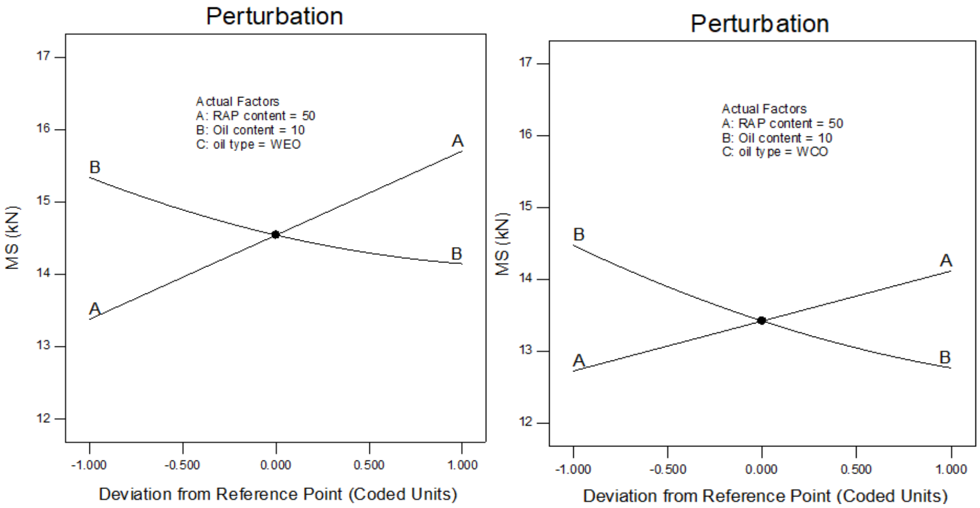
Perturbation plots are used to compare the main effects of independent variables at a selected point in the considered design space. Figures 6-8 show, respectively, the perturbation plots of the MS, flow and VMA. To generate a plot for a response, one of the variables is changed over its range while the other variables are held constant. In drawing the plots in Figures 6-8, the constant values of oils content and RAP content are 10 and 50%, respectively. It is clearly observed that MS, flow and VMA increase with increasing RAP content and decrease with increasing oil content. Grow of MS with increase in RAP content is attributed to the increase of stiffer aged binder in the mixture. However, inclusion of oil in the mixture results in softening of aged binder and reduction of stiffness, Marshall stability and VMA.

The variation of flow with RAP content in the mixtures rejuvenated by 10% of WEO and WCO can be related to the excessive softening and decrease of cohesion in the mixtures containing 25% of RAP, resulting in failure of specimen at a lower diametrical deformation, and contribution of more aged binder in the mixtures containing 75% of RAP to coat virgin aggregate particles, resulting in more deformation to be sustained before failure. The decrease of flow with increasing oil content in the mixtures containing 50% of RAP can be described by the increased softening and reduction of cohesion with increasing oil content. The increase of VMA with increasing RAP content in mixtures rejuvenated by 10% of oils is due to the reduction of workability and increase of resistance against compaction and air voids content.

The drop of VMA with increasing oil content in the mixtures containing 50% RAP is attributed to the increase of workability with increasing oil content, which results in decrease of air voids content and VMA. As can be seen in Figures 6 to 8, the slope of responses variation with RAP content is higher than that with oil content, indicating that RAP content has more effect on MS, flow and VMA than oil content. This is also seen in Tables 3-5 in which the F-value of term A is more than that of term B. It can also be seen in Figures 6-8 that the MS, flow and VMA of the mixtures rejuvenated by WEO is higher than those rejuvenated by WCO. Waste cooking oil has more softening effect on the virgin and aged binder resulting in more reduction of binder cohesion, stability and deformation at failure, with more increase in workability and reduction of VMA.

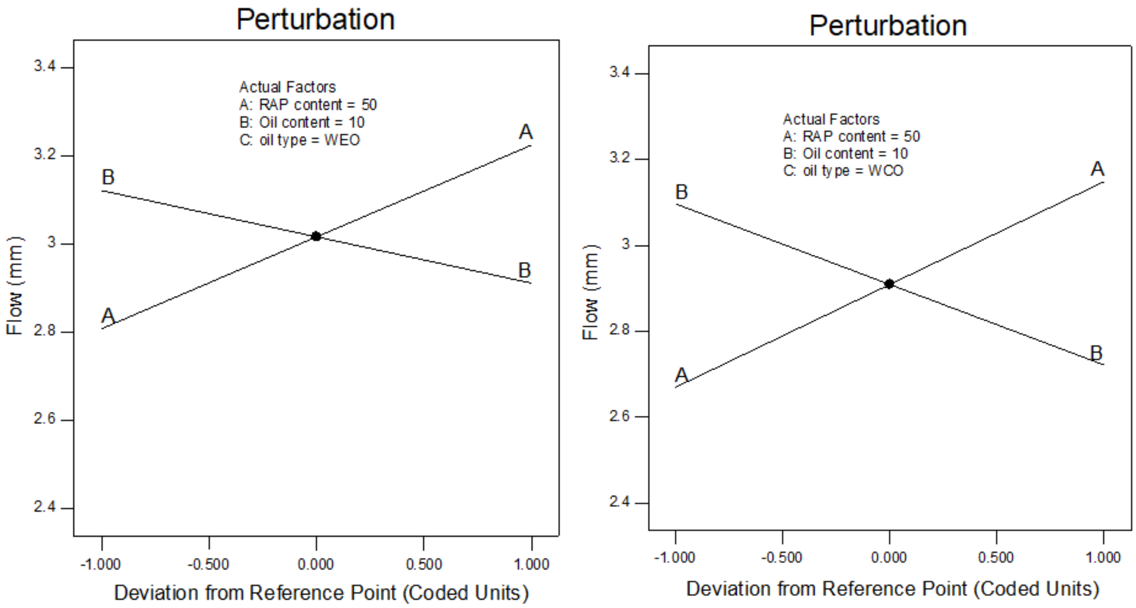
2D and 3D Plots of Responses

The interaction effects of independent variables on the investigated responses can be analyzed using the interaction plots, 2D and 3D plots generated by the software based on the proposed model. In this section, the main effects of RAP content, oil content and oil type and their interaction effects on the responses of MS, Marshall flow and VMA are presented.



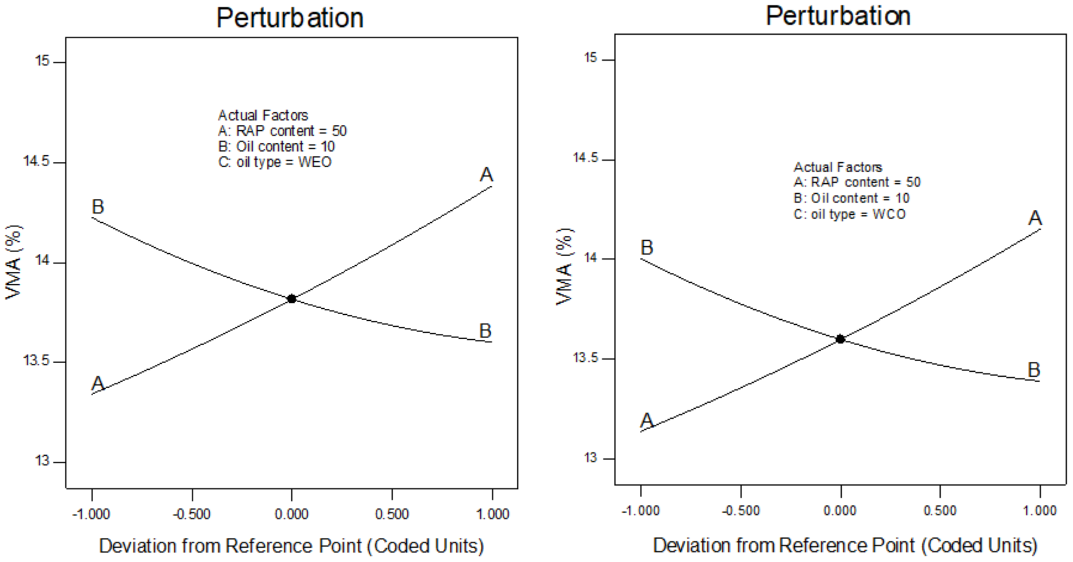
(a) **(b)**

Fig. 6. Perturbation plots for Marshall stability: a) WEO; b) WCO



(a) **(b)**

Fig. 7. Perturbation plots for flow: a) WEO; b) WCO

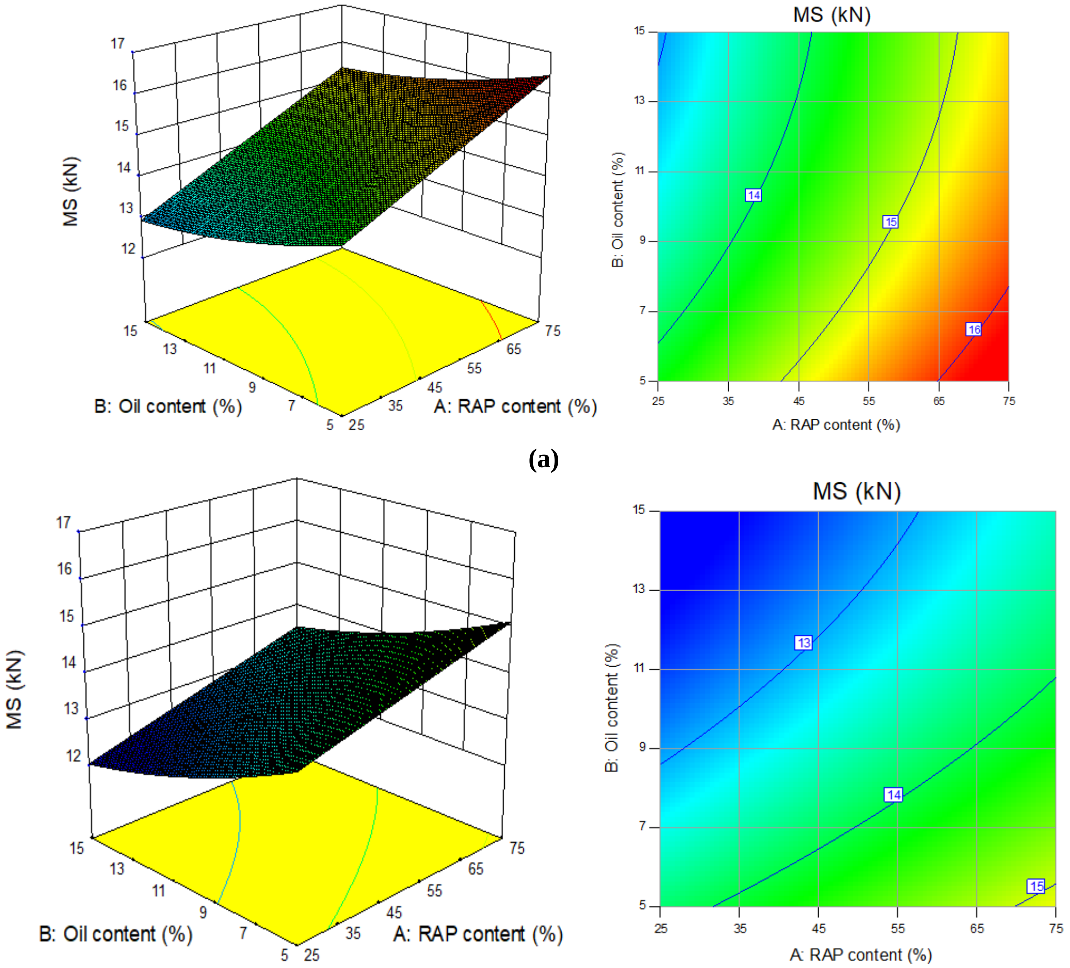


(a) **(b)**

Fig. 8. Perturbation plots for Marshall stability: a) WCO; b) WEO

Marshall Stability

Marshall stability is traditionally used as an index for the ability of asphalt mixtures to sustain traffic load at high temperatures. Specifications require higher MS for the mixtures used in pavements of highways with higher anticipated traffic. Figures 9a and 9b show the 2D and 3D plots of the variation of MS with RAP and oil content for the waste engine and waste cooking oil, respectively. As can be seen, the MS increases with increasing RAP content and decreases with increasing oil content. The increase of MS with RAP content is attributed to the stiff aged binder in RAP, and its drop with increasing oil content is attributed to the softening effect of oils on the binder and the decrease of cohesion in the mixture of virgin and aged binder.



(a)

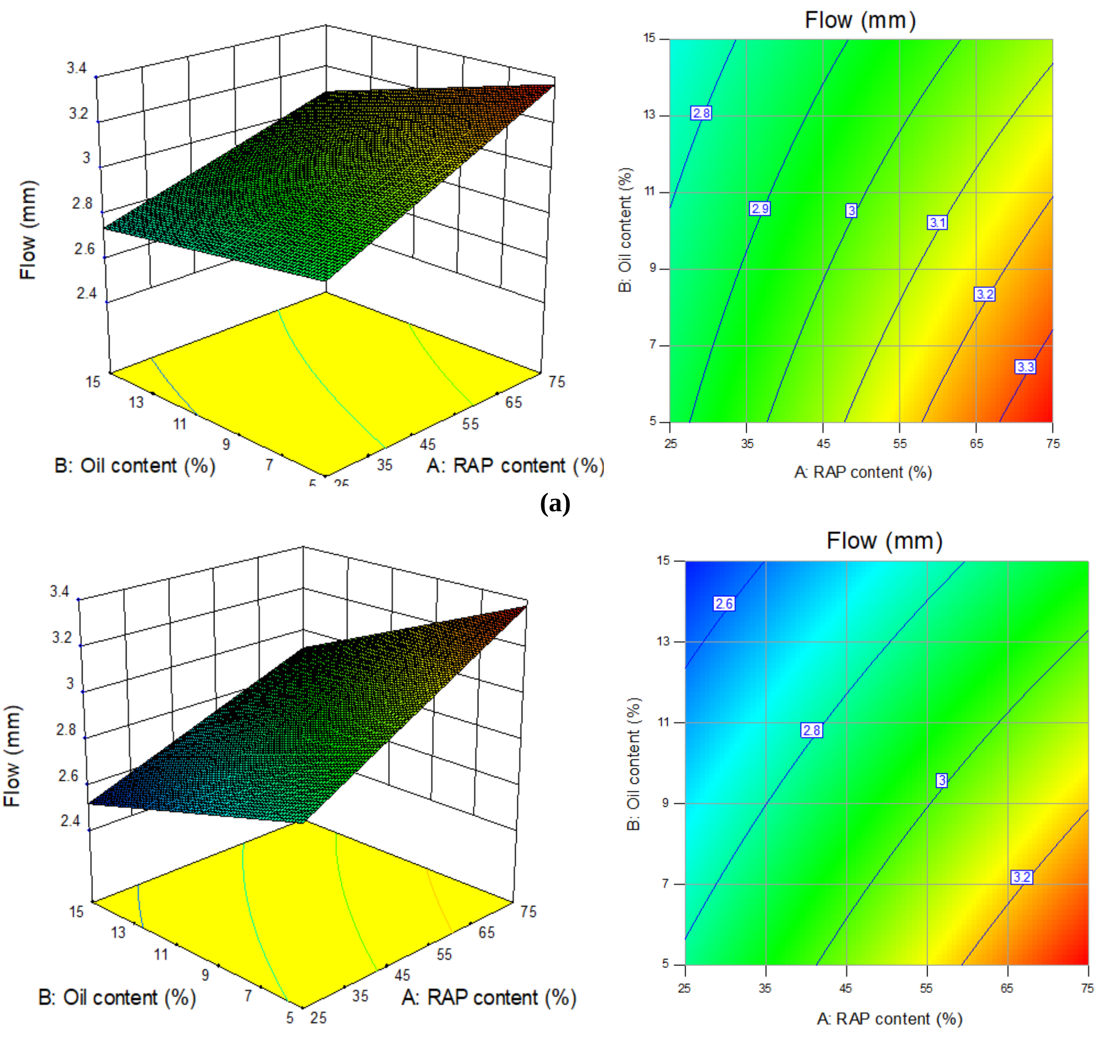
(b)

Fig. 9. 2D and 3D interaction plots for Marshall stability of mixtures containing: a) WEO; b) WCO

For both rejuvenators, the highest MS is achieved by using 5% of oil content. The figures also reveal that higher MS is achieved by using WEO than using WCO, indicating that WCO has more softening effect on the binder than WEO. From these figures it can be seen that the rate of increase of MS with RAP content is higher at lower oil content, indicating that RAP and oil content have interaction effect on the Marshall stability.

Flow

Flow is the diametrical deformation of the samples in Marshall test upon the failure under applied vertical load. Flow of a mixture is affected by the stiffness and cohesion of the binder. Specifications require a minimum flow for the mixtures to make sure that the mixture will not crack at intermediate and low temperatures, and a maximum value for flow to make sure the mixture will not excessively deform at higher service temperatures. Figures 10a and 10b show the 2D and 3D plots of the variation of flow with RAP and oil content for the mixtures rejuvenated with WEO and WCO, respectively. As can be seen, the flow increases with increasing RAP content and decreases with increasing oil content. For both rejuvenators, the rate of increase of flow with RAP content decreases with increasing oil content, indicating that RAP and oil content have interaction effect on flow. Figures also reveal that, the mixtures containing WCO have lower flow than those containing WEO.



(a)

(b)

Fig. 10. 2D and 3D interaction plots for Marshall flow of mixtures containing: a) WEO; b) WCO

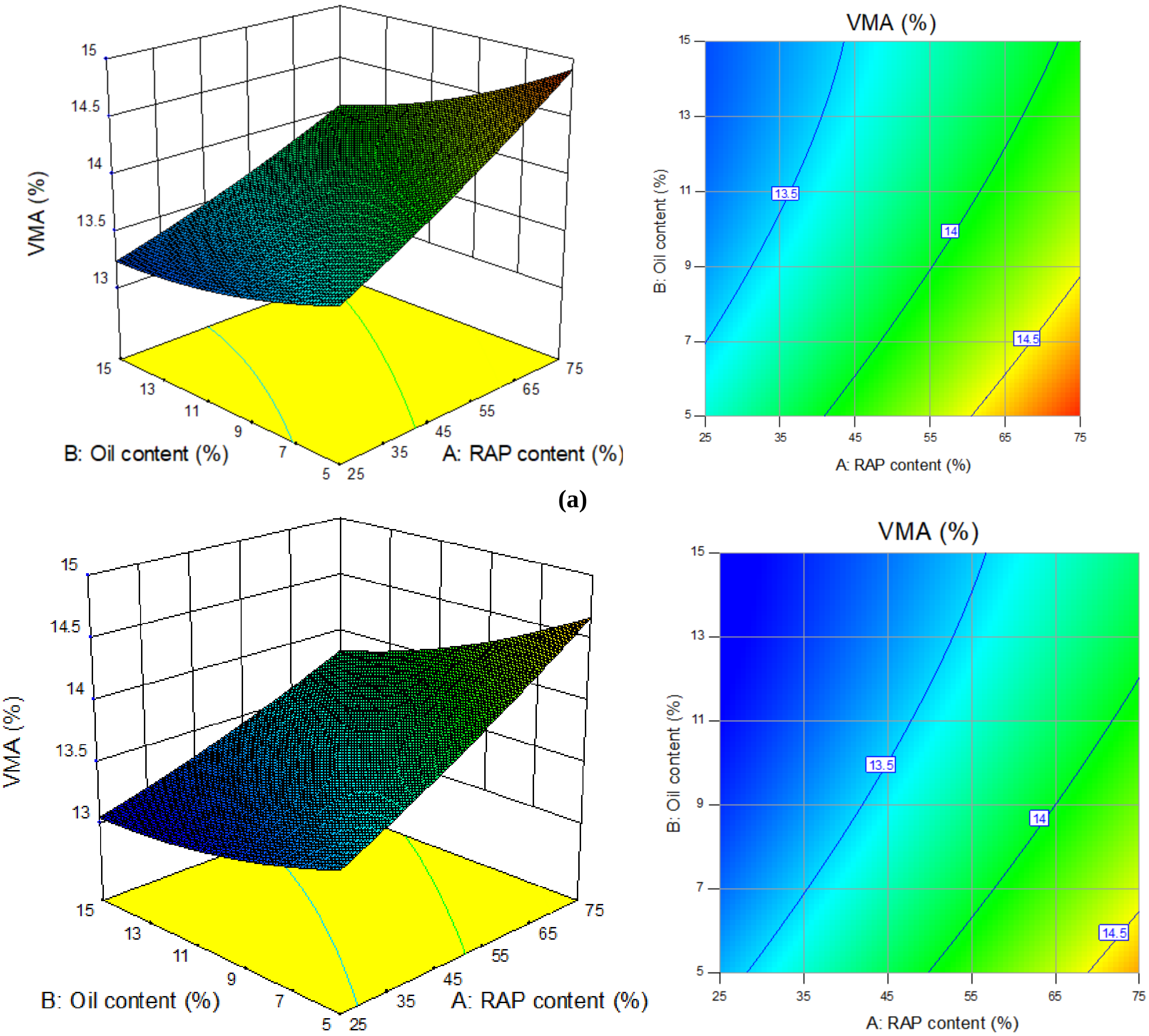
VMA

Voids in mineral aggregates (VMA) of a compacted asphaltic mixture include the air voids and the voids filled with effective asphaltic binder. A minimum VMA is required by specifications to ensure that the aggregate particles are coated with the binder at a thickness that ensures the mixture durability. Lower VMA due to dense gradation results in a mixture with lower space for the binder, which looks dry and is not durable.

Figures 11a and 11b show the 2D and 3D plots of the variation of VMA with RAP and oil content for the WEO and WCO, respectively. As can be seen, VMA grows with increasing RAP content and drops with increasing oil content. The increase of VMA with increasing RAP content is attributed to the decrease of workability and increase of air voids in compacted mixture, when the RAP content rises. Also, the decrease in VMA with increase of oil content is due to the increase of workability and more compaction resulting in lower air voids in the mixture. The figures also reveal that the VMA of the mixtures rejuvenated by WEO is higher than those rejuvenated by WCO. From these figures it can be seen that the rate of increase of VMA with RAP content is higher at lower oil content, indicating that RAP and oil content have interaction effect on the VMA. Also, the rate of increase with RAP is higher for the mixtures containing WEO than those containing WCO, indicating that RAP content and type of oil have interaction effect on the VMA.

Optimization

In recycled asphaltic mixtures, it is aimed to maximize RAP content and produce a mixture with the same or better performance than the control mixture. In this study, using the optimization in Design Expert software, the target for MS stability was set to that of the control mixture, while the flow was set to be within the range of 2.5 to 3.5 mm, and VMA to be at least 13%, as required by specification. Two solutions were provided, one for WEO and the other for WCO rejuvenated mixture, while the RAP content was set to be maximized. Table 7 shows the properties of the solutions and those for control mixture. As can be seen, using 10.6% of WCO allows applying 75% of RAP in the mixture, with the properties similar to the control mixture. However, in case of using WEO, the maximum RAP content to be allowed is 51.77%.



(a)

(b)

Fig. 11. 2D and 3D interaction plots for VMA of mixtures containing: a) WEO; b) WCO

Table 7. Properties of optimum solution

Properties	Solution 1	Solution 2	Control mixture
RAP content (%)	51.77	75	0
Oil content (%)	15	10.649	0
Type of oil	WEO	WCO	0
MS (kN)	14.23	14.022	14.19
Flow (mm)	2.923	3.11	2.785
VMA %	13.63	14.1	13.49

CONCLUSIONS

In this research, Different dosages of waste cooking and engine oil were used as rejuvenator in mixtures containing different percentages of reclaimed asphalt pavement, and the Marshall stability, flow and voids in mineral aggregates (VMA) were evaluated using response surface methodology (RSM). Over the range of RAP and oil contents used in this study, the following results can be drawn.

- Response surface methodology was appropriately used for modeling and investigating the properties of recycled asphalt mixture and the main and interaction effects of independent variables on the properties.
- One factor analysis in RSM showed that, Marshall stability, flow and VMA increase with increasing RAP and decrease with increasing oil content in the mixtures. The responses of the mixtures rejuvenated with waste engine oil were found to be higher than those rejuvenated with waste cooking oil.
- Linear two factor interaction model was generated for predicting flow and Marshall stability of the mixtures, and the VMA was well predicted using quadratic model.
- RAP and oil content have interaction effect on Marshall stability, flow and VMA responses. The higher the oil content, the responses grows at lower rate with increasing RAP content.
- Interaction effects were found between RAP and oil content and type of oil on the Marshall stability, flow and VMA. Waste cooking oil has more softening effect on the binder than waste engine oil.
- Using the rejuvenators allows high RAP concentration in the mixtures with almost the same properties as those of the control mixture without RAP content. Using 10.61% of WCO and 15% of WEO allows incorporating 75 and 5.77%, respectively, of RAP into mixture.

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